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Geo-Hazard

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Seismotectonic, Potential Seismic and Volcano Hazard of Minahasa Peninsula, Eastern Indonesia

Seismotektonik, Potensi Bencana Gempabumi dan Gunungapi di Semenanjung Minahasa, Indonesia Timur

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Abstract - The Minahasa Peninsula is located in the western flank of Mollucca seismotectonic zone existed, where are four active tectonic plates colliding from east to west are the Philippine Oceanic Plate, Halmahera Micro Continental Plate, Mayu Ridge Micro Oceanic Slab Plate and the Minahasa Peninsula Micro Continental Plate. The result of the probabilistic seismic hazard assessment in Manado City and surrounding area, Zone I (site class SE), Zone II (site class SD) and Zone III (site class SC), shows the building and non building for risk category I, II, III and IV, has the seismic disign category D. Building and non building in Zone I (SD1=0,80g) with risk category I, II, III has structure seismic design category E and risk category IV has seismic design category F.

The correlation of seismotectonic, structural geology, and seismicity to the volcanic centers distribution in this region, shows the Minahasa Peninsula volcanoes can be divided into two regions are the compressional and extentional volcanoes tectonic regions. To mitigate the seismic risk in this region, the structure for building and non building contraction is recommended to follow the procedures for planning earthquake resistance for building structures and non building (BSN, SNI 1726-2019). On another hand, for potential volcano hazard, recommended followed the guidance map of the volcanic hazard prone region by The Center for Volcano and Geological Hazard Mitigation, Geological Agency of Indonesia.

Keywords: Mollucca seismotectonic zone, potential seismic and volcanoes hazard.

Abstrak - *Semenanjung Minahasa terletak di sayap barat zona seismotektonik Maluku, dimana empat lempeng tektonik berbenturan dari timur ke barat, yakni Lempeng Tektonik Laut Philipina, Lempeng Mikro Benua Halmahera, Lempeng Tunjaman Mikro Samudera Punggungan Mayu dan Lempeng Mikro Benua Semenanjung Minahasa. Hasil penilaian potensi bencana kegempaan probabilistik Kota Menado untuk Zona I (kelas situs SE), Zona II (kelas situs SD) dan Zone III (kelas situs SC), menunjukKan bangunan gedung dan non gedung dengan kategori risiko I, II, III dan IV, memiliki struktur berkategori seismik desain D. Gedung dan non gedung pada Zona 1 (SD1=0,80g) dengan kategori risiko I, II, III memiliki struktur berkategori seismik desain E dan kategori risiko IV memiliki struktur berkategori seismik desain F.*

Keterkaitan seismotektonik, struktur geologi dan kegempaan terhadap distribusi pusat-pusat gunungapi di daerah ini, menunjukan gunungapi-gunungapi di Semenanjung Minahasa dapat dibagi atas dua daerah, yaitu daerah gunungapi kompresi dan tarikan. Untuk memitigasi risiko gempabumi di daerah ini, konstruksi struktur untuk gedung dan non gedung, direkomendasikan mengikuti tatacara perencanaan ketahanan gempa untuk struktur bangunan gedung dan non gedung (BSN, SNI 1726-2019). Untuk potensi bencana gunungapi, direkomendasikan mengikuti peta panduan bahaya gunungapi dari Pusat Volkanologi dan Mitigasi Bencana Geologi, Badan Geologi Indonesia.

Katakunci: *Zona seismotektonik Maluku, potensi bencana gempabumi dan gunungapi*

INTRODUCTION

Minahasa Peninsula at the western part of the Molucca Sea Collision Zone controlled by three active tectonic plates are Pacific Oceanic Plate/Philippine Sea Micro Plate (eastern), Micro Continental Plate of Molucca (middle) and Australia Continental Plate (west). Study areas (Figure 1).

The implication of this asymmetric collision, made the Minahasa Peninsula as an active tectonics, seismicities and volcanoes region. Regional geology of this peninsula as a part of the eastern section of Sulawesi (east and southeast arms) composed of a Paleogene-Neogene subduction melange, glaucophane schists and ophiolites. The eastern section of this region which are consist of Banggai-Sula and Buton Island is a part of continental fragments which are translated to westwards from New Guinea along the major Sorong strike-slip faults. North arm of this peninsula and Sangihe Islands arc are the youngest section as the western volcano-plutonic belt (Hamilton, 1979). Minahasa Peninsula and Sangihe Island Arcs as an active tectonic regions are connected to south eastern Mindanao Island. The active tectonic background made the Minahasa Peninsula as a prone region of seismic and volcano hazards. In order to assess the potential seismic and volcano hazard of this region, applied several methodologies are the studies of regional tectonics, seismicity, seismotectonic, geology, gravity, microzonation, and potential seismic hazard assesment.

