Development of remote monitoring system of rainfall-induced lahar at Mount Merapi

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論文内容の要旨

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論文題目（外国語の場合は，その和訳を併記すること。）

Development of remote monitoring system of rainfall-induced lahar at Mount Merapi

メラビ山における降水起源ラハールの遠隔監視システムの開発に関する研究

指導教員 OISHI Satoru

（注）2，000字～4，000字でまとめること。

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1. Background of the study

Before 1964, among human victims of total water-related hazards, 32% happens due to sediment disaster. Since 1965, this percentage has increased to approximately 50% (Takahashi, 2009). Amongst all of the sediment disasters, debris flows are the most frequent natural hazards, especially in mountainous, volcanic, semi-arid and sub-polar regions (Santi et al., 2011; Takahashi et al., 1981). Debris flows cover wide range of sediment movement events include debris torrents, debris floods, mudflows, mudslides, mudspates, hyper-concentrated flows, and lahars. In principle, they describe the flows where the interaction between solid and fluid particles plays an important role on the mechanism of the flow process (Iverson, 2010).

Volcanic debris flow or lahar is an Indonesian word that is defined as a rapidly flowing, high- concentration, poorly sorted sediment-laden mixture of rock debris and water from a volcano that is usually triggered by rainfall. It belongs to a continuum flow type includes debris flows, hyper-concentrated streamflows, and mudflows (Lavigne et al., 2007; Neal, 1976). Typically, lahar flows enter a river valley at a velocity of 2.5–11 m/s (Lavigne et al., 2007).

Lahar flow includes the direct and indirect effects of eruptions. The direct one is the hazard happens created by some large eruptions (Major et al, 2000). The indirect or secondary lahar is also known as the post-eruption lahar. The secondary lahar can occur even without an eruption and the initiation is a function of rainfall parameters, source material characteristic, and time since eruptive activity (Jones et al., 2017).

Between 17th and 19th century, lahars are responsible for 17% of deaths due to volcanic disasters, especially in Indonesia. In the 20th century, lahar takes a toll of 31,500 victims from two deadly disasters at Mount Kelud (1919) in Java and Nevado del Ruiz (1985) in Colombia (Lavigne et al., 2007). Lahar and pyroclastic flow contribute to the highest rate of erosion in the world (10^5-10^6 m^3 km^{-1} yr^{-1}) (Milliman and Syvitski, 1992; Major et al., 2000).

The precise timing of lahar events is unpredictable and working with active flows can be hazardous. This problem makes much of present knowledge of lahar flow behavior is inferred from the study of lahar deposits. Lee et al. (2015) simulates lahar deposition based on the satellite image and LAHARZ model, without considering the involvement of rainfall within the process. Lavigne and Thouret (2003) discussed the sediment yield of lahar in the downstream area of Mount Merapi by using rainfall information derived from rain gauges. More studies have been invested in studying critical rainfall leads to lahar initiation (Fitriyadi, 2009; Yulinsa, 2015; Fibriyantoro, 2015), but most of them relied on rainfall information in the downstream, which did not represent how the rainfall affected the geological condition in the upstream.

At Mt. Merapi of Indonesia, lahar occurs mostly as secondary disasters that happened almost every year during the rainy season (Lavigne et al., 2002). The lahar monitoring in this area mainly consists of some ground-based measurement by several instruments such as seismograph, wire sensor installed at river perimeter, automatic water level recording (AWLR), automatic rain gauges and video camera (Lavigne et al., 2000a; Legowo, 1981). Although the operation of those instruments are found to be useful for precise lahar monitoring, the risks carried in active volcanoes caused those instruments to be unable to monitor lahar occurrences following the eruption in 2010 (Hardjosuwarno, 2014).

The development of simulation techniques in recent years has allowed lahar modeling and simulation to be an assessment tool to understand debris flow and lahar behavior. The simulation technique helps to understand debris flow process by studying the geologic settings, triggering mechanisms, transport processes and deposition characteristics (Castrucci and Claverro, 2015; Jones et al., 2017; Procter et al., 2010). Nevertheless, the application in the catchment scale is still limited.

Lahar occurrences happen mostly under severe rainfall intensity and significantly increased during the rainy season. Thus, rainfall information becomes the fundamental element for lahar model application in the catchment-scale studies (Jones et al., 2017; Castruccio and Claverro, 2015). However, this study has two main problems. The first is that lahars usually occur at elevations higher than 1200 m amsl (Legowo, 1981), whereas most rainfall monitoring instruments are available only at lower elevations. The second problem is that lahars following an eruption are usually initiated in an area

that is relatively inaccessible and dangerous, making the direct verification difficult (Nikolopaulus et al., 2014; Staley et al., 2013).

