3-D GIS technique for seismic hazard assessment of subduction zone region

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Abstract

Globally areas of highest seismicity are located at subduction zone interfaces between converging tectonic plates. To model the complex geometry of subduction zone seismic source zones, it is advantageous to develop a 3-D Geographical Information System (GIS) to visualise and characterise the plate boundary tectonic structures. The GIS supported the definition of the orientation and dip angle of the subducting plates and the depth distribution of the earthquakes. The system also enables a detailed extraction of earthquakes to support recurrence rate calculations in Probabilistic Seismic Hazard Assessment (PSHA).

Japan and the Philippines are two countries straddling complex plate boundaries. Japan is situated at the junction of four plates; the Pacific Plate, the Philippine Sea Plate and the Amur Plate and the Okhotsk Plate, where subduction of the Pacific Plate underneath the Okhotsk Plate and the Philippine Sea Plate is occurring along the Japan Trough and the Izu-Bonin Trench respectively. The Philippines is located between the Philippine Sea Plate and the Sunda Plate where the Sunda Plate subducts along Manila Trench in the western extent and the Philippine Sea Plate subducts along the Philippine Trench in the eastern extent. Understanding the complex geometry and earthquake recurrence rates along these plates is essential in the development of seismic hazard evaluation for those regions.

Keywords: seismic hazard, subduction zone, Geographical Information System

1. INTRODUCTION

Japan and the Philippines are both located on convergent plate boundaries which create high seismicity activity. The convergence of the plates builds up the stress along plate boundaries and earthquakes are generated when the stress is released. The constant movement of the plates creates frequent large earthquakes in these two countries and elevates seismic hazard and risk.

Probabilistic Seismic Hazard Analysis (PSHA) is used to quantify seismic hazard by modelling the uncertainties of location, size and the intensity of ground shaking to determine site-specific ground motion parameters to evaluate the response of site and structure under seismic motion. In development of a PSHA, the definition of the seismo-tectonic source zones (source model) is required to quantify the geographical distribution of the earthquake activity. The source model describes both area sources or fault sources of which can represent areas where the seismicity is assumed to be homogeneous and can be quantified.

Plate boundaries have widely been defined by seismicity in 2D (e.g. Bird 2003) and the subsurface structure could be estimated by contouring slab related seismicity (e.g. Gudmundsson and Sambridge 1998). To visualise the subsurface structure in relation to the plate boundaries, 3D GIS can be served as a direct and convenient method.

As such, GIS is an effective tool to help to define the source zones based on the distribution of observed seismic activity together with geological and tectonic understanding in 3D. GIS helps to estimate the seismic activity represented as the rate of occurrence of earthquakes which is generally described in terms of magnitude recurrence relationship in the form of the 'Gutenberg-Richter' (Gutenberg & Richter 1954) relationship. The recurrence relationship can be estimated by using the recorded earthquake data within a source zone.

This paper presents examples of PSHA source model development in Japan and the Philippines where GIS was used to help to develop the seismic source model.

STUDY AREAS

Compared with "typical" subduction zones, for example Chile, where the Nazca Plate subducts beneath the South America Plate, Japan and the Philippines are located in the plate junction where a number of plates are undergoing subduction in a complex geometry. These two areas are presented in this paper where the subduction process is more complex.

Japan lies along the western edge of the Okhotsk Plate and the Amur Plate (**Figure 1 Regional Tectonic setting of JapanFigure 1**) and is bounded to the east and south by Pacific and Philippine Sea Plates. The main tectonic structures along the plate boundaries broadly consist of the Japan Trench and the Izu-Bonin Trench to the east and the Nankai Trough to the south. The Japan Trench is an expression of undergoing subduction of the Pacific Plate underneath the Okhotsk Plate and the Amur Plate and the Izu-Bonin Trench is an expression of the undergoing subduction of the Pacific Plate underneath the Philippine Sea Plate. The Philippines Sea Plate subducts obliquely (NW) beneath south-western Honshu and Shikoku along the Nankai Trough.

