Geological constraints for disaster mitigation model in South Sulawesi

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Abstract. South Sulawesi is one of the provinces in Indonesia with the highest economic growth index. This situation gives an impact to intensive infrastructure development including road access, bridge, dam, airport, seaport and other public facilities in the province. However, due to geological complexity of the region, the infrastructures developments are threatened by natural hazard. This paper outlines the characteristic of natural disaster in South Sulawesi using geological consideration of the region for mitigation strategy. The natural hazard in South Sulawesi consists of earthquake, landslide, tsunami and flood. Earthquake occurs in association with some major faults such as Walanae Fault, Palu-Koro Fault and Matano Fault. All areas located near these fault zones are classified as earthquake-prone areas. Landslides are classified as slides, flow and rock fall and takes place in some high topography areas which composed of moderately to highly weathered volcanic product material. Geologically the landslides are closely related with morphology, stratigraphy and structure (seismic-related) condition. Some coastlines in South Sulawesi province are tsunami-prone area, especially the area facing to the seismically-active region such as southern tip of the peninsula where tsunami is generated by the Flores back-arc thrust fault. Flooding shows a strong relationship to geological condition in the area especially low-lying topographic areas in some coastlines and river mouth areas. Three main causes of the flood have been considered namely deforestation due to land conversion, high sedimentation rate and sporadic urbanization coupled with heavy rain fall and tides. The study shows that all natural disasters in South Sulawesi are mainly controlled by geological condition such as fault, morphology, stratigraphy, petrology and seismicity. Therefore, in order to mitigate these natural hazards, geological constraints should be taken into consideration in natural hazard mitigation scheme in the regional level.

1. Introduction

Natural disaster or sometimes is translated as geological disaster, consist of earthquake (including liquefaction), landslides, volcanic eruption, tsunami and flood. These hazards are considered as a normal earth process. However, their existing as irregular and unpredictable events which closely related to the environment and human has been causing significant negative impact on civilization [1]. Almost all types of geological disaster occur in the South Sulawesi Province except hazards associated with glaciers and volcanic eruptions. Although mostly the geological hazards cannot be accurately predicted, proper mitigation and well-planned preparedness efforts can minimize the effects of these disasters and promote resilience, reducing the negative economic effects and eventually saving many lives and assets.
As one of the most progressive provinces with relatively highest economic growth in Indonesia, South Sulawesi plays an important role in supporting national development program. However, intensive development of some vital infrastructures including bridge, dam, national road, factory, seaport, airport, and other public facilities are threatened by these types of disaster. Natural disaster or geological disaster in South Sulawesi provinces are mostly induced by its complex tectonic setting as shown by figure 1 and 2 and other natural and human factors including geological condition (topography, weathering, stratigraphy, seismicity, deforestation and bad land conversion) of the area. However, due to limited study on relationship of geological condition and the natural disaster in this province and the low level of disaster awareness (both in decision maker level and public), most mitigation effort did not consider the geological conditions into the system. Hence, mitigation effort is not comprehensively provide maximum effect. This paper outlines the geological constraints for disaster mitigation model in South Sulawesi.

Figure 1. Tectonic of Indonesia and surrounding area showing major faults lineament. Note the major fault zone (red line) crossing Sulawesi Island [2]

Figure 2. Tectonic configuration of Sulawesi Island showing some major faults [3]
2. Geological Disaster

There are 5 common types of geological disaster, including earthquake, tsunami, volcanic eruption, flood and landslide. Below is a brief explanation of each type of geological disaster which common in Indonesia, especially in Sulawesi.

2.1. Earthquake

Earthquake is a rumbling or trembling of the ground produced by the sudden breaking of rocks in response to geological forces within the earth. Most of the quake is usually due to release of seismic energy following the rapid movement of large blocks along a geological fault zone [4]. An idealized model of an earthquake sources would show the rupture of the fault as originating at a point on the fault surface called the seismic focus or hypocenter. The majority of earthquakes occur in narrow zone defining the boundaries where lithospheric plates interact. Shallow earthquake, with epicentres less than 100 km below the surface, are recorded at all type of plate boundary, but deeper earthquakes (100 to 700 km) typically occur at destructive plate boundary and associated with subduction zone, where one plate plunge beneath the other.

2.2. Landslide

Landslide is the general term for the downward movement due to gravity of masses of rock, soil, debris material as a result of a variety of process [5]. The occurrence of downward movements is the consequence of a complex field of forces (stress is a force per unit area) which is active on a mass of rock or soil on the slope. Type of landslide includes rock-fall, mudflows and slumps.

