



# Preliminary Study to Estimate An Impact (Risk) Potential of The Major Earthquake $M > 7$ in Gorontalo Fault (Case Study: Gorontalo Earthquake 1941 M7.4)

Jaya Murjaya<sup>1</sup>, Petrus D. Sili<sup>1,2</sup>, Suaidi Ahadi<sup>1</sup>, Aditya S. Rahman<sup>1,\*</sup>, Dedi Sugianto<sup>1</sup>, Sutiyono Sutiyono<sup>1</sup>, Putu Hendra<sup>1</sup>

<sup>1</sup> Agency for Meteorology Climatology and Geophysics, Jakarta 10720, Indonesia

<sup>2</sup> School for Meteorology Climatology and Geophysics, Jakarta, Indonesia

\*Corresponding author. [aditya.rahman@bmkg.go.id](mailto:aditya.rahman@bmkg.go.id)

**Abstract.** Based on earthquake history, Gorontalo city is an earthquake-prone region due to its location near active faults, such as the Gorontalo fault, which crosses the Gorontalo City and its vicinity. The last large destructive earthquake occurred on November 8, 1941, with a magnitude of about 7.4, and the epicenter was located in the Gorontalo Fault. This paper estimates the potential ground shaking if the Gorontalo earthquake Mw 7.4 with a hypocenter depth ( $h$ ) of 10 km were to occur again in the same location. It also analyzes the earthquake return period using the kinematic model and scaling law relationships of earthquake parameters. The earthquake source model is considered as a point source with a strike-slip focal mechanism. The slip rate data for the Gorontalo fault is about 9-12 mm/y. After processing the potential for ground shaking, the Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV), and earthquake return period were estimated to be around VII-IX MMI, 49-56%  $g$ , 35-45 cm/s, and 68-200 years, respectively. This assessment aims to support earthquake hazard mitigation and landscape programs in the Gorontalo province.

**Keywords:** Gorontalo fault, earthquake-prone region, seismic hazard assessment, ground shaking estimation

## 1 Introduction

Gorontalo Province in Northern Sulawesi island is a seismic active region based on Indonesian earthquake data [1] and United State Geology Survey [2]. In the north of Gorontalo province region has been occurred some strong earthquakes with magnitude ( $M$ ) more than 7, such as the earthquake on May 19, 1991 (M7.0) and June 20, 1991 (M 7.5). Besides that, the strong earthquake (M 7.4) occurred on land in Gorontalo province on November 8, 1941 [2], as shown in Figure 1. The earthquake epicenter was M 7.4, and it is estimated that the earthquake was triggered by the Gorontalo active fault. The Gorontalo active fault is a dextral fault and is stretched from southeast to northwest, crossing Gorontalo city and its vicinity [3]. Figure 1 shows the seismicity map of the Gorontalo region and its vicinity. After the Gorontalo earthquake on November 08, 1941, no strong earthquakes occurred on land in Gorontalo, except in the northern part

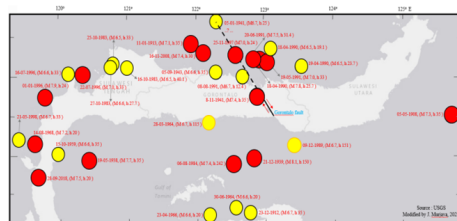
of the region. There are earthquakes on May 19, 1991 (M 7.0), June 20, 1991 (M 7.5), November 25, 1997 (M 7.0), and other small earthquakes.

In seismology, it is stated that an earthquake will be repeated in the future in the same region. Therefore, in this paper, we will study the impact estimation of a strong earthquake caused by the Gorontalo active fault. The impact consists of the earthquake shaking level (shakemap), Peak Ground Acceleration (PGA), and Peak Ground Velocity (PGV). The purposes of the results in this study are to support earthquake hazard risk mitigation and landscape programs in the Gorontalo region, or at least to assist in designing earthquake-proof buildings and landscape programs in Gorontalo province. We also create a model of the earthquake return period using scaling law relations of earthquakes. This model estimates the Gorontalo earthquake return period ( $T_r$ ) for  $M_w \leq 7.4$ .

