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Identifying and Assessing Geohazard in Indonesia Geothermal Area: How Difficult Is It?

Vicky R. Chandra[1], Dorman Purba[2,3], Arthur G.P. Nayoan[2], Ferdino R. Fadhillah[2,4], Rizki Fadhilah Ramadhan[2,5], Rio Anggara[2,6]

[1] Geo Dipa Energi, Aldevco Octagon, Jakarta, Indonesia

[2] Enerka Bhumi Pratama, Cibis Nine 11th Floor, Jakarta Selatan 12560, Indonesia,

[3] Geonergi Solusi Indonesia (Geoenergis), Cibis Nine 11th Floor, Jakarta Selatan 12560, Indonesia

[4] Geology, Faculty of Mathematic and Natural Science, University of Indonesia, Depok 16424, Indonesia

[5] Geological Engineering, Pertamina University, Jakarta, Indonesia

[6] Geological Engineering, University of Jambi, Jambi, Indonesia

vickyraychandra@gmail.com; dorman.drilling@gmail.com

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ABSTRACT

Indonesian geology that is formed by a complex of tectonic plate settings, subduction processes and lies along the Pacific Ring of Fire are not only give a vast geothermal energy potential but also high risk of geohazard that could occurs during geothermal exploration and development activities. Failure in identifying risks of geohazard in early phase of geothermal development plan might cause some problems and catastrophic events such as damages on bridge, well pad, road access, skewed pipeline, well leaks or broken, impairment of power plant facilities, and following cessation of electricity production. Moreover, these events also could impact the nature or environment surrounding the field and results fatality or loss of human lives. Therefore, it is very critical to have a well - structured and comprehensive method as a guide to identify and mitigate the geohazard risks.

The aim of this study is to gathers and reviews various geohazards in Indonesia geothermal prospect area. Several literatures, author's previous studies and records about various possible geohazard cases that have and possibly happen in Indonesia geothermal area are reviewed in this study.

1. INTRODUCTION

1.1 Geothermal Systems in Indonesia

Hochstein and Sudarman (2015) identified the two groups of Indonesian volcanic geothermal systems that defined by using fluid analyses and volcanic (terrain) settings. The larger group includes geothermal systems that are hosted by young strato-volcanoes and other smaller group includes steeply dipping 'volcanic feeder (plug-type) systems standing in moderate terrain. These two types of geothermal systems asserted that all geothermal fields and prospects in Indonesia are associated with volcanoes and located in the high terrain which is steep and prone to landslides event compare with flat area.

Additionally, it is common in Indonesia that in the adjacent of a geothermal field there are some active volcanic centers and that geothermal areas are enclosed within seismically active zones (Utami, 2010). Volcanic hazard, earthquake and other hazards indirectly related or even unrelated to geothermal activity may also affect a geothermal field.

Geothermal systems itself are dynamic. Their thermal and hydrological structures (and hence the thermal manifestations) to some extent, also affected by the history i.e. natural and artificial changes that has been experienced by the systems. Based on that condition it is understandable that there are plenty of geohazards in geothermal field which could occurs during exploration or development of the field. Understanding such structures is important when planning construction works on top of a geothermal system because they are directly related to the distribution of the hazard-prone sites and the sites that bear technical difficulties for construction.

1.2 Objectives

The study of geohazard assessment in geothermal field is crucial to finding better management for every geologic hazard that continually threatens some geothermal field in Indonesia from the exploration to the development period. Based on historical data from several developed field, the effects of these hazards have cost EDC in Philippine about USD $6.8 Million annually from 2006 to 2011 alone, in the form of disrupted operations, lost revenues and cost of slope stability program (Marasigan & Olivar, 2015).

Similar damaged condition that need high restoration cost also happens in Indonesia for example in Wayang Windu field due to massive landslides event in 2015 occurred around the steam pipeline and settlement area which make it worst due to fatality were recorded from this event, and also in Salak and Darajat field based on author's experiences. However, the published information regarding these sensitive issues was hard to find due to company preferences.

The key to effectively addressing the risks inherent to these hazards is timely access to information to aid engineers and management to make decisions that will minimize, if not fully eliminate, these risks. Eventually the study aims to reduce the vulnerability of the geothermal facilities, inhabited structures, roadways and local communities to natural disasters that potentially occurs in geothermal field.

2. METHOD

This study done by reviewing literatures, news, and professional experiences about geohazard assessment for geothermal field in Indonesia. Based on those, authors try to combine the geohazard occurrence, driving factor and impact. Moreover, several mitigations and monitoring plans also proposed.

3. DATA AND DISCUSSION

3.1 Landslide

Hydrothermal geothermal system associated with volcanic morphology is dominant geothermal system in Indonesia. Those system often located at stratovolcano with high relief and steep slope. (eg Mt. Salak, Mt. Lawu, Mt. Sinabung, Mt. Slamet, Mt. Merapi, Mt. Pulosari and Mt. Soputan) (Figure 1). This condition makes the flank of stratovolcanoes very prone to collapse and landslides (Francis & Wells, 1988). According to Varnes (1978) landslide is a slope movement of slope materials under the influence of Earth's gravity.