Recent studies have shown the effectiveness of remote monitoring; such as by weather radar, for debris flow estimation and risk management. Weather radar provides finer spatial and higher temporal resolution of rainfall, which is desirable for debris flow and lahar studies. It offers the advantage of being able to monitor rainfall in the area where lahars initiate (Chiang and Chang, 2009; David-Novak et al., 2004). Marra et al. (2014) confirm that the scarcity of rain gauges has resulted in the underestimation of the rainfall threshold for debris flow occurrence, and weather radar performs well for monitoring debris flow occurrence during short-duration convective storms.

Furthermore, population growth has driven development farther into debris flow prone areas (Jakob and Hungr, 2005). In Indonesia, an old paradigm of living together with disaster is still alive in volcanic areas especially Mt. Merapi. The people who live there are at extreme risk from the regular eruption and frequent secondary lahar events. Although they have understood the consequences of living in the hazard area, the disaster awareness remains an important issue. Hence, a non-structural countermeasure by a system developed to monitor the rainfall and the potency of lahar occurrences is urgently required.

2. Objectives of this study

The objective of this research is to develop a real-time lahar mitigation system at Mt. Merapi by the utilization of the X-MP radar into a distributed hydrological model, by conducting these activities:

(1) Applying a graphical user interface of a numerical model of debris flow to simulate lahar at Mt. Merapi;
(2) Integrating rainfall data estimate by X-MP radar to optimize the numerical model of lahar performance;
(3) Applying an ensemble short-term rainfall prediction to the lahar critical rainfall to know the potency of lahar occurrence;
(4) Improving a distributed hydrological model performance by integrating X-MP radar rainfall, modifying the flow stoppage mechanism and applying lahar empirical models to simulate lahar flow; and

(5) Combining predicted rainfall values and a modified distributed hydrological model to simulate lahar flow based on real lahar event.

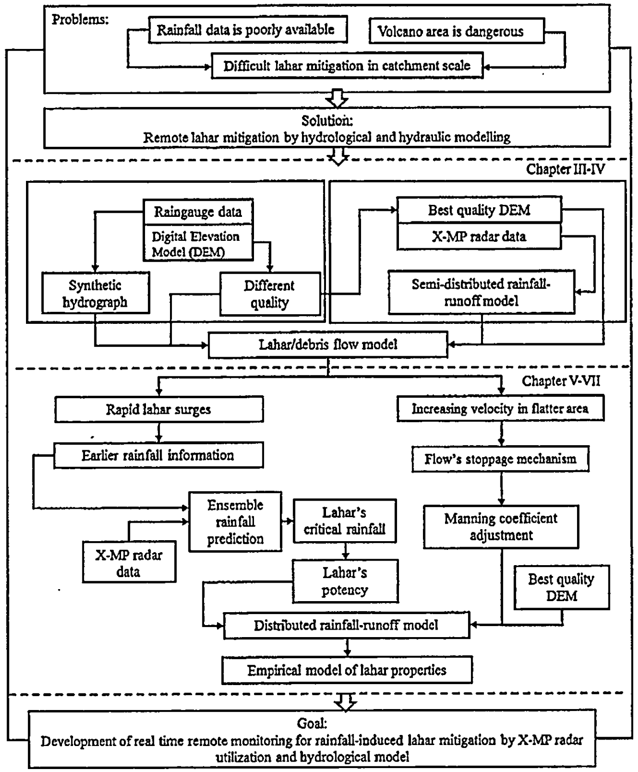

Figure 1 Problems identification and the research frame goals

3. Conclusions

The results showed that the remote monitoring of lahar prediction by X-MP radar and hydrological and numerical model was well performed to deal with the problems of rainfall data unavailability and inaccessible location of rain triggered lahar generation. The results show this method is feasible for lahar mitigation in terms of fast response and earlier warning information.

The outcomes of this work are concluded based on the sub-objectives as follows.

1. By applying rainfall information and terrain data (DEM and DSM), the lahar could be simulated by a numerical and hydraulic model of HyperKANAKO. The rainfall intensity is important for 1D simulation. This indicated rainfall role on triggering lahar, as the model assumed debris flow or lahar initiated as a 1D model and then transformed into a 2D model for the deposition. Terrain data quality is important to analyze the inundation and the deposition area. False deposition area was resulted by using the lower resolution of 30 m and 90 m resolution, while the finest resolution at 5 m could identify the channel stream and give better simulation results.
2. The X-MP radar is known to be an important and useful tool for giving higher spatial and temporal resolution of rainfall. The X-MP radar could be used to replace the rainfall data from rain gauges directly. Integrating the X-MP radar to a numerical and hydraulic model of HyperKANAKO was able to simulate lahar occurrence based on a real event on 17 February 2016. However, increasing flow velocity was monitored in the downstream area, where it should have a slower rate of discharge and velocity.
3. An application of short-term ensemble rainfall prediction is a useful study in order to give earlier lahar potency information. The analysis was done by applying the ensemble rainfall prediction to a critical line. The predicted rainfall in Gendol catchment, showed the potency of lahar occurrence in this catchment after the snake line exceeded the critical line. Relying on this result, further analysis of the hydrometeorological condition in the catchment for lahar occurrence is recommended by applying the predicted rainfall values into a modified distributed model of the RRI.
4. The modification of RRI model for lahar estimation was done by applying some empirical equations and X-MP radar rainfall integration. The Manning roughness coefficient was modified as an inverse proportion to the slope, caused the model becoming able to perform stoppage mechanism of lahar. The modified model was able to give the similar result to the real condition, and so was the predicted rainfall values obtained by the ensemble model. The ensemble prediction correctly confirmed the lahar event based on the real condition in Gendol catchment, while in Putih catchment were the lahar occurrence was not reported, the predicted rainfall and the snake line analysis did not give a false alarm. An application of adjusted ensemble prediction model gave a similar result with the real data of adjusted X-MP radar. The simulation also showed the superiority of X-MP radar comparing to the rain gauge based model, as the later mention overestimated the water depth, resulting in Putih river to have some inundation area which has never been reported.