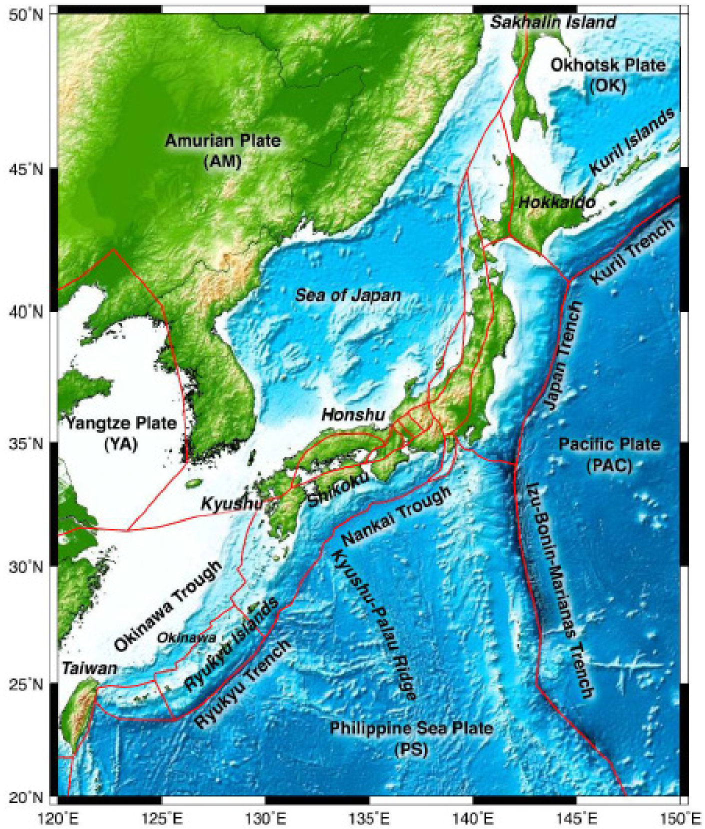

Figure 1 Regional Tectonic setting of Japan (Loveless & Meade, 2010)

The Philippines is between the Philippine Sea Plate and the Sunda Plate (Error! Reference source not found.). The Sunda Plate subducts along the Manila Trench in the west and the Philippine Sea Plate subducts along the Philippines Trench in the east.

The complex geometry of the subduction plates in the two countries can be visualised in 3-D GIS to help to develop source seismic model.

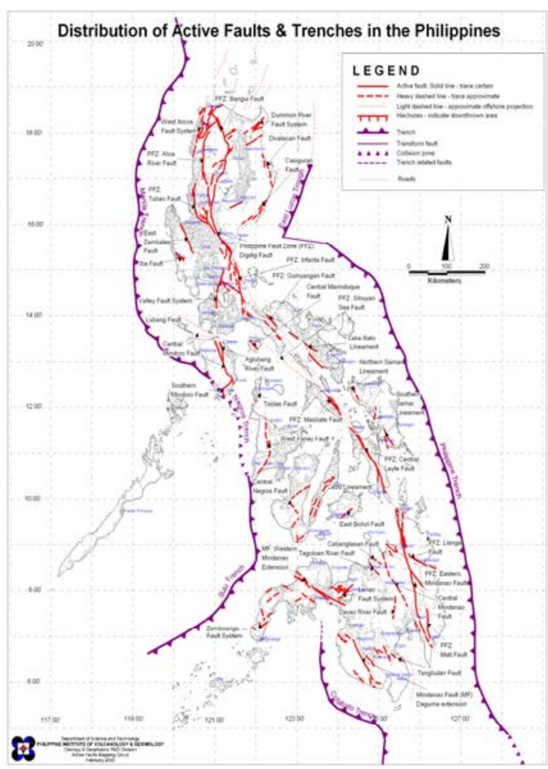

Figure 2 Regional tectonic setting of the Philippines (Phivolcs, 2012)

