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Flow behavior and mobility of contaminated waste rock materials in the abandoned Imgi mine in Korea

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ABSTRACT

Incomplete mine reclamation can cause ecological and environmental impacts. This paper focuses on the geotechnical and rheological characteristics of waste rock materials, which are mainly composed of sand-size particles, potentially resulting in mass movement (e.g., slide or flow) and extensive acid mine drainage. To examine the potential for contaminant mobilization resulting from physicochemical processes in abandoned mines, a series of scenario-based debris flow simulations was conducted using Debris-2D to identify different hazard scenarios and volumes. The flow behavior of waste rock materials was examined using a ball-measuring rheometric apparatus, which can be adapted for large particle samples, such as debris flow. Bingham yield stresses determined in controlled shear rate mode were used as an input parameter in the debris flow modeling. The yield stresses ranged from 100 to 1000 Pa for shear rates ranging from 10^{-5} to 10^{2} s^{-1}. The results demonstrated that the lowest yield stress could result in high mobility of debris flow (e.g., runout distance >700 m from the source area for 60 s); consequently, the material contaminants may easily reach the confluence of the Suyoung River through a mountain stream. When a fast slide or debris flow occurs at or near an abandoned mine area, it may result in extremely dynamic and destructive geomorphological changes. Even for the highest yield stress of debris flow simulation (i.e., $\tau_y = 2000$ Pa), the released debris could flow into the mountain stream; therefore, people living near abandoned mines may become exposed to water pollution throughout the day. To maintain safety at and near abandoned mines, the physicochemical properties of waste materials should be monitored, and proper mitigation measures post-mining should be considered in terms of both their physical damage and chemical pollution potential.

1. Introduction

The magnitude of ecological and environmental impacts from past mining activities is often considerable (Helm et al., 2013; Neiva et al., 2014). One of the major environmental problems related to mining is the follow-up management of abandoned mine sites. In the case of incomplete mine closures, an abandoned mine presents chemical and physical risks. Chemically, acid mine drainage (AMD) due to low pH and sulfide oxidation is unavoidable (Singer and Stumm, 1970; Johnson and Hallberg, 2005; Natarajan, 2008), and physically, mass movements, including slides, debris flow and flash floods with a large amount of sediment, are a significant risk during high-precipitation events (Vaziri et al., 2010; Jiao et al., 2013; Pankow et al., 2014). Therefore, preventing and controlling physicochemical modifications, e.g., acid mine drainage and mass movements, from waste deposits is a key concern at operating mine sites and after mine closures. For this reason, robust mine reclamation should be enforced where mining activities have occurred.

Over the years, hazards and remediation related to abandoned mines have been emphasized, especially concerning heavy metal contamination, such as with As, Pb, Sb, and Cu (Lee, 2003; Sheoran and Sheoran, 2006; Ferreira da Silva et al., 2009; Nam et al., 2010; Andras et al., 2012; Name and Sheridan, 2014; Neiva et al., 2014). Compared to chemical contamination, mass movement and ground subsidence problems, such as slides, debris flows or subsidence of contaminated soils and water, have not been extensively examined. When debris flows occur with contaminated soils, which are potentially contaminated with heavy metals, there are numerous risks. As expected, the risks are due to multiple causes (e.g., geochemical and geophysical hazards) that are much more severe together than a given individual risk in abandoned mines. In this study, we focus on debris flow occurrences with contaminated soils.

The kinematic theory and simulation techniques to model debris flows have made great progress during recent decades (e.g., Mangeney-Castelnau, 2005; Liu and Huang, 2006; Rickenmann et al., 2006; Liu et al., 2009; Ancey et al., 2012; Iverson and George, 2014; Quan Luna

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et al., 2014; van Asch et al., 2014; Iverson and Ouyang, 2015; Schilirò et al., 2015). Several multidisciplinary studies can be used, e.g., soil mechanics, viscoplastic fluid dynamics and a two-phase mixture model. The most popular is a free-surface shallow water theory combined with a depth-averaging method. However, even starting from different fundamental disciplines, the resulting system of governing equations is similarly nonlinear and hyperbolic. Therefore, the shock-capturing method is required for precise calculation of flow motion and any possible discontinuity or shock in the flow domain. Recently, some well-balanced finite volume schemes have been successfully applied to model debris flow or relevant mass flows (e.g., Kuo et al., 2009; George and Iverson, 2014; Kurganov and Miller, 2014). The main advantage of the application of the finite-volume scheme is that it is straightforward to implement and has high computational efficiency. Therefore, in this study, the simulations of debris flows formed from waste rock deposits will be based on the two-dimensional debris flow theory proposed by Liu and Huang (2006) and will use the well-balanced central-upwind scheme (Kurganov and Petrova, 2007), which is an efficient and Riemann-solver-free finite-volume scheme, with special treatment on the drying and wetting front (Bollermann et al., 2013) for numerical computations.

This paper addresses the physicochemical hazards of waste rock materials in the Imgi pyrophyllite mine, which is located in Busan Metropolitan City, Republic of Korea, where there is the potential for debris flow occurrence due to torrential rain. To understand the physicochemical changes in the abandoned Imgi mine, the geochemical, geotechnical and rheological characteristics of waste materials are emphasized. In this respect, we first examined the geological and geomorphological characteristics of the mining area associated with surface erosion and debris flow based on a field investigation. Second, we reviewed the geochemical characteristics, such as heavy metal contamination in response to rainfall events. Third, to estimate the debris flow mobility, the geotechnical and rheological characteristics of waste materials were examined. The strength parameters, i.e., yield stress and viscosity, were determined to estimate the runout distance and velocity of released debris from the sources of debris flows. Fourth, the potential of debris flow impact was evaluated to determine the possible physicochemical hazards at and near the abandoned mines.