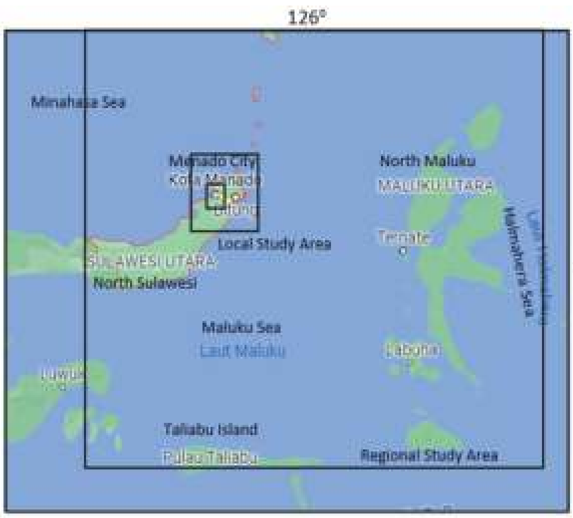

Figure 1. Index map of local and regional study areas.

SEISMOTECTONIC SETTING OF MOLUCCA ZONE

Seismotectonic of Molucca Zone is a center of a convergent tectonic activity, which has 140 km width and 555 km long. This region located in between Minahasa Peninsula and Halmahera Island Arcs. The boundaries of this region are the Philipine Trench (eastern) and Eastern Minahasa Peninsula Thrust Fault (western; Figure 2). The seismotectonic cross sections analyses from east to west, shown there are 1. Philippine Trench, 2. Thrust Fault of Halmahera as the magmatic chamber of Halmahera Volcanoes Arch, 3. Halmahera Thrust Belt, 4. Mayu Ridge Micro Oceanic Slab, 5. Eastern Minahasa Peninsula Thrust Fault. Walpersdorf et al. (1998) interpret the double collision zones in the Molucca Sea to be a result of the Eurasian-Philippine collision. The Sangihe collision activities started 25 Ma and the Halmahera collision started 7 Ma and the North Sulawesi Trench started 5–8 Ma, is much younger (Di Leo et al., 2012). Tectonic activity in this region is estimated from the early Miocene to the Present. Earthquakes measuring M $\geq$4 often occur in this zone. In generally, the earthquakes in this region shown the revers fault earthquakes focal mechanism, some of them shown the ablique revers fault focal mechanism, this fenomenon estimated due to different compression forces from the earthquake source (Figure 3).

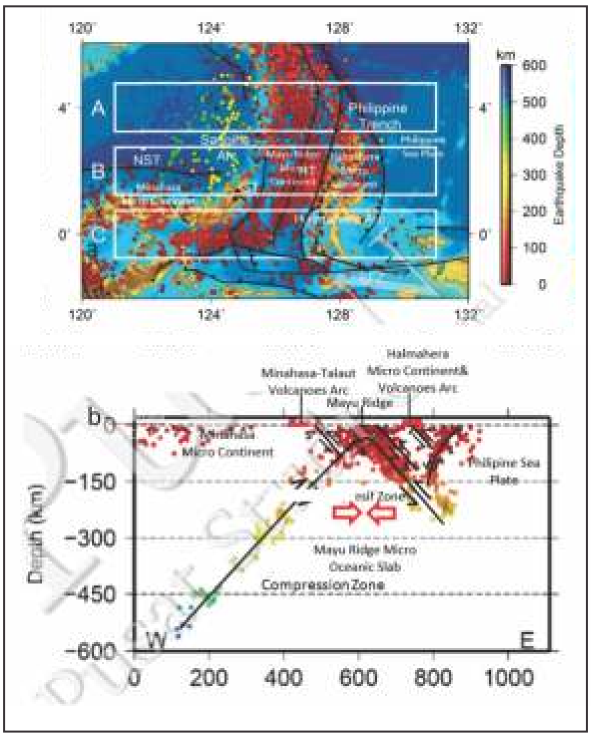

Figure 2. Seismotectonic Setting of Molluca Zone and vetical cross section B (b) modified from Shiddiqi, 2015 in Pusat Studi Gempa Nasional, 2017.

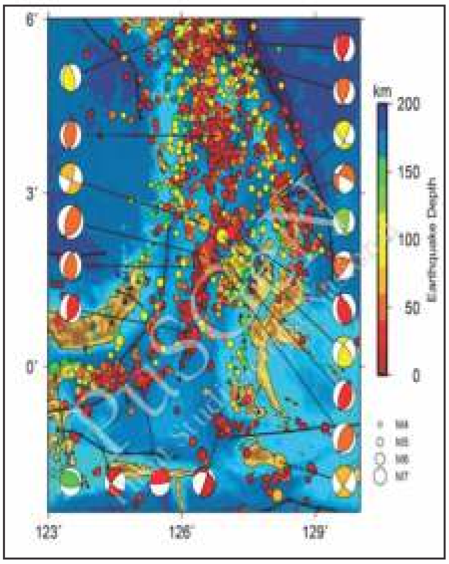

Figure 3. Focal mechanism distribution of earthquake dept $\leq$ 200 km and magnitude $\geq$6 in Molucca Zone (Shiddiqi, 2015 in Pusat Studi Gempa Nasional, 2017).

GEOLOGICAL AND GEOPHYSICAL OF MINAHASA PENINSULA

In order to find out more detailed the conditions of this region, evaluation and analyses of geological and geophysical is needed.

Geological of Minahasa Peninsula

Geological of Minahasa Peninsula consist of geomorphology, stratigraphy and lithology and structure geology.