Figure 1: Left: Steep morphological of Mt. Pulosari (Nayoan et al., 2019). Right: Very steep slope at volcanic dome of Mt. Marapi (Ashari, 2017)

The factors that control landslide are the type of sliding, the structure and strength of slope material, and the geometry of the slope which has correlation with geological-geomorphological condition (McColl, 2015). According to Karnawati (2005) there are several factors that trigger landslides such as the process of rain infiltration, earthquake or vibrations of heavy vehicles / equipment, human activities that changes land use and load on slopes. Those all factor increases the critical slopes condition moreover, the presence of geothermal manifestation also controls the occurrence of landslide (Utami, 2010).

The existence of geothermal manifestations will alter the surrounding area. Example of this case can be found at steaming ground manifestation which alter and forming swelling clay on topsoil. This material on steep slope is unstable and prone to induce the landslides (Utami, 2010). Landslides that commonly occur in soil materials are circular based on the landslide classification according to Varnes (1978) and proven by the landslides that occurred at Lembata Island in the 1979 that show main scrap feature on the crown side and (Yudhicara et al., 2015) (Figure 2). Lembata landslide were caused by geothermal manifestation proven by landslide materials contains clay mineral. Hydrothermal alteration creates of clay mineral (smectite and zeolite) on the altered topsoil. This material will be expansive when exposed to water and induce the landslide.

Figure 2: Evidences of the 1979 landslide taken on April 2013, the crown (Left) and the landslide body (Right) (Yudhicara et al., 2013)

Manifestations such as hot springs and fumaroles are strongly associated with faults/fractures presences as in Mataloko geothermal field (Nanlohy et al., 2001). Fractured zone can stimulate rockfall-type landslides caused by structural control (Varnes, 1978). While the planar type landslides tend to rarely occur in geothermal areas because they are more common in strike and dip rocks such as sedimentary rock. The landslide events have similarity of geothermal fields with hydrothermal geothermal systems, Stratovolcano with steep slopes formed from magma with intermediate composition based on the classification according to Wohletz & Heiken (1992). Several landslides related to geothermal working area shown in Table 1. Geological landslide disasters also very sensitive to the local community environment and can cause social problems, therefore mitigation is needed to minimize this impact.

Table 1: List of several landslide events in Indonesia's geothermal field

Geothermal Field	Pangalengan	Sungai Penuh	Hululais
Location	Wayang Windu, West Java	Kerinci, Jambi	Lebong, Bengkulu
Geothermal System	Hydrothermal System	Hydrothermal System	Hydrothermal System
Time of Incident	May, 2015	January, 2013	April, 2016
Developer (EBTKE, 2017)	PT Pertamina Geothermal Energy KOB Star Energy Wayang Windu	PT Pertamina Geothermal Energy	PT Pertamina Geothermal Energy
Reference	cnnindonesia.com	beritasatu.com	petroenergy.id

Initial field identification is required to determine the risk of landslides. Several field indicator that need to be monitor during survey are: rock cracking in outcrop, the emergence of a water seepage on the slope, bulging and lipping at the foot of the slope, the amount of material escaping from a slope, and the presence of manifestations on the slopes that can flow and form mineral clay on the slope material (Figure 3).

Mitigation related to landslide hazards can be done by providing non-structural mitigation such as providing information, disseminating landslide disasters, training and simulating landslide disasters which can provide insight for the local community (Rahman, 2015). Desktop studies and regional mapping are important things to do to determine the condition of the geothermal area, the GIS method is also important to use to determine landslide-prone areas in geothermal fields by making a slope and FFD map overlaid with a surface manifestation to determine the orientation of the structural control. on a geothermal field (Figure 4).

Figure 3: Structural indication of rock-fall landslide on outcrop scale (Left) and Fumarole manifestation with landslide material (Right)