## 2 Tectonic Setting and Seismicity Review in Gorontalo fault and Its Vicinity

Sulawesi lies within Eastern Indonesia in a highly complex plate tectonic setting located at the junction of some fragmented oceanic crust [4, 5]. In northern Sulawesi and the Gorontalo region, there is a North Sulawesi Trench that runs almost from west to east. This trench is caused by the Eurasian plate subducting beneath the Sulawesi crust from north to south. The double subduction zone is located in the eastern and northeastern parts of northern Sulawesi (Gorontalo-Manado) and in the Moluccas. This region is highly seismically active.

The Toli-Toli region is a complex fault system in Central Sulawesi. It is located in the western Gorontalo region and is also an area prone to major earthquakes. One significant earthquake occurred near the Toli-Toli region on January 1, 1997 (Mw 7.9). The Gorontalo fault crosses the Gorontalo City region and its vicinity, having triggered a major earthquake on November 8, 1941 (M 7.4). The Kuandang fault and Tribawa fault are near the Gorontalo fault. The Kuandang fault is located to the north and acts as a conjugate fault to the Gorontalo fault [3], and it is estimated to be a sinistral strike-slip fault. The Tibawa fault is located to the west of the Gorontalo fault and is classified as a dextral strike-slip fault. The Gorontalo fault is estimated to be a dextral strike-slip fault, stretching from southeast to northwest.



**Fig. 1.** Seismicity map of Gorontalo region and its vicinity for strong earthquakes ( $6.5 \leq M_w \leq 8.5$ ) during 1900-2022. Modified from USGS earthquake data [2].

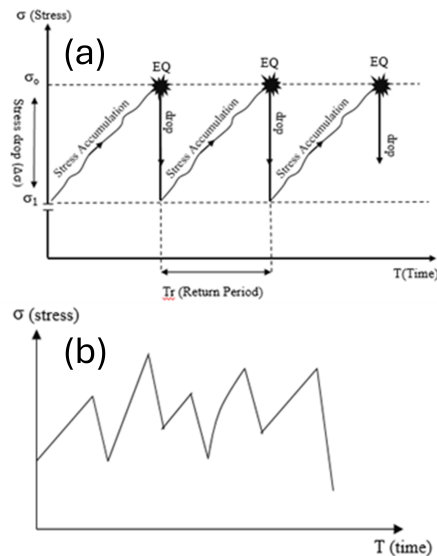
The distribution of earthquakes that occurred in the northern Gorontalo region is estimated to align with the straightness of the Gorontalo fault. Several strong earthquakes have occurred in the northern part of the Gorontalo region, such as those on May 19, 1991 (M 7.0), June 20, 1991 (M 7.5), November 25, 1997 (M 7.0), and other smaller earthquakes. However, earthquakes inland and in the southern part of the Gorontalo fault are rare, except for the earthquake in 1941 (Mw 7.4).

### 3 Method

#### 3.1 Data

We compiled all earthquakes which occurred in Gorontalo region and its vicinity from Indonesian earthquake catalogue and others [1, 2] (Table 1). One major earthquake on Nov 08, 1941 (Mw 7.4) occurred near Gorontalo city.

This earthquake will become a basic analysis to know how the impact if that earthquake will occur again in the same location in the future. Then to estimate the earthquake repeat time, we used the slip rate value of Gorontalo fault about 11 mm/y [6], 9-12 mm/y [3] and magnitude  $M_w \leq 7.4$ . Furthermore, we used the scaling law relation for earthquake to estimate the repeat time earthquake model. In this model, we consider the source mechanism as a strike-slip fault. Illustration of earthquake repeat time model [7] is shown by cartoon in Figure 2.



**Fig. 2.** Illustration an Earthquake sequence (return period- $T_r$ ), critical stress ( $\sigma_0$ ), initial stress ( $\sigma_1$ ) value and static stress drop. (a) Regular sequence.model (b) Irregular sequence model in temporal variations. (Modified from Kanamori).

### 3.2 Static Stress Drop Theory

The tectonic energy is made up by a tectonic process. During the interseismic period, it will be accumulated and it will be released after exceeding the rock strength or exceeding the critical stress  $\sigma_o$  as an earthquake and drop to initial stage  $\sigma_1$  as shown in Figure 2. The difference of  $\sigma_o$  and  $\sigma_1$  is called a static stress drop. After the earthquake happened, the cycle will begin again to accumulate stress until reaching the next critical stress stage. Furthermore, the static stress drop is used in the Kanamori and Anderson [8] formula as follows:

$$\Delta\sigma = c\mu\frac{\bar{D}}{L} \quad (1)$$

where  $\mu$  is rigidity (SI),  $\frac{\bar{D}}{L}$  is strain change, and  $C$  is a non-dimensional shape factor. To determine the shape factor ( $C$ ) and  $L$  for the shallow infinite transverse shear (dip-slip) faults, they referred to the formula from Starr (1928) and Aki (1966) for  $C = \frac{4(\mu+\lambda)}{2\mu+\lambda}$ , where  $\lambda$  is the Lamé constant. Furthermore, to calculate a static seismic moment ( $M_o$ ), the formula used is:

$$M_o = \mu S\bar{D} \quad (2)$$

where  $S$  is a rupture area and  $\bar{D}$  is the offset.