2. GIS APPLICATION FOR THE TECTONIC MODEL

The complete earthquake catalogue for Japan is plotted in the model (**Figure 3**). The earthquake catalogue has been compiled from instrumental data and historical data using United State Geological Survey (USGS), International Seismological Centre (ISC) website and historical records published in 1998 by the National Astronomical Observatory of Japan (NAO). In the Philippines model, the earthquake data was compiled from the Philippine Institute of Volcanology and Seismology (PHIVOLCS) and IRIS (**Figure 4**). Both earthquake catalogues have had aftershocks removed using the procedure suggested by Gardner & Knopoff (1974).

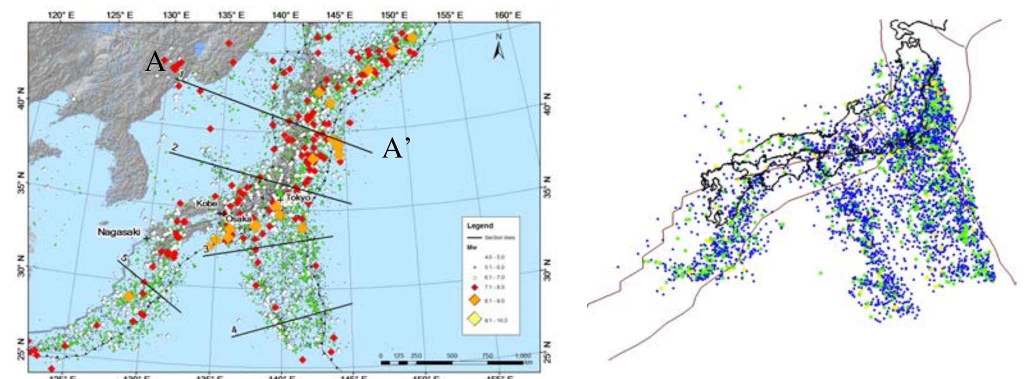

Figure 3 Compiled Catalogue after aftershock removal for Japan, (left) in 2-D and (right) in 3-D

The earthquake data shows the seismicity varies along the same plate boundary due to oblique convergent to the strike of the subduction zone and complicated interaction of the plates. The activities also vary with depth because tension and compression changes along the subducting plate which affect the inter-plate and intra-plate earthquake distribution. To evaluate the seismic hazard, a simplified model of fault planes is made. The model represents their general orientation and dimensions which characterise the seismic activity for the analysis. Orientations of the faults are determined by reviewing the 3-D model which helps to draw proper sections to estimate the dip angle of the plate.