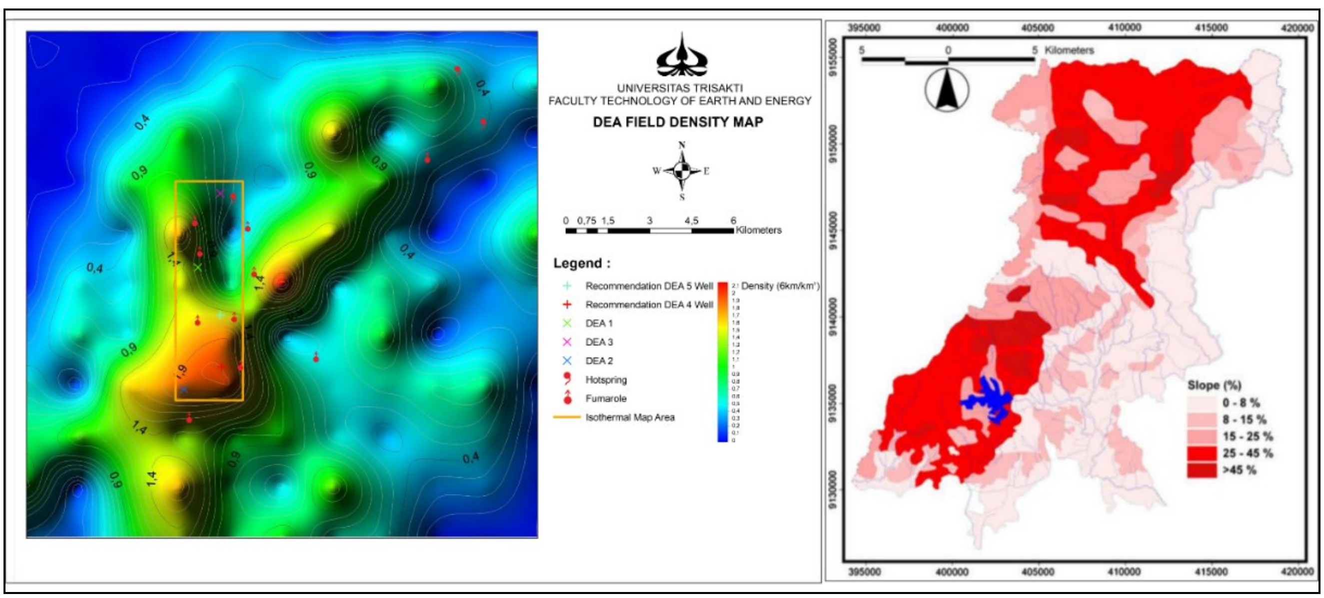

Figure 4: Example of FFD Map overlaid with Geothermal Manifestation (Left) (Nayoan et al., 2020) and Example of Slope Map to Predict Landslide in Menoreh Mountains (Hadmoko et al., 2010)

3.2 High Temperature and Gas Zone

The existence of geothermal manifestations indicates that the geothermal area system is active. This area associates with high temperature and gaseous zone that must be identify and monitor to prevent further hazard. According to Utami (2010) (Table 2) in a hydrothermal geothermal system with a high relief order, the existence of geothermal manifestations has potential for disasters such as the presence of thermal & altered ground, fumaroles & gas vents, and acid hot springs.

Early identification of manifestations location associated with high temperature zones can be execute using remote sensing analysis based on satellite imagery and gravity data. This method has conducted on northern Sulawesi area with result accuracy up to 87.5% (Julzarika and Nugroho, 2019). Moreover, the manifestation risk must be identified by field survey as basis of high temperature mitigation plan. The mitigation that needs to be done is the socialization of the community and the company, giving a warning sign on several manifestations that can injure or threaten human life (e.g. fumaroles & gas vent which may contain H2S and CO2 or acid supply hot spring). An example cases from this geohazard like in the not-yet produced Dieng geothermal system a high CO2 gas concentration is uncommon in Indonesian fields, but during the eruption of the Kawah Sinila in 1979 which claimed 182 lives (Harian Sinar Harapan 23 Februari 1979 in Wintolo, 1979).

Table 2: Gas & High Temperature Zone Description and Potential Hazard Table

Manifestation	Description	Potential Hazard	Picture
Thermal & Altered Ground	Ground that has sufficient heat in the range 80 - 90 °C (Lahendong, North Sulawesi). Some minor steam can be diffusively discharged through the surface but significant steam is often discharged directly to the air through cracks, vents and fumaroles. The surface and near surface rocks at the thermal ground are commonly altered, meaning that their primary minerals have been replaced by new minerals as the consequences of hydrothermal alteration processes.	At the surface where acid fluids/steam condensate present the rocks are leached and hence becoming less stable. Kaolin + alunite and silica other than quarts occur,and at the fumarolic thermal area common as the surface alteration products and they are often accompanied by sulfate-rich aluminous efflorescence. These indeed have different engineering properties from soils or weathering products.	
Fumaroles & Gas Vents	Fumarole is a geothermal manifestations of gas bursts, which are mostly water vapor and have high temperatures. In steep terrain, fumaroles usually occupy the higher elevations, and become one of the indicators of the thermal fluid upflow zone of the geothermal system. Gas vents manifestations resemble fumaroles, but have different compositions and are dominated by elements such as H_2S and CO_2 (ESDM, 2015)	Gas vents are abundant at the most vigorous parts of the thermal area such as those in Kamojang, Ungaran, Lahendong, and other geothermal fields. Gas vents with a H_2S concentration higher than 150 m/m^3 causes eye and respiratory irritation, and possible death within few to tens of hours. CO_2 gas which is colorless and odorless may be present, and when it is discharged in high concentration (>9000 mg/m^3) is health/life threatening (Rolfe, 1980).	
Acid Hot Springs	The most obvious manifestation of a geothermal system that transfers heat to the ground (White, 1973 in Sumotarto, 2015) via a water due to structural geological controls.	Springs / pools with boiling, neutral-pH alkali chloride fluids (these are not so cofilmon in Indonesia) are clear and often associated with silica deposit (sinter) which is not always safe enough to step on, as the scalding grorurdwater occurs in a shallow depth. Acid sulfate hot springs (pH: 3 or less) are milky; this appeamnce results from dissolution of the rocks by the acid water. The high temperature and the acidity of the water can cause severe m: ury. Ground collapse can occur naturally in areas associated with acid fluid	

3.3 Flash Flood

Flash floods is sudden water movements in short duration with massive volumes carrying debris materials such as soil, trees and rocks at high velocities associated with heavy rain, cyclones, and storms (WMO, 2012; PUPR, 2012; Otieno, 2018).

This disaster start by significance in-charge to the stream by high intensity rainfall at the upstream area creates the water volume above stream capacity. Natural dam formation from landslide or illegal logging activity could block the stream flow and trigger the energy accumulation. At some point this natural dam will release the destructive water flow simultaneously with high velocity up to 160 km/h and destroy any buildings along stream flow (WMO, 2012; PUPR, 2012; BNPB, 2016). Based on National Disaster Management Authority/BNPB (2016), the area with steep slope and high intensity rainfall that has stream is the characteristic of flash flood prone area.