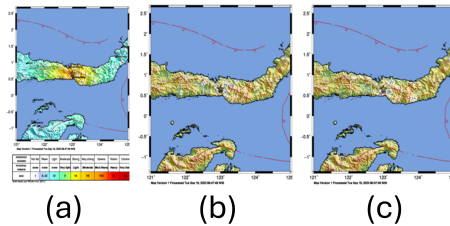
### 3.3 Earthquake Shaking Impact

Effect of the earthquake is generally viewed which related to the level of ground shaking or macroseismic effect. There are earthquake intensity, peak ground acceleration (PGA), peak ground velocity (PGV) and peak ground displacement (PGD). The Gorontalo earthquake 1941(M 7.4) has just limited information of damage. We used scenario model to put the epicentre of the Gorontalo earthquake 1941(M 7.4) in fault and near Gorontalo city relatively to find of intensity level, PGA and PGV. In this research is just discussed model of shake map, PGA and PGV which caused by major earthquake near Gorontalo city. Epicentre is considered as a point source in Gorontalo fault. In this study the potential of earthquake shaking impact was divided 2 kind of hypocentre depth there is about of 15 km and 5 km.

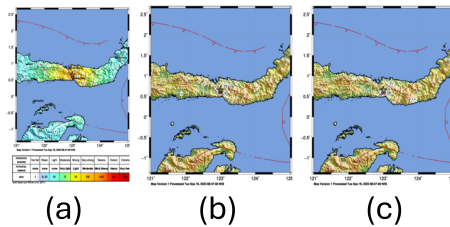
Figure 3 shows the result model of the potential earthquake shaking impact in Gorontalo region and its vicinity by using a magnitude scenario about of 7.4 and hypocentre depth 15 km. The result for earthquake intensity (Figure3 a), peak ground acceleration (PGA) (Figure 3 b) and peak ground velocity (PGV) (Figure 3 c) respectively. Whereas Figure 4 shows the result model of the potential earthquake shaking impact for a worst scenario of magnitude 7.4 and focal depth 5 km. The result for earthquake intensity (Figure4a), peak ground acceleration (PGA) (Figure 4 b) and peak ground velocity (PGV) (Figure 4c) respectively.

We used a hypocentre depth scenario 5 km as a worst scenario of depth earthquake to refer on Agadir city (in Maroco) earthquake 1960 with magnitude about of 5.9 with hypocentre depth  $\pm 5$  km. The epicenter location is about of 2 km WNW of Agadir and that earthquake caused damage at level intensity about of VIII-IX MMI. To refer on

Figure 3 above using the earthquake magnitude scenario for Mw 7.4 and hypocentre depth 15 km, the focal mechanism assumed as strike slip and epicentre located in the Gorontalo fault. The result that the ground shaking or intensity level about of VII-IX MMI (3a), the largest PGA about of 49 % g in the epicentre area (3b) and the largest PGV about of 35 cm/s in epicentre area (3c). Whereas for an earthquake scenario Mw 7.4 and hypocentre depth 5 km, the result that the maximum intensity about of VII-IX MMI (4a), the largest PGA about of 56 % g in the epicentre area (4b) and the largest PGV about of 45 cm/s in epicentre (4c). We also calculate the PGA for Mw 7.4 based on some formula. The results are about of 335 gal (Donovan, 1973), 689 gal (Esteve, 1974), 686 gal (Matuschka, 1980), 657 gal (Joyner and Boore, 1981) and 390 gal (Fukushima and Tanaka, 1990). If the PGA result this study is compared with their result it is still consistence.