Geomorphology of Minahasa Peninsula divided into 3 (three) blocks are Southern Block, Middle Block and Northern Block. Southern Block mainly consist of young volcano cone of Soputan and eroded cone of old Kasuratan Volcano. Middle Block consist old crater of Tondano Volcano, young volcano cones of Soputan and Mahawu. Northern Block consist old volcano cone of Klabat and young volcano cone of Tangkoko. Other geomorphology expression of this region is the linier eroded ridge of the Peleogene-Neogene marine sediment.

Based on the sistematic geological map of Manado, North Sulawesi on scale of 1 : 250.000 (Effendi & Bawono, 1997), Minahasa Peninsula consist of 6 (six) units of lithology are the Paleogene-Neogene Marine Sediment Unit (Ts), Quarternary Old Volcanic Unit (Qtv), Quarternary Young Volcanic Unit (Qv), Quarternary Coral Rift Limestone Unit (Ql), Quarternary Lake and River Deposite Unit (Qs) and Quarternary River Alluvial Deposite Unit (Qal). All of these lithologic units has different character one each other. Mainly of lithologic units are soft and losses (Qtv, Qv, Qs and Qal). The geological map of Minahasa Peninsula shown in Figure 4.

Geological structure of Minahasa Peninsula controlled by northwest-southeast main faults and north-south secondary fault. Northwest-sSoutheast faults consist of right lateral strike slip fault namely as south of Soputan Fault, south and north Tondano Faults, south Klabat and north Tangkolo Faults. North-south secondary faults are west and east Klabat right lateral strike slip faults.

Geological evolution of Minahasa Peninsula shown by the volcanic rock and carbonated marine sediment deposited at concurrent marine transgression and volcanic activity during the Miocene age. A regression and volcanic activity caused the explotion of Tondano, later followed by the Pangalombian eruption during the Pliocene/Pleistocene (Siahaan et al., 2005). Two calderas still dominate the present day topography and were transformed by Lake Linau and Lake Tondano (Le'cuyer et al., 1997). Other eruptions during Holocene is the Linau volcanoes complex which are consist of small volcanoes are Kasuratan, Tampusu, Kasuan, Linau and Masarang (after Yani, 2006)

Gravity

Geological map of Minahasa Peninsula in figure 2, shown the liniation of regional structural geology of this region mainly in the NW-SE direction, part of them in N-S direction. In order to clarify the continuity of these regional structural geology under surface, we used the residual anomaly and residual anomaly gravity second derivate (SVD). Base on SVD map, the liniation of regional structural geology under surface shown and controled by the contrasity between high and low residual anomaly gravity region (Figure 5).

The SE-NE vertical cross section, has been made at gravity anomaly and second vertical derivative (SVD) gravity anomaly and shown in Figure 6. The cross section of gravity anomaly show there are two region of low anomaly gravity are the low anomaly gravity of Tondano and Klabat. The low anomaly gravity of Tondano possibly as an old crater of Tondano Volcano, in other hand the low anomaly gravity of Klabat possibilty as the old crater of Klabat Volcano. The high anomaly gravity in this cross section, sugested as the volcanic neck and ridge of Lokon active volcano.

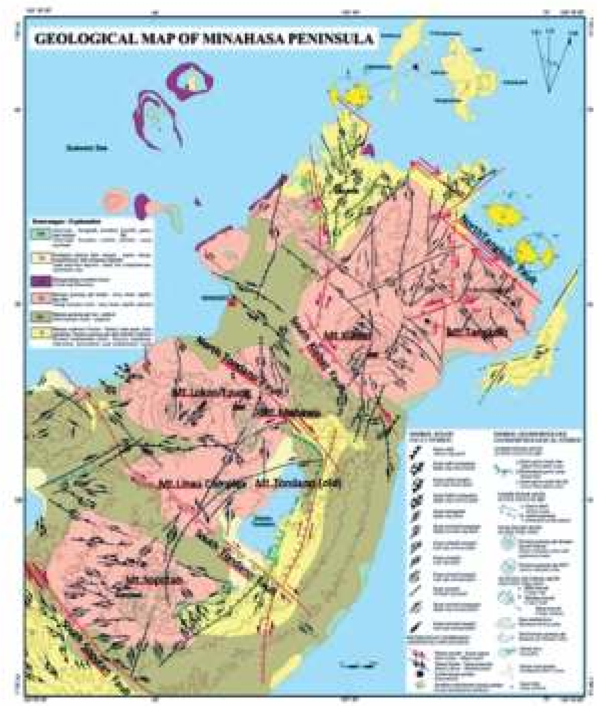

Figure 4. Geological map and volcano tectonic complexs of Minahasa Peninsula (Modified from Setiawan et al., 2002)

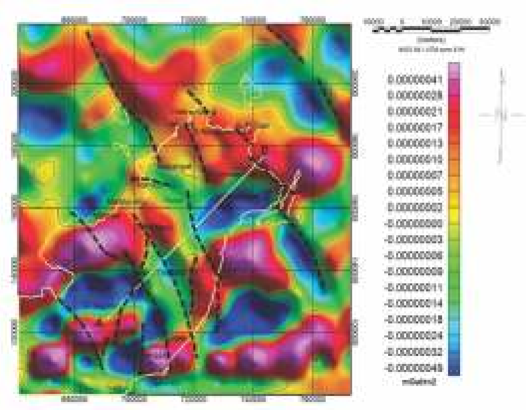

Figure 5. Second vertical derivative (SVD) and structural geology lineaments of Minahasa Peninsula.