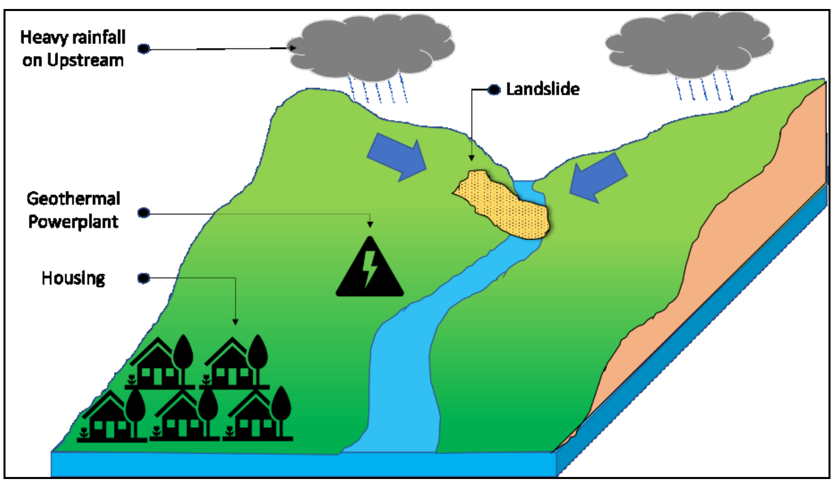

Figure 5 Illustration of flash flood related to geothermal area

The characteristic of flash flood prone area also has similarity with Indonesia geothermal area which on high relief terrain and tropical climates. Flash flood disaster will be very dangerous at geothermal working area due to the facility and drilling activity. This incident has occurred in Lebong Geothermal Area with causalities, injuries, missing victims from employees, contractor, and locals (Progres.ID, 2016; Bengkulu Government, 2018; KOMPAS, 2018)

Several mitigations could be executed, such as:

- Risk identification and assessment
  Flash flood risk map creates by integration of natural disaster history, hydrology, and remote sensing analysis to identify flow height and velocity at the prone area (Psomiadis, Soulis, Zoka, & Dercas, 2019). Landslide risk map also can add as input data since that hazard also contributes for flash flood generation. The coverage area of this map is relative wide, so the utilizations of remote sensing with 30 meters to 0.5-meter resolution is effective for geomorphological and land utilization at upstream area (Psomiadis, Soulis, Zoka, & Dercas, 2019). Most of input data is open access data that available on related government institution. Furthermore, this map can be used as parameter of working area development and disaster task force preparation since the prediction of flash flood has high level uncertainties due to complexity and varieties of driving factor (Montz & Gruntfest, 2002)

- Warning system
  Early warning by live monitoring of natural and early sign of flash flood along stream flow is the simplest way for flash flood. The monitoring can be done by operators, CCTV or locals report to the certain task force of geothermal developer. Based on those reports, the risk assessment will be performed to determine evacuation (PUPR, 2012). The key parameters for this method are:
  - Forming natural dam on upstream
  - High intensity rainfall within long duration
  - Heavy cloud on upstream
  - Rapid change on stream level
  - Environmental damage activity on upstream
  - Increasing of sediment on stream
  - Roar from upstream

Figure 6 shows the warning stage from monitoring to execution of evacuation.

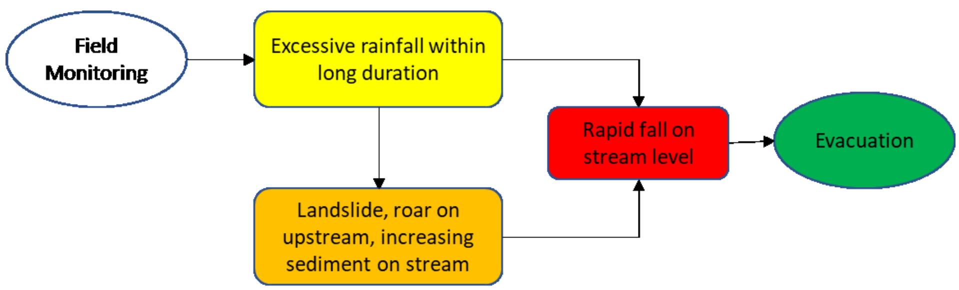

Figure 6: Warning stage of flash flood (modified from PUPR,2012)

- Effective communication
  Effective risk communication is crucial part to raise knowledge and awareness from all stakeholders and locals to reduce the risk of hazard. Pitfalls from this aspect will show significance impact (Kellens, Terpstra, & Maeyer, 2013). By effective communication between geothermal developer, government, and locals the prevention of flash flood hazard can be optimized from hearing activity about local activity on upstream, education about flash flood hazard and simulation of evacuation plans. The communication also prevents miss-perception between locals and developer about occurrence of natural disaster.