2.3. Tsunami

Tsunami is derived from a Japanese term that means ‘harbour wave’. It is used to describe the gravity wave system generated by large-scale disturbance of the sea-floor. When the wave breaks over the coastline, water body piles up and cause massive destruction along the coastline and adjacent land. Some spectacular tsunamis such as the 1883 Krakatoa, 1998 Aitape, and the most recent 2018 Palu (Central Sulawesi) and Tanjung Lesung (West Java) tsunamis were caused by the disturbances of the sea-floor following the volcanic eruptions or sub-marine landslides. However, subduction zone earthquakes are still considered as the most common source of destructive tsunamis. Tsunami originating in the vicinity of the earthquake epicenter is produced by vertical faulting on the sea floor, which draws in the water surface and produces a seismic sea wave.

2.4. Flood

Flooding is a naturally occurring event which refers to the function of rain fall on the surface at certain area and the drainage capacity of the area. Flooding often occurs at regular events but it is most likely more intensive during wet seasons and affected a larger area due to extensive urban development. However, flooding can also be sudden and unpredictable causing destruction in people’s lives, and reduces their livelihood assets. Flooding, to some extent, will changes the way people live their lives which led to the damages of the social structure of the community [6]. Fig.3 shows anatomy of natural hazard generated by geological process.

2.5. Volcanic eruption

Volcano refers to an opening in the crust through which material erupt due to pressure underneath from magma chamber to form a mountain. The materials that erupt from a volcano include magma,
hot gases and solid rock. During an explosive eruption, materials spread out from the vent in all directions and sometimes the material (magma, hot gases and solid rock) will harm people and destruct infrastructure due to its high temperature. The nature of volcanic eruption is largely determined by the viscosity and gas content of its magma. The behaviour of volcanoes is a matter of great practical importance to the human population living near them. Volcanoes emitting lavas of low viscosity tend to erupt frequently but fairly quietly, and do not cause much damage except in the path of the lava flows themselves. Some volcanoes have a periodicity in its eruptions, a phase of activity being followed by a much longer phase of quiescence which may last for hundreds of years and led people to conclude that the volcano is extinct. The longer the quite period, the more violently is likely to be the ultimate explosion. The eruption of Vesuvius which destroyed Roman town of Pompeii in A.D 79 seems to have follow centuries of quite, and Krakatao had been dormant for two centuries before its eruption of 1883. Warning of volcano eruptions may be given first by relatively small explosions and by frequent local earthquake.

![Figure 3](image-url)  
*Figure 3.* Typical natural hazard generated by geological process (geological hazard). (upper left) anatomy of earthquake; (upper right) anatomy of landslide; (lower left) origin of Sumatra tsunami due to earthquake; (lower right) factor contribute to floods [5], [7], [8].

### 3. Regional Geology of Sulawesi

Regional geological of Sulawesi are have been reported by previous workers, including [9],[10],[11]. The island can be divided into four (4) distinctive tectonic provinces, namely (1) the Western Sulawesi
Province, (2) the Eastern Sulawesi Province, (3) the Northern Sulawesi province and (4) the Banggai-Sula and Tukang Besi Continental Fragments (Fig.4).

3.1. Geology of South Sulawesi

Detail geology of South Sulawesi below is mainly based on study from [11] and reference therein. The area consists of a continental margin segment with pre-Tertiary metamorphic basement composed of low to medium pressure metamorphic rocks and ultramafic rocks which area overlain by Upper Cretaceous (Balangbaru and Latimojong Formation) and Cenozoic volcanic-sedimentary sequences. Some various ages of pluto-volcanic rocks rocks intruded the basement. Tertiary sediments are found in the west of the Walanae Graben known as the Mallawa Formation, and to the north near Latimojong Mountain known as the Toraja Formation. The Mallawa Formation unconformably overlies the Balangbaru Formation and locally the Langi Volcanics, whereas the Toraja Formation overlies the Latimojong Formation. Eocene to Mid Miocene carbonates are found in many spotted areas including southern tip of the Western Sulawesi known as Selayar Formation, in the vicinity of the Bantimala Complex (known as Tonasa Formation) and in the northern part of the area (known as Makale Formation). Since Middle Miocene a major orogenic event took place, followed by andesitic volcanism and granitic intrusion spanning from the southern tip to the northern tip of the area. Quaternary sediments covers the central part of the area which formed by Walanae Fault Zone.