（別紙１）

論文審査の結果の要旨

氏名	MAGFIRA SYARIFUDDIN
論文題目	Development of remote monitoring system of rainfall-induced lahar at Mount Merapi （メラピ山における降水起源ラハールの遠隔監視システムの開発に関する研究）

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要旨

本研究では火山地帯における火山噴出物由来の不安定土砂による降雨起源の土砂災害であるラハールの発生リスクと，それに引き続いて発生する土砂輸送堆積過程で河床上昇が起こることによる氾濫発生リスクに対して，レーダーによって得られる詳細な時空間分布を持つ降雨情報と数値シミュレーションによるリスク計量方法を考案して，インドネシアのメラピ火山周辺域を対象にして検討を行ったものである．

本研究では，新たに導入されたＸバンド偏波ドップラーレーダーによる降雨観測結果を，標高の高い斜面域の土石流シミュレーションや，標高が低い地域での流出・氾濫シミュレーションに導入するという点で，研究成果を地域の災害リスク軽減に対するソフト施策として利用させる狙いを持っている．

本研究の新規性としては，以下が挙げられる．

1）土石流シミュレーションに導入する地形の空間解像度が，標高の高い地域のシミュレーション結果に与えている影響について考察を行った点．

2）Ｘバンド偏波ドップラーレーダーによる降雨観測結果を用いたアンサンブル短時間降雨予測手法を用いてラハールの発生を捉える手法を提案している点．

3）標高の高い地域からメラピ火山の麓に至る地域で，レーダーからの分布雨量を与え，また新たに提案された粗度係数を与えることで土砂の輸送及び堆積を従来よりも適切に推定できる数値計算手法を実装して，氾濫発生リスクを計量する提案を行ったことである．論文は８章からなっている．

第１章では，序論として火山地域の土砂災害をもたらす現象を記述するための既存の研究成果を挙げ，本論文が取り扱う現象の範囲と定義およびその必要性を説明している．

第２章では，メラピ火山とその周辺域そのものの説明と，メラピ火山周辺域におけるラハールの発生要因，輸送過程，堆積過程について説明している．

第３章では，既存の１層流としての土砂輸送堆積過程モデルの説明をして，それをメラピ火山周辺域に適応した事例について説明している．さらに，標高が高くラハールの直接観測が困難な地域において，それを数値シミュレーションする際の地形の空間解像度が結果に与えている影響について調査している．

第４章では，メラピ火山周辺域に新たにＸバンド偏波ドップラーレーダーを設置して，降雨観測を行い，その定量的降雨量推定（QPE）を検討している．

第５章では，Ｘバンド偏波ドップラーレーダーによる降雨観測結果を用いたアンサンブル短時間降雨予測手法を，ラハールという数 10m スケールでありながら破壊規模の大きな災害の発生を見逃しなく捉える手法を提案している．アンサンブル短時間降雨予測手法を土砂災害発生リスクの算定に応用した例はなく，新規的な提案といえる．

第６章では，分布型降雨流出モデルに新たに土砂輸送堆積過程を取り込んで，メラピ火山周辺域に適用し，上流のラハール発生によって河道に運ばれた土砂が輸送し，堆積することで河床上昇をもたらして，流域の氾濫発生リスクを上げている点をシミュレートする手法を開発している．火山周辺域に適用する際に下流での計算精度を向上させる点において新規的な提案をしている．

第７章では，メラピ火山周辺域のゲンドール川やプチ川に上述した手法を導入して，ケーススタディを行っている．

第８章では，まとめと今後の研究に対する提案を行っている．

本研究はインドネシアの火山地域の土砂に関連する土石流および氾濫災害について，その予測可能性を研究したものであり，先端のレーダー水文学，水理学，砂防学を統合して市民に適切な情報を提供できる災害危険予測手法を開発した点で価値ある集積である。提出された論文は工学研究科学位論文評価基準を満たしており，学位申請者の Magfira Syarifuddin は，博士(工学)の学位を得る資格があると認める。