3.4 Eruption

Considering Indonesia is inhabited by 128 volcanoes (Table 3) with 4 volcanic arcs (Sunda Arc, Banda Arc, Halmahera Arc, and North Sulawesi-Talaud Arc) the danger of eruptions in Indonesia has become a general matter that must monitored. According to Zaennudin (2010) about 13 % of the world's active volcanoes are located in Indonesia. If we look a little to the past regarding geothermal exploration in Indonesia, over 20 volcanic geothermal systems were explored in Indonesia between 1970 and 2000 (Hochstein and Sudarman, 2008) and most prospects are associated with volcanoes of high relief (mainly strato-volcanoes) (Hochstein and Sudarman, 2015).

This indicates that almost all geothermal fields (WKP) in Indonesia are located in volcanic areas and geohazard constraints must be very vigilant because they can impact social-economic problem in geothermal industry itself and local community in the surrounding area. Examples case of volcanic eruptions in geothermal areas are located in Mt. Tangkuban Parahu on West Java with PT. PLN (Persero) as the developer (ESDM, 2017). Based on the press released by MAGMA Indonesia (https://magma.esdm.go.id/) that Mt. Tangkuban Parahu erupted (Figure 7) on 2 August 2019. From geological agency profile report about Mt. Tangkuban Parahu (https://vsi.esdm.go.id/) the latest volcanic activity occurred in 2004 with an increase in seismicity in the volcanic area while the latest eruption occurred in 1994 with an increase in strong activity with shallow seismic earthquakes with small phreatic eruptions.

Therefore, what we need to be done to minimize the problem of eruption geohazards is coordination between geothermal field developer with the local government volcanology agency (PVMBG or ESDM) in monitoring volcanic activity. Mitigation like socialization to the local community regarding the geohazard disaster of volcanic eruptions can at least provide insight into the worst possible scenario to the community. Training or safety induction about eruption needs to be done to the local community, even workers in the geothermal field. For example as suggested by Hermon et al (2019) in the case of the Mt. Sinabung in North Sumatra that Karo Regency government have to include disaster education curriculum starting from the elementary to secondary schools, conducting socialization in disaster-prone zones, and conducting disaster-based spatial planning to reduce the risks that will occur in the future.

Table 3: Distribution of Indonesian Active Volcanoes (Zaennudin, 2010)

Area	Active Volcanoes			Sum
	A Type	B Type	C Type	
Sumatera	12	12	6	30
Java	21	9	5	35
Bali	2	-	-	2
Lombok	1	-	-	1
Sumbawa	2	-	-	2
Flores	17	3	5	25
Laut Banda	8	1	-	9
Sulawesi	6	2	5	13
Kepulauan Sangihe	5	-	-	5
Halmahera	5	2	-	7
Sum	79	29	21	129

Definition Of Active Volcanoes Indonesia:

A - Type: Volcano since the year 1600 shows an increased activity, magmatic or even only phreatic eruption.

B - Type: Volcano in solfataric and/or fumarolic activity, since the year 1600 there is neither evidence of increasing of its activity nor eruption.

C -Type: Solfatara and/or fumarole field, some times the volcanic edifice is not clear.

Figure 7: Photo of Mt. Tangkuban Parahu eruption in 2 August 2019 (https://magma.esdm.go.id/)

Remote sensing analysis combine with geomorphology analysis is very good for use in volcanic eruption mitigation. Joyontono et al (2019) using LaharZ software modelling primary lahar in Ijen Volcanic Complex, to know where the potential place or area that damage or causality in Ijen Caldera Complex near Pahit River by calculate the volume that being fill pixel value in river valley considered as lahar mass trough channel (Figure 8). LaharZ give a result when it's used to zoning lahar hazard zone in Sempol Sub-district, Bondowoso. The Primary Lahar Hazard Maps give very good guidance to the volcanic hazard management, especially to reduce casualties by primary lahar and even secondary lahar. Ijen Volcanic Complex is also one of the Geothermal Field (WKP) in Indonesia that developed by PT. Medco Cahaya Geothermal (ESDM, 2017).