4. Geological Disaster of South Sulawesi

4.1. Earthquake
Geologically, Sulawesi is one of the most complex islands in the world (Fig. 2 & 6) [3], [12]. The island is cross cut by some major faults as seen in Fig. 2. Earthquake in South Sulawesi are located in regions where major fault occurred such as Walanae Fault in the central part of the province and Matano Fault in the northeastern part of the province and Palu-Koro Fault in the northern part. Small extension of these three major faults sometime generated small scale earthquake such as in Belopa, Toraja and Palopo area. Based on geological background, earthquake in south Sulawesi can be classified into three segments, Walanae Fault Segment, Palu-Koro Fault segments, and Matano Fault segment.

1) Walanae Fault segment cover a large area in a depression structure that strike northwest to southeast direction in central part of the province. Maximum magnitude of this segment (Mmax) can reach until 6.1 for 200 years period. The most vulnerable area in this segment are Sengkang Town (Wajo Regency), Watansoppeng (Soppeng Regency) and Watampone City (Bone Regency) and small villages across the fault zone. In addition, the segment extends into Selayar Island passing through Sinjai City and Bulukumba Regency before crossing the sea into Selayar Island.

2) Palu-Koro Fault segment is a left-lateral strike slip fault system, striking from the northwestern to southeastern of Sulawesi. The slip-rate is between 25 – 30 mm and maximum magnitude based on slip-rate reach 7.6 in 162 year period. This fault is one of the most active fault systems in Indonesia. The earthquake in South Sulawesi generated by this fault took place in Palopo and surrounding area. The orientation of the earthquake shows an oblique motion of M of 6.8 [13], [14].

3) Matano Fault segments

Earthquake hazard in South Sulawesi is extremely high along Matano Fault zone. The Matano Fault strikes just exactly in Soroako City, North Luwu which is located on an alluvium material and surrounding lacustrine lowlands. The seismicity of Matano Fault can be seen in Fig. 5. Earthquake in South Sulawesi have caused damages including including ground shaking and surface rupture.

4.2. Landslide

Landslide in South Sulawesi is classified based on characteristic of material as follow:
(1) Rock slides and avalanches,
(2) Mudflows and lateral spreads (liquefaction phenomena), and
(3) Rock falls

Rock slides and avalanches are very rapid movement of colluvial material on over-steepened slopes under conditions of high moisture. This type of landslide occur commonly to frequently and can cause moderate to great damage in infrastructure, especially road access in high topographic areas such as in Malino (Gowa), Buludua (Barru-Soppeng), Enrekang, Palopo – Toraja and Masamba. Mudflow and lateral spreads or liquefaction is the rapid downhill movement of a fluid mixture of soil, rocks and water on gently sloping to nearly flat area. This type of landslide occurs in the area such as East Luwu and Malino. Rock falls are referred to free-falling or plunging rocks from cliffs and steep slopes which are found in some areas namely Gowa – Sinjai road access, Maros – Bone road access and Toraja – Palopo road access.

Based on their origin, landslide in South Sulawesi is geologically classified into three groups; 1) morphology-related, 2) structurally or seismically-related, 3) stratigraphically-related. Areas in high topography such as Gowa, Sinjai, Toraja, Luwu Utara, Jeneponto, Bulukumba and Bone are categorized as landslide-prone area induced by morphology-related process. Structurally or seismically-related landslides is due to structural process such as fault generated by earthquake. This type of landslide causes damages in some areas, especially road access, bridge and settlement. This landslide type producing faulting, fracturing and jointing in the rock formation which causing rocks formation unstable and easy to slide. Stratigraphically-related landslide in South Sulawesi can be
found in areas dominated by sedimentary and volcanic material. The boundary layer within the sedimentary formation will be acting as sliding surface which intensifies the sliding process.

Petrological aspect along with mineralogical characteristic (clay formation) also plays an important role in some landslide-prone area. High weathering process due to tropical condition in South Sulawesi is also responsible in provoking the landslide. Most of landslides are triggered by torrential rains lasting more than two day periods which severely add the impact of the landslide. Figure 6 shows some characteristic of landslide in South Sulawesi.

4.3. Tsunami

South Sulawesi is surrounded by seas including Bone Gulf in the east, Flores Sea in the south and Makassar Strait in the west which are related by some seismic activity. Bone Gulf in the east is still associated with the extension of Palu-Koro Fault Zone whereas Flores Sea in the south is linked to the active Flores Sea up thrust and Makassar Strait is attached to the Mangkalihat Fault. These faults system were recorded to generate tsunami in the past and hence some coastline areas facing to these seas in South Sulawesi are tsunami prone-area. Bantaeng, southern part of Bulukumba (Bira Beach), Makassar, Pare-pare and Palopo are the area in which tsunami has been recorded to strike in the past.