POTENTIAL SEISMIC AND VOLCANIC HAZARD OF MINAHASA PENINSULA

The active tectonic collitions activities which are existed in and around Minahasa Peninsula, made this region as a potensial seismic and volcano hazards.

Potential Seismic Hazard

In order to assess the potensial seismic hazard of this region, used as the references are the basic maps of PGA, PSA (0,2 and 1 seconds) 2% probability 50 years at site class SB (BSN,SNI 1726 : 2019), shown in figure 7, 8 and 9.

Based on these basic seismic disater map, the Region of Minahasa Peninsula located at the region of PGA = 0,4 – 0,5 g and PSA= 0,9- 1 g (Ss = 0,2 second, site class SB) and PSA= 0,4 – 0,5 g (S1 = 1 second, site class SB). Shear wave velocity (Vs30) map of Northern Sulawesi, shown the Minahasa Peninsula located at the region of Vs30 = 200 – 400 m/sec and divided in to site class SC,SD and SE (Matsuoka, M et.al, 2006), shown in Figure 10 and 11.

Potential Volcanic Hazard

Indonesia has 127 (one hundred twenty seven) volcanoes. Based on their historical of explosions records, the volcanoes in Indonesia divided into three types of volcano are type A (at less one time explosions after 1600), type B (after 1,600 without explosions and shown geothermal activities), type C (no historical explosions during human live, low geothermal activity).

In and around Mollucca Sea Structure, the volcanoes region can divided into 2 (two) arcs are Sangihe and Halmahera Volcanoes Arcs. Sangihe Volcanoes Arc consist of 17 (seventeen) volcanoes namely Awu, Banua Wuhu, Karangetan, Ruang, Tangkoko, Klabat, Mahawu, Lokon, Sarongsong, Lahendong, Tompuso, Tempong, Batukolok, Sempu, Soputan, Ambang, Colo (Submarine volcano). 11 (elevent) of them are the volcanoes type A (Awu, Banua Wuhu, Karangetang, Ruang, Tongkolo, Mahawu, Lokon, Soputan, Ambang and Colo). 7 (seven) volcanoes located in Halmahera volcanoes arc namely Dokono, Malupang, Ibu, Gamkonora, Todoko, Gamalama and Makian, 6 (six) of them are the volcanoes type A (Dokono, Malupang, Ibu, Gamkonora, Gamalama and Makian).

Tectonic and structural geology analyses shown the volcanoes in Minahasa Peninsula located in two regions are the compressional and extensional regions. The volcanoes which are located at the compressional region in between two major right lateral strike slip fault of north and south Tondano are Lokon, Mahawu, Pangalombian, Toulangkow, Kasuratan, Tampusu, Kasuan, Linau and Masarang volcanoes and located at the region in between right lateral strike slip fault of south Kelabat and north Tangkolo are Tangkolo, Batuangus, Kelabat and Tokaro. These volcanoes controlled by extensional zone of north - south secondary fault. The compressional volcanoes of Soputan located in between right lateral strike slip fault of southTondano and south Soputan, shown in Figure 2. Base on the present historical of volcanoes activity of this region, shown the compression volcanoes (Lokon, Mahawu and Soputan Volcanoes) frequently active compere to the extensional volcanoes (Klabat and Old Tondano Volcanoes).

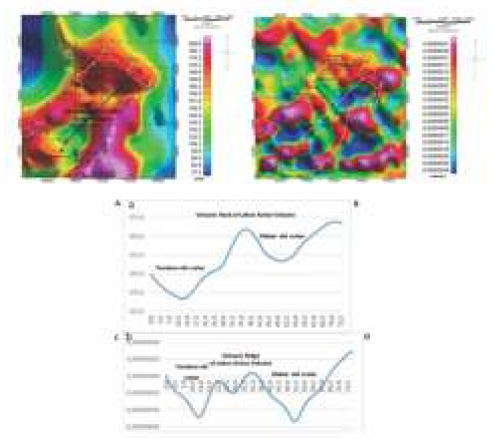

Figure 6. The NE-SW cross section of gravity anomaly and SVD gravity anomaly.

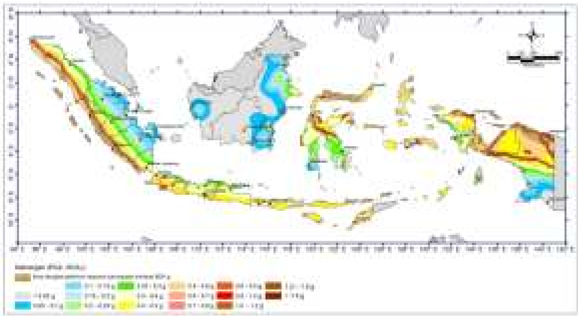

Figure 7. PGA map of Indonesia at site class SB, 2 % probability in 50 years (BSN, SNI1726:2019).