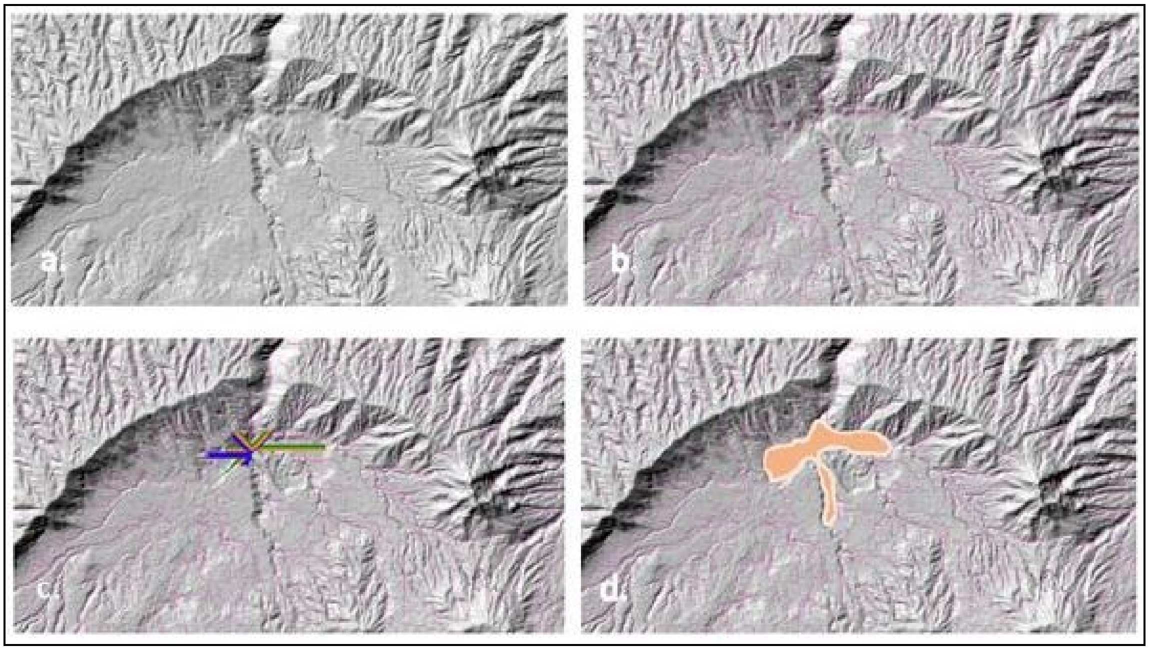

Figure 8: Example of lahar hazard zoning processing in Sempol Area District, Bondowoso. (A.) DEM Hillshade Model of Sempol Sub-district, (B.) River Identified by running LaharZ, (C.) Volume 1% of Ijen Crater Lake is performed to fill channel, (D.) Re-delineate scope area of LaharZ modelling result (Joyontono et al, 2019)

4. RECOMMENDATION

Most of geohazard has natural sign that can help geothermal developer to identify the risk and impact. Since the impact of geohazard related geothermal site and development often reach catastrophic level, the awareness and understanding about this challenge needs improvement includes the understanding of hazard record. Figure 9 shows the frequencies of published geohazard occurrence related to geothermal site in last ten years, this data needs elaboration for better understanding of geohazard condition in geothermal area.

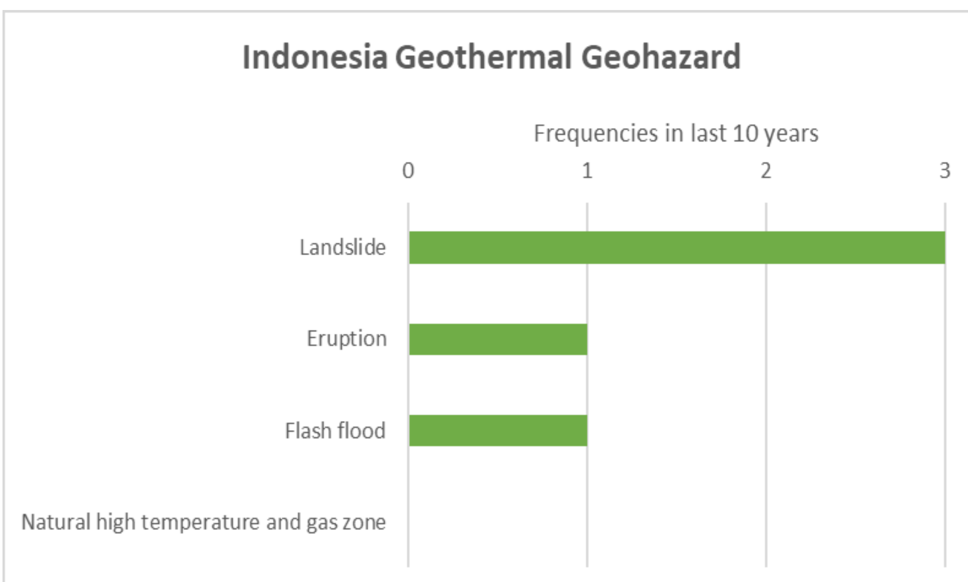

Figure 9: Geohazard frequencies related to Indonesia geothermal site in last 10 years

The geothermal hazard will have big impact related to geothermal exploration and development activity not only for technical aspect but also the social impact around geothermal area. It is important to prevent geohazard by geothermal developer. Several action that recommends executing are summarize in Table 4.

Table 4: Mitigation action of geohazard (modified from PUPR,2012)

Action	Description	Activity
Risk assessment	Geothermal developer determines and predict hazard risk related to stakeholder, project and development	- Hazard identification - Vulnerability analysis - Risk prediction
Monitoring and early warning	HSE team with locals monitor the prone area related to the activity that increase the risk and early natural sign of hazard	- Early warning system - Task force team preparation - Evacuation plan
Communication	Establish the effective communication related to information exchange, early warning, and evacuation coordination between all stakeholder under certain task force	- Provide communication tools and procedure

4. CONCLUSION

It is clear that although Indonesia has an abundant geothermal potential, it is also accompanied by high geohazard risks due to its geological setting. Natural geological hazards such as landslides, high-temperature and gas zones, flash flood, and eruptions (hydrothermal, phreatic and volcanic) may occur and harm the developed geothermal field or even the unexploited geothermal prospect areas. A detailed and well-structured geological mapping, which consists of geological structures, eruption centers, volcano stratigraphy and thermal manifestations, is the best method to reduce the risk from natural geological hazard. Moreover, reviewing map of volcanic hazard and volcanic activity and earthquake history data from Volcanology Board Indonesia will also help to minimize the risk.

At the development stage, geothermal fields might suffer more geohazards such as landslides, subsidence, rock falls and all other natural geohazards. Integration between geological, slope stability and GIS map with rainfall data might be the best tool to reduce the landslide risk within the fields. Furthermore, tiltmeter and inclinometer should be installed to monitor the landslide prone area. Drone is one of the most recent technologies that can help to survey the remote area where it is inaccessible.