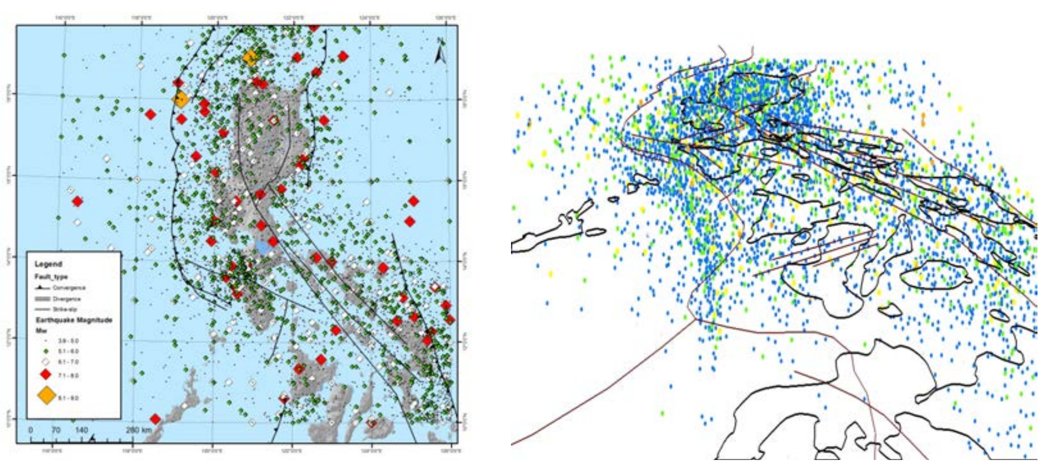

Figure 4 Compiled Catalogue after aftershock removal for the Philippines, (left) in 2-D and (right) in 3-D

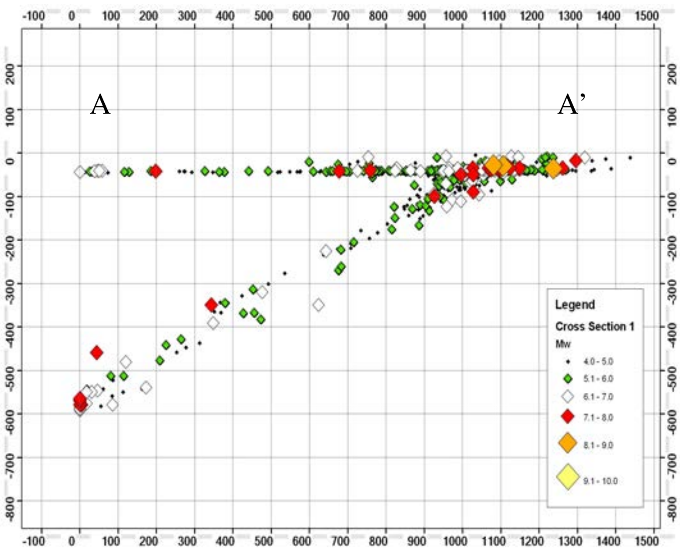

Figure 5 Cross Section A-A' shown on plan in Figure 3

Figure 3 shows a few section lines that have been drawn for the Japan model and **Error! Reference source not found.** demonstrates a cross section from one of these section lines. The earthquake data can also be extracted for each source zone using GIS to measure the seismic activity.

3. EXAMPLE OF JAPAN

3.1 TECTONIC STRUCTURE

The Japan 3-D GIS model demonstrates the subducting Pacific Plate and the Philippine Sea Plate clearly below 50km at the plate boundaries along the Japan Trench, the Izu-Bonin Trench and the Nanki Trough. The orientation and dip of the plate were also estimated using GIS and they are described as follows:

3.1.1 Japan Trench

For about the upper 50km depth, this process is characterised by shallow crustal earthquakes. A depth of 33km is assigned to crustal earthquakes whose depths could not be resolved. The subducting slab extends down to 500km depth and is characterised by a gentle dip angle of approximately 25º and slightly deeper at 27 º further to the south.

3.1.2 Izu-Bonin Trench

The earthquakes show the orientation of the Pacific Plate subduction changes from NWW to SWW. Earthquakes concentrated within the top 50km are characterised as shallow crustal events. The subduction dip angles become steeper from about 45º to very steep to about 70º. The deep earthquakes became more dispersed from about 300km to 500km depth. The subduction underneath the Izu-Bonin Trench appears to be more ductile in nature than that of the Japan Trench subduction, with the deep earthquakes underneath the Izu-Bonin Trench appearing to be comparatively smaller in magnitude.

3.1.3 Nankai Trough

Earthquakes near the Nankai Trough are concentrated at shallow depth within 100km and the earthquakes along the subduction are not as well developed as those along the Pacific Plate. The subduction earthquakes only extend down to about 300km.