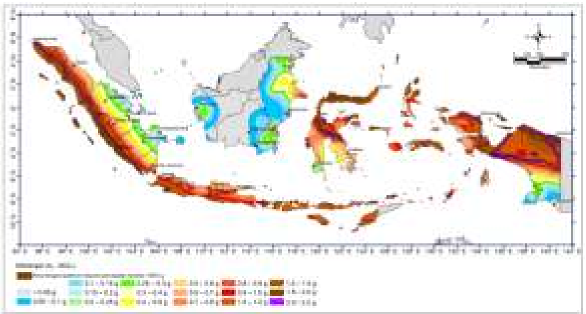

Figure 8. PSA map of Indonesia for 0,2 second, at site class SB, 2% probability in 50 years (BSN, SNI 1726:2019,

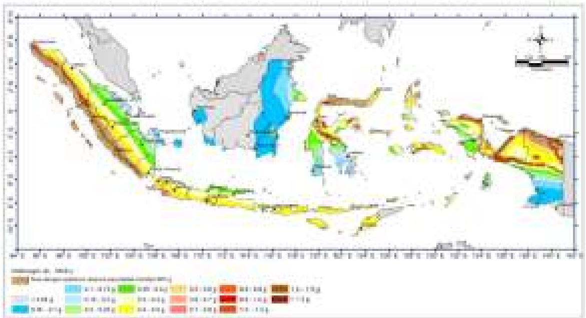

Figure 9. PSA map of Indonesia for 1 second at site class SB, 2% probability in 50 years (BSN, SNI 1726:2019).

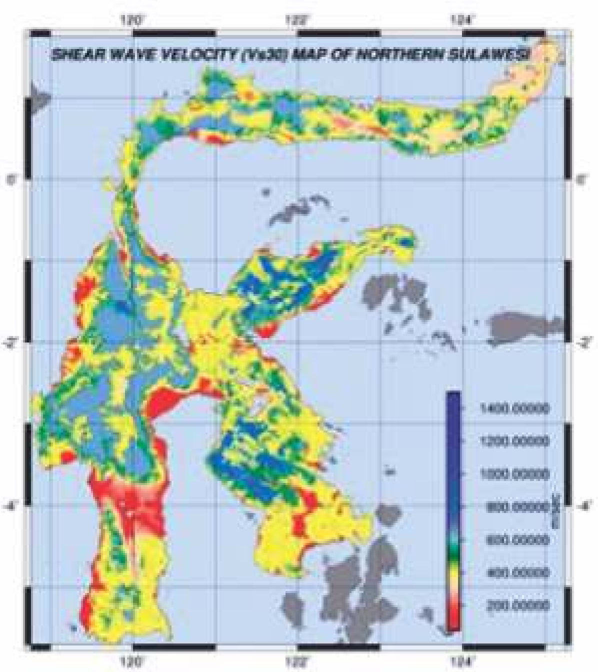

Figure 10. Shear wave velocity (Vs30) map of Sulawesi Island (Matsuoka et al., 2006).

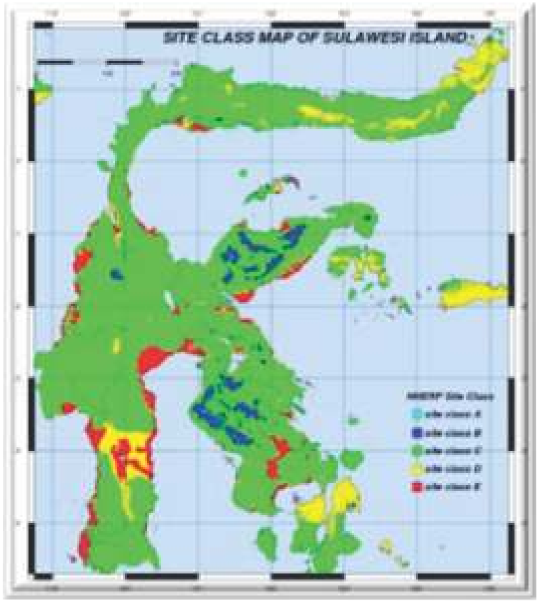

Figure 11. Site class map of Sulawesi island (Matsuoka et al.,, 2006).

Volcano stratigraphy analyses of Miocene Holocene- age in this region, shown the volcanism tectonics of the Minahasa Peninsula divided in four periods are Pre Tondano, Syn Tondano, Post Tondano and Present Active Volcanoes. Pre Tondano Period (Middle Miocene-Pliocene) indicated as as the submarine volcano, which are characterize by marine sediment (marl and limestone) intercalated by volcanic rock. Syn Tondano Period (Pliocene-Pleistocene) characterized by uplifting and regression process, block faulting and volcano Tondano activity. Post Tondano Period (Pleistocene - Holocene) characterized by the activities of the Pangalombian, Toulangkow, Tompusu and Linau volcanoes. Post Tondano and active volcanism Period (Holocene), characterized by activity of Lokon, Mahawu and Soputan volcanoes.

SEISMIC HAZARD AND RISK ASSESSMENT IN MANADO CITY

Based on the microzonation map of microtremor (Centre for Volcanology and Geological Hazard Mitigation, 2020), which is shown the distribution areas of Vs30. The site class classification refers to BSN, SNI 1726 : 2019 (Table 1), the Manado City and surrounding areas has the site class SA, SB, SC, SD and SE(Figure 12).