Geohazard assessment is an essential step in exploration stage, so the risk that might be occurred caused by geohazard can be minimized. Therefore, geohazard study needs to become a mandatory evaluation at the exploration stage, before the geothermal prospect area is exploited further. Government may conduct a strict regulation regarding this geohazard assessment in order to attract the investor to develop geothermal prospect area and reducing the loss, e.g. financial, human lives, and nature environment.

Finally, this preliminary study has reviewed several geohazards that has occurred in the past and has the potential to reappear in the future, in various geothermal areas in Indonesia. Several points that can become a potential path forward for this study are:

1. Conduct interviews with or surveys to various geothermal developers in Indonesia regarding the geohazard identification methods and mitigation action plan that the developers have applied in their geothermal field.

2. Develop a geohazard identification and mitigation procedure that can serve as a general guidance for geothermal exploration projects in Indonesia.

REFERENCES

Ashari, A. (2017). *Geomorphology of the Southern Flank of Merapi Volcano in Relation to the Potential Hazards and Natural Resources: A Review*. Geomedia: Majalah Ilmiah dan Informasi Kegeografian Volume 15 Nomor 2.

Bengkulu Goverment. (2018, 03 28). *DPD RI Gelar Rapat Terkait Dampak Lingkungan PGE Lebong*. Retrieved from Pemerintah Provinsi Bengkulu: https://bengkuluprov.go.id/dpd-ri-gelar-rapat-tekait-dampak-lingkungan-pembangunan-pge-lebong/

BNPB. (2016). *Resiko Bencana Indonesia.* Jakarta: Badan Nasional Penanggulangan Bencana

ESDM. (2015). *Buku Panduan Penyelidikan Panas Bumi*. Pusat Sumber Daya Geologi, Badan Geologi ESDM. ISBN: 978-602-9105-64-3

ESDM. (2017). *Potensi Panas Bumi Indonesia Jilid 1*. Jakarta: Direktorat Jenderal Energi Baru, Terbarukan Dan Konservasi Energi.

Francis, P.W., Wells, G.L. (1988). *Landsat Thematic Mapper observations of debris avalanche deposits in the Central Andes*. Bulletin of Volcanology 50, 258–278. https://doi.org/10.1007/BF01047488

Hadmoko, D.S., Lavigne, F., Sartohadi, J., Pramono, H., & Winaryo. (2010). *Landslide hazard and risk assessment and their application in risk management and landuse planning in eastern flank of Menoreh Mountains, Yogyakarta Province, Indonesia*. Nat Hazards 54, Page 623–642. https://doi.org/10.1007/s11069-009-9490-0

Hermon, D., Ganefri, Erianjoni, Dewata, I., Iskarni, P., and Syam, A. (2019). *A Policy Model of Adaptation Mitigation and Social Risk the Volcano Eruption Disaster of Sinabung in Karo Regency-Indonesia*. International Journal of GEOMATE, Aug. 2019, Vol.17, Issue 60, pp.190-196. ISSN: 2186-2982.

Hochstein, M.P., Sudarman, S. (2008). *History of geothermal exploration in Indonesia from 1970 to 2000*. Geothermics, 37, 220-266.

Hochstein, M.P., Sudarman, S. (2015). *Indonesian Volcanic Geothermal Systems*. Proceedings World Geothermal Congress 2015.

Joyontono, P., Harijoko, A., and Wibowo, H.E. (2019). *Geomorphological Analysis to Determine Hazard Map Related to Primary Lahar of Ijen Crater Lake, Ijen Volcanic Complex, Indonesia*. PROCEEDINGS JOINT CONVENTION YOGYAKARTA 2019, HAGI – IAGI – IAFMI- IATMI (JCY 2019). ISBN-978-979-8126-37-6.

Karnawati, D. (2005). *Bencana Alam Gerakan Massa Tanah di Indonesia dan Upaya Penanggulangannya*. Jurusan Teknik Geologi, Universitas Gadjah Mada, Indonesia. ISBN 979-95811-3-3.

Kellens, W., Terpstra, T., & Maeyer, P. D. (2013). *Perception and Communication of Flood Risk: A Systematic Review of Empirical Approach.* Gent.

KOMPAS. (2018, 03 09). *Dituding Penyebab Banjir, Anak Perusahaan Pertamina Digugat dan Dilaporkan ke Presiden*. Retrieved from Kompas Media Digital Group: https://regional.kompas.com/read/2018/03/09/13432101/dituding-penyebab-banjir-anak-perusahaan-pertamina-digugat-dan-dilaporkan-ke?page=all

Marasigan , R., & Olivar, R.: Distributing Access to Geohazard Information Using Web GIS for EDC Geothermal Field Sites. Proceedings World Geothermal Congress 2015. Melbourne (2015).

McColl, S. T. (2015). *Chapter 2 - Landslide Causes and Triggers*. Landslide Hazards, Risks and Disasters, Academic Press Pages 17-42. ISBN 9780123964526

Montz, B. E., & Gruntfest, E. (2002). Flash flood mitigation : recommendation for research and application. *Environmental Hazard*, 15 - 22.