3.2 SOURCE MODEL FOR SUBDUCTION PLATE

The earthquake source model has been divided into area sources above a depth of 100km and fault model sources for deeper events as follows:

- Shallow Crustal Area Source (0 - 50km)
- Intermediate Subduction Area Source (>50 - 100km)
- Fault Model Source 1 (>100 - 200km)
- Fault Model Source 2 (>200km - 300km)
- Fault Model Source 3 (>300km - 500km)

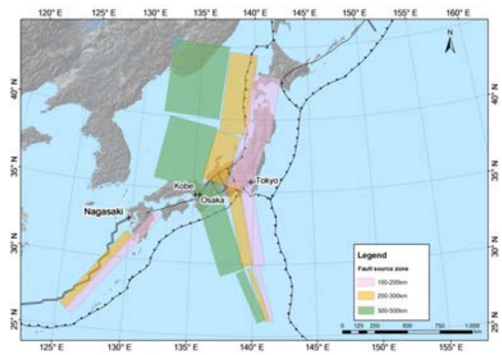

Figure 6 Fault source of the subducting plates

Shallow Crustal Area Source includes shallow crust and interface earthquake. The detailed definition of Shallow Crustal Area Source was taken into account of NILIM (2003).

Intermediate Subduction Area Source and Fault Mode Source were not clearly defined in NILIM (2003) and definition was assisted by the 3D model in GIS. Based on seismicity distribution in 3D model, the earthquakes in these sources are classified as intraslab events.

The Fault Model along the Japan Trench and Izu-Bonin Trench both are segmented into northern and southern part to better capture the orientation and dip of the subducting Pacific Plate (**Figure 6**). The general trench of the fault sources are broadly consistent with slab structures defined in Gudmundsson & Sambridge (1998) (**Figure 7**).

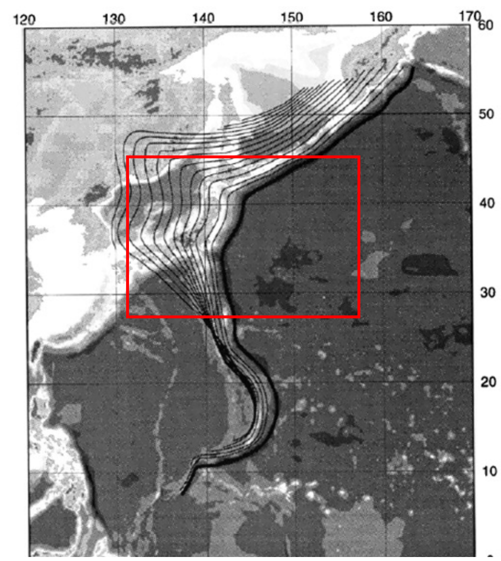

Figure 7 The slabs of northwest Pacific presented in Gudmundsson & Sambridge (1998). The red box bound the approximate extent of Figure 6.

The modelled fault planes were further put into 3-D GIS to verify their orientation and dip (**Figure 8**).