The site coefisient Fa dan Fv using in this assessment shown in Table 2 and 3 (BSN, SNI 1726:2019). The ground shaking parameters analyses for site class SE, SD and SC shown in Tabel 4, 6 and 8 and spectral elastic desain analyses for site class SE, SD and SC in Manado City and surrounding areas, shown in table 5, 7 and 9. The response elastic desain spectra in site class SE, SC and SD, with Ss= 0.75 g and S1 = 0,40 g, shown in Figure 13,14 and 15.

The result of probabilistic seismic hazard and risk assessment, shown the Manado City and surrounding area can divided in to three zones. Zone I (site class SE), has the risk category I, II, III and IV with the category desain seismic D (SDS=0.60g) and risk category I, II, III has category desain seismic E and IV has category desain seismic F (SD1=0.80g). Zone II (site Class SD), has the risk category I, II, III and IV with the category desain seismic D (SDS=0.73g) and risk category I, II, III, IV has category desain seismic D (SD1=0.50g). Zone III (site class SC), has the risk category I, II, III and IV with the category desain seismic D (SDS=0.67g) and risk category I, II, III, IV has category desain seismic D (SD1=0.43g).

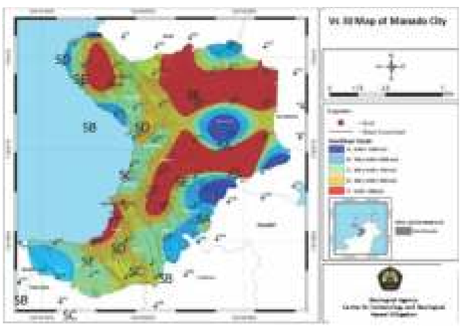

Figure 12. Vs30 map of Manado City and surrounding area (modified from Centre for Volcanology and Geological Hazard Mitigation, 2020 in Supartoyo et al., 2020).

Table 1. Vs30 (BSN,SNI 1726:2019)

Site Class	$\bar{V}_s$ (m/s)	$\bar{N}$	$\bar{S}_u$ (kPa)
Site Class A	$\bar{V}_s \geq 1500$	N/A	N/A
Site Class B	$750 < \bar{V}_s \leq 1500$	N/A	N/A
Site Class C	$350 < \bar{V}_s \leq 750$	$\bar{N} > 50$	$\bar{S}_u \geq 100$
Site Class D	$175 < \bar{V}_s \leq 350$	$15 \leq \bar{N} \leq 50$	$50 \leq \bar{S}_u \leq 100$
Site Class E	$\bar{V}_s < 175$	$\bar{N} < 15$	$\bar{S}_u < 50$

Table 2. Respond spectral earthquake accelaration parameters Ss (BSN, SNI 1726:2019)

Site Class	Respond spectral earthquake accelaration parameters S_s,T=0,2 sec					
	$S_s \leq 0,25$	$S_s = 0,5$	$S_s = 0,75$	$S_s = 1,0$	$S_s = 1,25$	$S_s \geq 1,5$
SA	0,8	0,8	0,8	0,8	0,8	0,8
SB	0,9	0,9	0,9	0,9	0,9	0,9
SC	1,3	1,3	1,2	1,2	1,2	1,2
SD	1,6	1,4	1,2	1,1	1,0	1,0
SE	2,4	1,7	1,3	1,1	0,9	0,8
SF	$SS^{(a)}$					

Table 3. Response spectral earthquake accelaration parameters S1 (BSN, SNI 1726:2019)

Site Class	Respond spectral earthquake accelaration parameters S_1,T= 1 sec					
	$S_1 \leq 0,1$	$S_1 = 0,2$	$S_1 = 0,3$	$S_1 = 0,4$	$S_1 = 0,5$	$S_1 \geq 0,6$
SA	0,8	0,8	0,8	0,8	0,8	0,8
SB	0,8	0,8	0,8	0,8	0,8	0,8
SC	1,5	1,5	1,5	1,5	1,5	1,4
SD	2,4	2,2	2,0	1,9	1,8	1,7
SE	4,2	3,3	2,8	2,4	2,2	2,0
SF	$SS^{(a)}$					

Table 4. Ground shaking parameters for site class SE in Manado City and surrounding areas

Parameters	Value (g)
S_s	1
S_1	0.50
S_{MS}=Fa S_s= 0.9 x 1	0.90
S_{M1} = Fv. S_1 = 2.4 x 0.50	1,2
S_{DS} = 2/3 S_{MS}	0.60
S_{D1} = 2/3 S_{M1}	0.80
T_0 = 0,2 (S_{D1} : S_{DS})	0.9 sec
T_s = (S_{D1} : S_{DS})	1.3 sec

Table 5. Spectral elastic desain for building and non building at site class SE

Period , T(s)	Spectral Accelation, Sa (g)
0	0.24
0.9 (= T_0)	0.60
1.3 (= T_s)	0.60
1	0.8
2	0.4
3	0.27
4	0.20
5	0.16
6	0.13