Nanlohy, F., D. Kusnadi, dan B. Sulaeman. (2001). G*eology and Geochemistry of Mataloko Geothermal Field Central Flores-East Nusa Tenggara*. PROCEEDING OF THE 5th INAGA ANNUAL SCIENTIFIC CONFERENCE & EXHIBITIONS. Yogyakarta.

Nayoan, A.G.P., Naslan, M.R., Pauling, L., & Deny. (2019). *Potensi Geowisata Desa Sukasari, Kabupaten Pandeglang, Provinsi Banten*. Seminar Nasional Ilmu Kebumian-Geodiversity 2019.

Nayoan, A.G.P., Sammuel, E.R., Widiastrawan, I.M.D., Pudyastuti, K., & Hendrasto, F. (2020). *Recommendation in Geothermal Well Targeting in the "DEA" Field Based on Isothermal Model and Geological Indication*. Proceeding Digital Indonesia International Geothermal Convention (DIIGC) 2020. ISBN 978-602-52132-3-6

Otieno, V. (2018). Geohazards in Geothermal Resource Exploitation. *SDG Short Course III.* Kenya: United Nation University.

Progres.ID. (2016, 04 28). *Ini korban bencana banjir bandang di PGE Lebong*. Retrieved from progres.id: https://progres.id/peristiwa/ini-korban-bencana-banjir-bandang-di-pge-lebong.html

Psomiadis, E., Soulis, K. X., Zoka, M., & Dercas, N. (2019). Synergistic Approach of Remote Sensing and GIS Techniques for Flash-Flood Monitoring and Damage. *MDPI*.

PUPR. (2012). *Pedoman Manajemen Penanggulangan Bencana Banjir Bandang.* Jakarta: Kementrian Pembangunan Umum Republik Indonesia.

Rahman, A.Z., (2015). *Kajian Mitigasi Bencana Tanah Longsor di Kabupaten Banjarnegara*. GEMA PUBLICA Jurnal Manajemen dan Kebijakan Publik Vol. 1, No. 1. ISSN 2460-9714.

Rolfe, K.A. (1980). *Air pollutants associated with geothermal energy*. The New Zealand Energy Joumal. 25 May 1980.

Sumotarto, U. (2015). *Eksplorasi Panas Bumi*. Penerbit Ombak. Yogyakarta.

Utami, Pri. (2010). *High-temperature Geothermal Area and its Challenges for Civil Engineering Works*. PERTEMUAN ILMIAH TAHUNAN XIV HATTI. Indonesia.

Varnes, D.J. (1978). *Slope Movement types and Processes*. Special Report Page 68 - 76. Washington D.C.

WMO. (2012). *Integrated Flood Management Tools Series : Management of Flash Floods.* World Meteorogical Organization

Wohletz, Kenneth, and Grant Heiken. (1992). *Volcanology and Geothermal Energy*. Berkeley: University of California Press. http://ark.cdlib.org/ark:/13030/ft6v19p151/

Yudhicara, Hidayati, S., and Suparan R. (2013). *Laporan Penyelidikan Tsunamigenik di Pulau Lembata, Nusa Tenggara Timur*. Internal report of Center for Volcanology and Geological Hazard Mitigation, Geological Agency.

Yudhicara, Bani, P., & Darmawan, A. (2015). *Geothermal System as the Cause of the 1979 Landslide Tsunami in Lembata Island, Indonesia*. Indonesian Journal on Geoscience Vol. 2 No. 2, Pages 91 – 99.

Zaennudin, A. (2010). *The characteristic of eruption of Indonesian active volcanoes in the last four decades*. Jurnal Lingkungan dan Bencana Geologi, Vol. 1, No. 2, 113 – 129.

"Longsor di Pangalengan, 14 Orang Masih Tertimbun", 2015, cnnindonesia.com. https://www.cnnindonesia.com/nasional/20150505224600-20-51444/longsor-di-pangalengan-14-orang-masih-tertimbun. Accessed 15 January 2021.

"Longsor di Pengeboran Panas Bumi Sungai Penuh, 5 Tewas", 2013, beritasatu.com. https://www.beritasatu.com/nasional/93786/longsor-di-pengeboran-panas-bumi-sungai-penuh-5-tewas. Accessed 15 January 2021.

"Bencana Tanah Longsor Bukit Besar Timbun Lokasi Panas Bumi Hululais PGE", 2016, petroenergy.id. https://www.petroenergy.id/article/bencana-tanah-longsor-bukit-besar-timbun-lokasi-panas-bumi-hululais-pge-. Accessed 15 January 2021.

"Press Release Erupsi Gunung Tangkuban Parahu, Jumat 2 Agustus 2019", 2019, MAGMA Indonesia. https://magma.esdm.go.id/v1/press-release/186?signature=79adbfb40870ed74139bfa87de828ccece619871ab5eac3449db3e8e75ed7bb7#:~:text=Erupsi%20G.%20Tangkuban%20Parahu%20pada,terjadi%20pada%2026%20Juli%202019.&text=Erupsi%20terjadi%20pada%201%20Agustus,m%20di%20atas%20permukaan%20laut). Accessed 31 January 2021.

"G. Tangkuban Parahu", 2014, Badan Geologi. https://vsi.esdm.go.id/index.php/gunungapi/data-dasar-gunungapi/516-g-tangkuban-parahu. Accessed 31 January 2021.