In debris flow modeling, the mobilization mechanism and initiation process from failure to post-failure (i.e., the transition from slide to flow) were not considered for flow simulation in this study. Therefore, the failure stage, like a slide, was directly changed to a post-failure stage, like a debris flow, without any change in the total volume of released debris. Based on field monitoring of the observed failed conditions, adequate mass volumes and locations were selected, including four different scenarios, from a simplest cases to an extreme case. Then, a series of numerical simulations was conducted to examine the characteristics of flow motion and the affected areas in the four plausible scenarios. From the simulation results regarding the debris flow mobility of contaminated soils, we analyzed the hazardous impacts of debris flow on water resources and the environment at and near the Imgi abandoned mine area. Finally, we provide a brief summary and conclusions.

2. The mine site

In total, 5396 mines exist in South Korea; approximately half of them are metal mines. The Republic of Korea still has an estimated 1000 abandoned mines (KMOE, 2007; Hyun et al., 2012). Both metal and non-metal mining are potential sources of heavy metal-contaminated soils and water pollution near abandoned mine areas. The Imgi Pyrophyllite Mine is located at Imgi-ri, Busan Metropolitan City, Republic of Korea (Fig. 1). Mining activities operated in this area from 1980 to 1992 (KIGAM, 2013). The mining area is approximately 40,000 m^2. Open-pit mining was employed for the Imgi ore deposits. The geological characteristics of the pyrophyllite ores encountered in the Imgi mine deposit are related to widespread hydrothermal alteration of andesitic rocks (Cheong et al., 2004). Sericite-type pyrophyllite is a main product. The minerals are mainly composed of quartz, sericite, pyrophyllite, muscovite, kaolinite and pyrite. Due to acid mine drainage (AMD), which refers to the acidic water that is created where sulfide minerals are abundant and exposed to air and water, the Imgi Creek water is strongly acidic (pH $= 2.3$–4.2) and contains a high concentration of various metals (e.g., Al, Fe, and Mn) and SO_4. Of particular concern is that the mine was inadequately closed and had a red or yellow cap of oxidized material. The rate of acid mine drainage mainly depends on the surface area of exposed sulfide minerals, the type of minerals present, the amount of oxygen present, the amount of water available, the temperature and the type of microorganisms present (Singer and Stumm, 1970; Johnson and Hallberg, 2005). An acid-generating mine has the potential for long-term devastating impacts on rivers, streams and aquatic life (ELAW, 2010). In the Imgi mine, it is well known that the acidity loading was 65 kg $CaCO_3$ day^{-1}, and the metal loading, of Fe, Al and Mn, was 12 kg day^{-1} (Ji and Cheong, 2005).

The geological and geomorphological features are reviewed here. Geological maps of the Imgi mine display a wide variety of rock types, such as andesite, granite, plutonic rock, tuff and other sedimentary rocks, including shales (Fig. 2). The Imgi mine appears on part of the Dong-nae/Wall-nae and the northern Yangsan geological maps, which have a scale of 1:50,000 (KIGAM, 2013). This area exhibits a small mass of Cretaceous sedimentary rocks, andesite, andesitic tuff and various types of plutonic rocks. Unconsolidated Quaternary sediments are deposited near riverine and valley regions. Black and dark gray shale deposited in the lowest layer appear as xenolith in the andesite region. The andesitic lava and tuff have covered the study area by the Cretaceous volcanism, and chronologically correspond to the Yuchen Formation in the Kyungsang Supergroup. Plutonic rocks, such as granodiorite, biotite granite, micrographic granite and basic/acidic dykes intruded after the andesitic extrusion. There is also a diagenetic lead found in the andesite area.

2.1. Mass movement: from surface erosion to gully erosion and to debris flows

Due to a low pH and high concentration of heavy metals, natural revegetation near a mine waste dump is almost infeasible. The large area of the Imgi contaminated zone is covered by only sparse vegetation and stunted trees (Fig. 3). As shown in Fig. 3a, the first visit to the mine dump occurred on Feb. 28, 2012. The mine was left for a long time without any physical or chemical treatment. Three berms existed on the slope and appeared to exhibit severe surface erosion across the entire mine waste deposit. The waste materials mostly consist of sand and gravel. There are a number of gully erosion sites. Most gully erosions appeared to be approximately 1 m high. The estimated total volume of gully erosion is approximately 70,000 m^3 (Jeong, 2015). For emergency management, slope flattening was completed to improve the slope safety; then, erosion control blankets (blue color in Fig. 3b) were placed on the slope to prevent surface erosion and washout from water or other gravitational forces. After a summer torrential rainfall season, the erosion blankets placed on the slope were torn to pieces. Uncovered surfaces and partial erosions on the slope were observed in Sept. to Nov. 2013 (Fig. 3c,d). It is clear that slope erosion has been worsening with time. In particular, in Nov. 2013, various types of erosion were observed, including sheet erosion, rill erosion and gully erosion. Large amounts of waste rock materials were eroded and deposited repeatedly at the bottom of slope from erosion forces. In early 2014, the slope was reseeded (e.g., lime); it was partially vegetated at the bottom but had almost no vegetation at the top of slope. In particular, a small-scale rotational slope failure occurred at the bottom left of the slope, which is approximately 10 m wide and has a maximum thickness of 1 m; as a consequence, failed materials from the slope were deposited on the road and even entered into the mountain stream