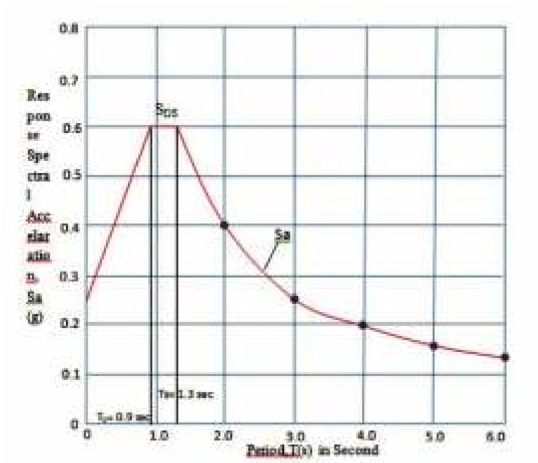

Figure 13. Response of elastic desain spectra for building and non building, at site class SE with Ss= 1 g and S1 = 0.50 g in Manado City and surrounding areas.

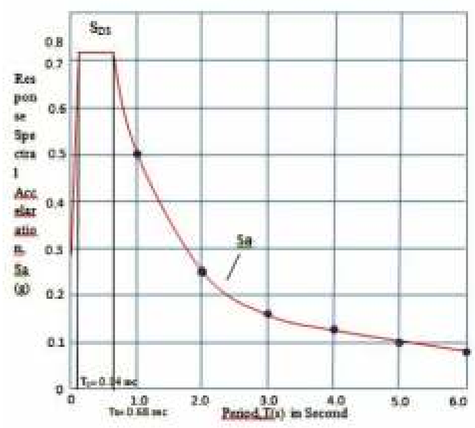

Figure 14. Response of elastic desain spectra for building and non building, at site class SD with Ss= 1 g and S1 = 0.50 g.

Table 6. Ground shaking parameters for site class SD in Manado City and surrounding areas

Parameters	Value (g)
S_s	1
S_1	0.50
S_{MS}=Fa S_s=1.1 x 1	1.1
S_{M1} = Fv. S_1 = 1.5 x 0.50	0.75
S_{DS} = 2/3 S_{MS}	0.73
S_{D1} = 2/3 S_{M1}	0.50
T_0 = 0,2 (S_{D1} : S_{DS})	0.14 sec
T_s = (S_{D1} : S_{DS})	0.68 sec

Table 7. Spectral elastic desain for building and non building at site class SD in Manado City and surrounding areas

Period , T(s)	Spectral Accelation, Sa (g)
0	0.29
0.14 (= T_0)	0.73
0.68 (=T_s)	0.73
1	0.50
2	0.25
3	0.17
4	0.13
5	0.1
6	0.08

Table 8. Ground shaking parameters for site class SC in Manado City and surrounding areas

Parameters	Value (g)
S_s	1
S_1	0.50
S_{MS}=Fa S_s=1 x 1	1
S_{M1} = Fv. S_1 = 1.3 x 0.50	0.65
S_{DS} = 2/3 S_{MS}	0.67
S_{D1} = 2/3 S_{M1}	0.43
T_0 = 0,2 (S_{D1} : S_{DS})	0.13 sec
T_s = (S_{D1} : S_{DS})	0.65 sec

Tablel 9. Spectral elastic desain for building and non building at site class SC in Manado City and surrounding areas

Period , T(s)	Spectral Accelation, Sa (g)
0	0.27
0.13 (= T_0)	0.67
0.65 (=T_s)	0.67
1	0.43
2	0.22
3	0.14
4	0.11
5	0.09
6	0.07

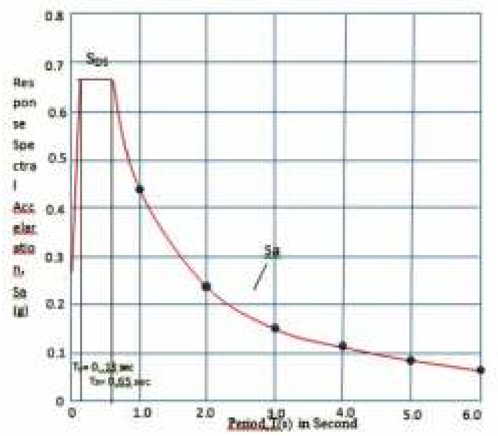

Figure 15. Response of elastic design spectra for building and non building at site class SC with Ss= 1 g and S1 = 0.50 g in Manado City and surrounding areas.