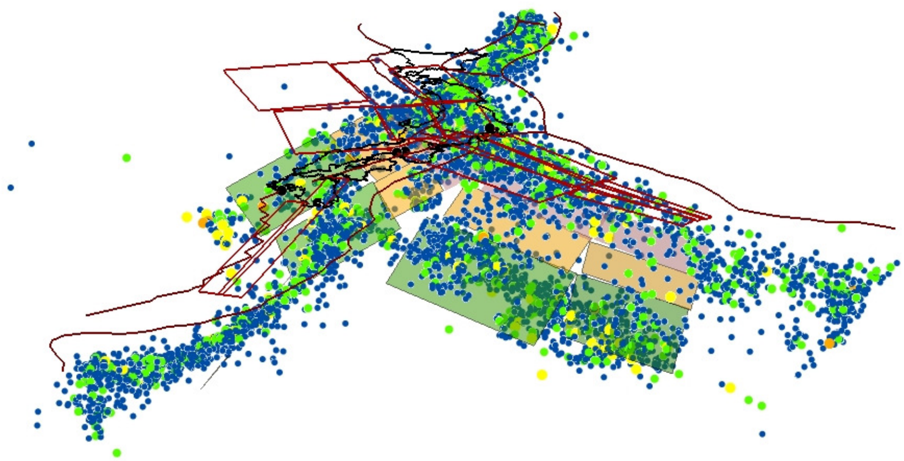

Figure 8 The modelled fault planes plotted with the earthquake data

3.3 EARTHQUAKE RECURRENCE

An understanding of earthquake recurrence can be determined from the slip rate of a fault or observed seismicity with respect to earthquake magnitude. In current study, observed seismicity was used to show how GIS can be assisted to develop recurrence relationship for Intermediate Subduction Area Source and Fault Mode Source, which are associated with intraslab events.

GIS extracts earthquake data for recurrence calculation. **Figure 9** shows the polygon drawn in GIS which was used to extract the earthquake data. The extracted data was used subsequently to estimate the seismic activity by "Gutenberg-Richter" relationship. The calculated recurrence *a* and *b* values are be assigned to the fault source zone in PSHA to represent the seismic activity.

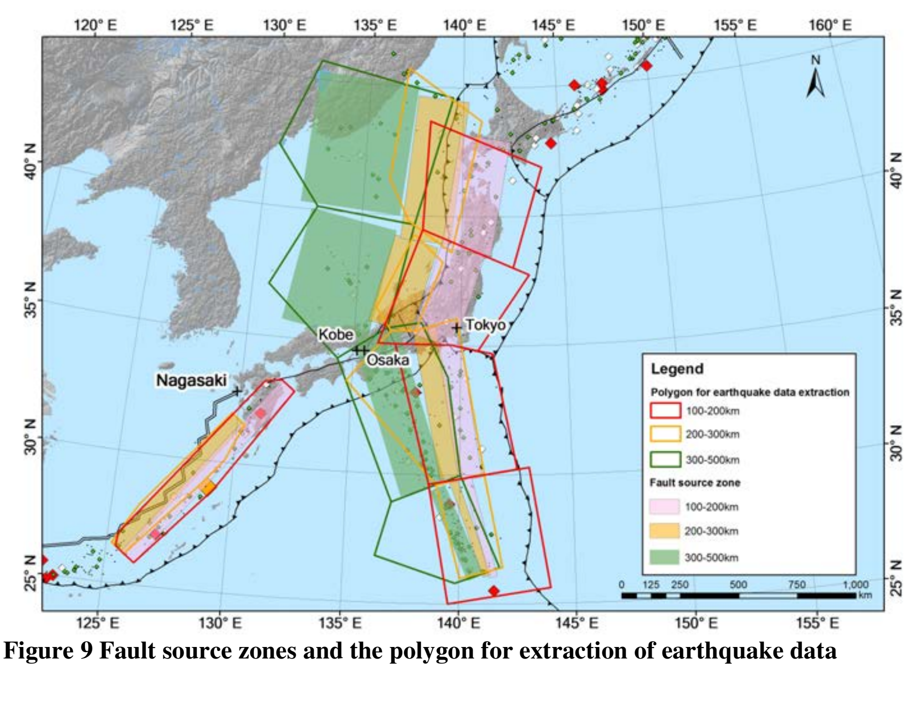

Figure 9 Fault source zones and the polygon for extraction of earthquake data

4. CONCLUSIONS

To develop a PSHA model in a tectonically complex region, 3-D GIS is an effective tool to visualise the earthquake distribution and provide a general representation of tectonic structure. GIS can be used as an effective tool to help to define the source zones based on the distribution of observed seismic activity together with geological and tectonic understanding. GIS helps to estimate the seismic activity represented as the rate of occurrence of earthquakes. This faciliates source zone definition and recurrence rate calculation in the early steps of PSHA. The resultant PSHA will be a better reflection of the actual seismo-tectonic conditions and therefore provide a better estimate of the seismic hazard and seismci risk.

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