**Fig. 3.** The potential of earthquake shaking impact based on modelled scenario magnitude 7.4 and depth 15 km. (a) The Shakemap model. (b) The PGA map and (c) The PGV map



**Fig. 4.** The potential of earthquake shaking impact based on scenario magnitude 7.4 and depth 15 km. (a) The Shakemap. (b) The Map of PGA and (c) The map of PGV

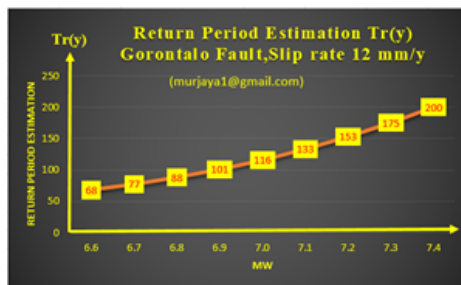
### 3.4 Estimation Model of Earthquake Return Period

Table 1 compiled from the earthquake catalogue. We used some formula of earthquake parameter relations to calculate of moment seismic ( $M_o$ ), fault length ( $L$ ) and Area ( $km^2$ ) and of the static stress drop ( $\Delta\sigma_{obs}$ ) estimation respectively as like showed in Table 2.

**Table 1.** Significant earthquakes M more than 6.5 scale in Gorontalo region.

No	Event EQ	Location	Mag	Depth (km)	Remark
1	Jan 11, 1913	1.373 N - 121.392 E	7.5	35	No remark
2	Jan 05, 1941	0.659 S - 122.272 E	6.7	25	No remark
3	Nov 01, 1943	1.129 N - 123.018 E	6.6	35	No remark
4	Sept 08, 1943	0.141 N - 122.781 E	7.0	15	No remark
5	Mar 28, 1955	0.21 N - 123.429 E	6.4	30	No remark
6	Dec 09, 1989	0.42 N - 121.918 E	7.8	150	3 people died, 25 houses damaged
7	Apr 18, 1989	1.186 N - 122.857 E	7.8	25	Bolang Goolandoo and its vicinity
8	Apr 19, 1990	1.190 S - 123.018 E	6.5	19	No remark
9	Dec 29, 1990	0.49 S - 123.429 E	7.0	33	No remark
10	May 19, 1991	1.156 N - 122.957 E	7.0	33	Felt at Manado III MMI
11	Jun 20, 1991	1.196 N - 122.78 E	7.5	6.7	Felt at Gorontalo I MMI IV-VI; one house damaged in Gorontalo
12	Aug 08, 1991	0.972 N - 123.63 E	6.0	31	Felt at Gorontalo I MMI VI; minor cracks in buildings
13	Nov 25, 1997	1.241 N - 122.53 E	7.4	24	Felt at Gorontalo I MMI VI-VII; some houses damaged in vicinity of epicenter
14	Nov 16, 2008	1.271 N - 122.09 E	7.4	30	Felt at Gorontalo I MMI VI-VII; old buildings damaged in Buol (Toli-Toli); one building damaged in Suwawa (Central Sulawesi); felt (312 km) at Manado (Gorontalo II/III)

Table 2 shows a result significant earthquake parameter using scaling law relation. Seismologist used three basic parameter to describe stress release. There are static stress drop, Coulomb stress transfer and dynamic stress drop [9]. Then static stress drop value is compared [8] and all of result about of 10-100 bars. This result is consistent, and located in the fixed line. Furthermore we used the scaling law to estimate the earthquake return period. The return period for significant earthquakes in the Gorontalo region is calculated based on historical data and seismic activity models.



**Fig. 5.** Graph show an estimation result of relation between Tr and Mw model for earthquake Mw ≤ 7.4 and slip rate 12 mm/y for Gorontalo active fault.