4.4. Flood

Flood is a most recurrent hazard throughout the South Sulawesi Province, especially in highly populated areas. Flood Disaster in Sinjai Regency in 2004 was an example of a debris floods causing a devastating damaged in the city of Sinjai and surrounding area.

In term of geology point of view, flood in South Sulawesi is due to three main factors, namely 1) deforestation, 2) high sedimentation and 3) sporadic urbanization. More recently (January 2019), flood in Makassar and surrounding area including Gowa and Jeneponto was due to combination of extremely high rain-fall, high-tide and uncontrolled land conversion including deforestation. The latter have shown its effect in many areas in which flood struck several regency due to deforestation or excessive logging practices which reduce a capacity of water absorption in the forest, hence increasing runoff in lowland-lying area especially surrounding coastline and river mouth areas. In fact, flood reaching up to 3 meter height in some areas especially in Sinjai, Gowa, Luwu Utara and Wajo due to this phenomenon. The relatively low-lying area coupled with constant heavy rain made the flood more severe is some area such as Sinjai, Walanae Depression areas (Bone, Soppeng, Wajo) and East Luwu.

Some areas especially surrounding Tempe Lake in Walanae Depression are inundated by flood periodically due to high-sedimentation rate. The uncontrolled sedimentation has been covering almost one-fouth of the lake pile and hence decreasing the accommodation space of the water. Consequently, water from some rivers discharged into the lake will overflow and submerge the area attached to the lake. Soppeng, Wajo, Bone and Sidrap Regency are the most affected and suffered area by this type of flood. Urbanization of a floodplain or adjacent areas in major City like Makassar will increases amount of runoff since it reduces the amount of surface area available to absorb rainfall. Coupled with high tide during full moon and high rain fall, the impact of flooding in Makassar, Gowa and surrounding areas which are located close to the sea will be very destructive.
5. Geological Hazard map

We have produced an outline map of geological hazard in South Sulawesi to show the distribution of natural hazard. The map production is based on mapping activity and other sources by Field Geology Laboratory, Department of Geology, and Research and Development Centre for Disaster Study, Hasanuddin University during 2013 - 2017. The result of mapping is shown in Fig. 7. The map show that natural hazard such as earthquake, landslide, tsunami and flood are closely controlled by the geological condition of the area. All areas across fault zone direction are earthquake-prone areas. Landslide map showing a very well-related pattern between landslide and geology (morphology, stratigraphy and structural geology). Most of landslides occur in high topography area with highly weathered volcanic material. Tsunami map also show concentration of tsunami-prone area in some coastline facing to the some active faults extension such as southern coastline of South Sulawesi, Makassar coastline and Pare-pare. Flood zonation map display a concentration of flood area and low-lying areas such as coastline areas, catchment area in some major rivers, and depression area related to Walanae Basin.
6. Conclusions

Geological disaster in South Sulawesi consists of earthquake, landslide, tsunami and flood. These hazards are closely controlled by geological condition of the province.
- Earthquake in South Sulawesi are located in regions where major fault occurred such as Walanae Fault in the central part of the province and Matano Fault in the northeastern part of the province.
and Palu-Koro Fault in the northern part.
- Based on the material, landslide in South Sulawesi can be classified as slide, flow and rock fall. Furthermore, the origin of landslide in South Sulawesi is geologically classified into three groups; 1) morphology-related, 2) structurally-related, 3) stratigraphically-related. High weathering process due to tropical condition in South Sulawesi is also responsible in provoking the landslide. Most of landslides are triggered by torrential rains lasting more than two day periods which severely add the impact of the landslide.
- Some coastline areas facing to the seismically-active sea in which active faults are developed generating tsunami. Bantaeng, southern part of Bulukumba (Bira Beach), Makassar, Pare-pare and Palopo are included as tsunami-prone area.
- In term of geology point of view, flood in South Sulawesi is due to three main factors, namely 1) deforestation, 2) high-sedimentation rate and 3) sporadic urbanization. The low altitude coupled with constant heavy rain fall and high tide made the flood more severe in some areas such as Makassar, Gowa and surrounding city close to the coastline.

The result of this study shows that geological characteristic intimately controls the occurrence of natural disaster in South Sulawesi and therefore the geological data should be considered in mitigation strategy. Intensive and detail geological study is needed to produce a detail micro-zonation map to build a strong disaster mitigation model in the future.

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