TablE 10. Ground accelaration Parameters, Risk Category and Seismic Desain of Manado City for each site class

Manado City	S_s	S_1	S_{DS}	Risk Category	Seismic Desain Category	S_{D1}	Risk Category	Seismic Desain Category
Zone I (Site Class SE)	1g	0.50g	0.60g	I,II,III,IV	D	0.80g	I,II,III IV	E F
Zone II (Site Class SD)	1g	0.50g	0.73g	I,II,III,IV	D	0.50g	I,II,III,IV	D
Zone III (Site Class SC)	1g	0.50g	0.67g	I,II,III,IV	D	0.43g	I,II,III,IV	D

CONCLUSIONS

Minahasa Peninsula is the western part of the Seismotectonic Molucca Sea Collision Zones. There are three active tectonic plates collition from East to West are the Philippine Oceanic Plate, Halmahera Micro Continental Plate, Mayu Ridge Micro Oceanic Slab Plate and the Minahasa Peninsula Micro Continental Plate. Therefore this region is an active seismicities and volcanoes. The structure of building and non building (risk category I, II, III and IV) in Zone I (site clas SE), II (site class SD) and III (site class SC) which has the SDS= 0.60 g and 0.50 g, has the seismic desain category D. Zone I (site class SE) which has SD1=0.80 g, the building and non building with risk category I, II, III has seismic design category E and risk category IV has seismic design category F. The correlation between active tectonic, seismicity and kinematic of structural geology, shown the Minahasa Peninsula volcanoes can divided in two regions are the compressional and extentional volcanoes tectonic regions. The present historical of volcanoes activity in this region, shown the compression volcanoes (Lokon, Mahawu and Soputan Volcanoes) frequently active compere to the extensional volcanoes (Klabat and Old Tondano Volcanoes). In order to mitigate risk of potential seismic hazard in this region, building and non building contraction must follow risk and seismic desain category according to SNI 1726-2019. In other hand, for potential volcano hazard, must follow the guidance map of volcanic hazard prone region from Center for Volcano and Geological Hazard Mitigation, Geological Agency of Indonesia.

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REFERENCES

Badan Standarisasi Nasional, 2012. *Earthquake Resistance Planning Procedure for Building and Non Building, SNI 1726-2019*. BSN, Jakarta.

Brehme, M., Moeck, I.,Yustin Kamah, Zimmermann, G. and Sauter, M., 2014. A Hydrotectonic Model of a Geothermal Reservoir - A Study in Lahendong, Indonesia. *Geothermics*, 51: 228 -239.

Di Leo, J.F., Wookey, J., Hammond, J.O.S., Kendall, J.M., Kaneshima, S., Inoue, H.,Yamashina, T., and Harjadi, P., 2012. Deformation and Mantle Flow Beneath the Sangihe Subduction Zone from Seismic Anisotropy. *Physics of the Earth and Planetary Interiors*, 194-195: 38–54.

Effendi, A.C. dan Bawono, S, 1997. Peta Geologi Lembar Manado, Sulawesi, Skala 1:250.000. Puslitbang Geologi, Bandung.

Lécuyer, F., Bellier, O., Gourgaud, A., and Vincent, P.M., 1997. Tectonique Active du Nord-Est de Sulawesi (Indonésie) et Contrôle Structural de la Caldeira de Tondano. *Comptes Rendus de l'Académie des Sciences – Series IIA, Earth and Planetary Science*, 325: 607-613.

Hamilton, W., 1979. *Tectonics of the Indonesian Region*. U.S. Geol. Surv., Prof. Pap. 1078, 345 pp.

Matsuoka, M., Wakamatsu, K., Fujimoto S. and Midorikawa, 2006. Average Shear-Wave Velocity Mapping using Japan Engineering Geomorphologic Classification Map. *JSCE*., 23(1): 57–68.

Pusat Vulkanologi dan Mitigasi Bencana Geologi, 2021. *Peta Sebaran Gunungapi Aktif Indonesia, Skala 1:5.000.000.* PVMBG, Bandung.

Pusat Studi Gempa Nasional, 2017. *Peta Sumber dan Bahaya Gempa Indonesia Tahun 2017.* Pusat Litbang Perumahan dan Pemukiman, Badan Penelitian dan Pengembangan, Kementerian PUPR, 375 h, Bandung.

Setiawan, J.H., Lumbanbatu, U.M. dan Pudjoprayitno, S., 2002. *Peta Seismotektonik Daerah Manado dan Sekitarnya Skala 1:100.000, Provinsi Sulawesi Utara*. Puslitbang Geologi, Bandung.

Siahaan, E.E., Soemarinda, S., Fauzi, A., Silitonga, T., Azimudin, T., and Raharjo, I.B., 2005. Tectonism and Volcanism Study in the Minahasa Compartment of the North Arm of Sulawesi Related to Lahendong Geothermal Field, Indonesia. *ProceedingsWorld Geothermal Congress 2005, Antalya, Turkey*, 24–29 April 2005, 5 pp.

Supartoyo, Afif, H., Arifin,M., Pradipto, J., Nurfalah, F., Solang, M., Walandouw, J., dan Hompas, M.H., 2020. Pemetaan Mikrozonasi Bahaya Gempabumi di Kota Manado, Provinsi Sulawesi Utara. *Bulletin Vulkanologi dan Bencana Geologi*, 14(1): 19-30.

USGS, 2015. *Earthquake Catalog dan Global Centroid Moment Tensor Catalog, 2015*. Data gempa bumi tahun 1970 – 2015, M> 4 Mb.

Walpersdorf, A., Rangin, C., and Vigny, C., 1998. GPS Compared to Long-Term Geologic Motion of the North Arm of Sulawesi. *Earth and Planetary Science Letters*, 159: 47-55.

Yani, A., 2006. Numerical Modelling of the Lahendong Geothermal System,Indonesia, United Nations University. Report, pp. 547–580.