**Table 2.** Significant earthquakes M more than 6.5 scale in Gorontalo region.

No	Event EQ	Location	Mag	$M_0$	L	A	$\tau$ (obs)
1	Jan 11, 1913	1.373 N - 121.928 E	7.1	$4.467 \times 10^{26}$	$5.06 \times 10^6$	1125	$1.65 \times 10^7$
2	Jan 05, 1941	1.659 N - 122.272 E	6.7	$1.122 \times 10^{26}$	$2.60 \times 10^6$	456	$1.101 \times 10^7$
3	Nov 08, 1941	0.731 N - 122.835 E	7.4	$1.259 \times 10^{27}$	$8.400 \times 10^6$	2215	$2.238 \times 10^7$
4	Sept 05, 1943	1.029 N - 122.269 E	6.6	$7.943 \times 10^{25}$	$2.16 \times 10^6$	364	$9.951 \times 10^6$
5	Mar 28, 1964	0.418 N - 122.174 E	6.7	$1.122 \times 10^{26}$	$2.60 \times 10^6$	456	$1.101 \times 10^7$
6	Dec 09, 1989	0.141 N - 123.340 E	6.7	$1.122 \times 10^{26}$	$2.60 \times 10^6$	456	$1.101 \times 10^7$
7	Apr 18, 1990	1.186 N - 122.857 E	7.8	$5.012 \times 10^{27}$	$1.667 \times 10^7$	5464	$3.356 \times 10^7$
8	Apr 18, 1990	1.315 N - 123.018 E	6.5	$5.623 \times 10^{25}$	$1.820 \times 10^6$	290	$8.992 \times 10^6$
9	Apr 19, 1990	1.108 N - 123.429 E	6.5	$5.623 \times 10^{25}$	$1.820 \times 10^6$	290	$8.992 \times 10^6$
10	May 19, 1991	1.156 N - 122.957 E	7.0	$3.162 \times 10^{26}$	$4.266 \times 10^6$	898	$1.492 \times 10^7$

Parameter using scaling law relation. Seismologist used three basic parameter to describe stress release. There are static stress drop, Coulomb stress transfer and dynamic stress drop [9]. Then static stress drop value is compared [8] and all of result about of 10-100 bars. This result is consistent, and located in the fixed line. Furthermore we use the value  $M_w \leq 7.4$  like and slip rate value 12 mm/y to calculate or estimate of Gorontalo earthquake return period based on model as showed in Figure 5.

This model used presumption of point source epicentre, strike slip fault and shallow focus depth. Then Kanamori and Anderson stated that intraplate earthquake has average stress drop higher and repeat time (return period) longer than interpolate earthquake [8]. The repeat time estimation of Gorontalo fault earthquake to use assumption that accumulation strain energy is happened during interseismic period for several years or hundred years without earthquake in this area. Then after the critical stress of rock is passed over, the accumulation strain energy will be released which called as a stress drop static. Based on model in this study the repeat time of Gorontalo earthquake for magnitude  $M_w \leq 7.4$ , and slip rate 12 mm/y is about of 200 years ( $M_w 7.4$ ) and 68 years ( $M_w 6.6$ ) for strike slip model respectively.

## 4 Conclusion

To Refer of Gorontalo earthquake  $M_w 7.4$  as input to our model and we consider that earthquake will be repeated in the future. Furthermore, after processing the model result, three ground parameter there are maximum intensity (shakemap), PGA and PGV about of VII-IX MMI, 49-56 %g and 35-45 cm/s respectively in epicentre area. Besides that, this research use scaling law relation of earthquake, slip rate value 12 mm/y and magnitude  $6.6 \leq M_w \leq 7.4$  to estimate of return period. We found the return period of earthquake about of 68-200 years. This result can be considered to support in designing earthquake proof buildings and landscape program in Gorontalo province.

## References

1. BMKG - The Indonesia Agency for Meteorology, Climatology, and Geophysics, *Indonesian Earthquakes Catalogue* (Jakarta, 2020)

2. United States Geological Survey. Earthquake information (2020). Available at: <http://www.usgs.gov/earthquake>
3. Sidarto, S. Bachri, *Struktur Geologi-Geologi Sulawesi* (LIPI Press, Jakarta, 2013)
4. W. Hamilton, *Tectonics of the Indonesian Region* (United States Government Printing Office, Washington, 1979)
5. R. Hall, SE Asia Research Group, Department of Geology, Royal Holloway University of London (1998)
6. PUSGEN - Indonesian Earthquake Study Center. Peta sumber dan bahaya gempa indonesia tahun 2017 (2017). Consortium of some relevant Indonesian earthquake institutions
7. T. Lay, T.C. Wallace, *Modern Global Seismology* (Academy Press, 1995)
8. H. Kanamori, L. Anderson, *Bulletin of the Seismological Society of America* **65**(5), 1073 (1975)
9. W. Debski, *Pure and Applied Geophysics* **175**, 4165 (2018)

**Open Access** This chapter is licensed under the terms of the Creative Commons Attribution-NonCommercial 4.0 International License (<http://creativecommons.org/licenses/by-nc/4.0/>), which permits any noncommercial use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license and indicate if changes were made.

The images or other third party material in this chapter are included in the chapter's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the chapter's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.

