学　位　論　文　内　容　の　要　旨

博士の専攻分野の名称　　博士（工学）　　氏名　Khy Eam EANG

学　位　論　文　題　名

Geochemistry, Evolution, and Mixing Estimation of Groundwater for Identifying Zones Affecting the Stability of Rock Slopes
(岩盤斜面の安定性に影響を及ぼす地層を同定するための地下水の化学、進化、混合)

Groundwater is a really crucial factor in rock slope issues of limestone quarries. After a limestone deposit is mined out, a huge final slope is left in the mountainous area. This leads to slope instability as a major problem. This instability frequently suffers from the effects of groundwater. Although the effects of groundwater level and flow on the mechanical properties of limestone itself have been adequately investigated in previous researches, monitoring and assessment of geochemical properties and geochemical processes of groundwater for rock slopes are rarely reported. Therefore, this dissertation focused on the geochemistry, evolution and mixing estimation of groundwater of an open-pit limestone quarry in Japan for identifying zones affecting the stability of rock slopes. In addition, mixing verification and groundwater age estimation were also included for the confirmation and extensive comprehension. The followings are the summaries of each chapter in the dissertation.

In Chapter 1, the general introduction of limestone, groundwater managements, groundwater chemistry and groundwater effects on rock slopes are described. The statement of the problem and objectives of the study are highlighted to understand the key points of context and structure of the entire research.

Groundwater flow and its geochemical evolution in mines are important not only in the study of contaminant migration but also in the effective planning of excavation. The effects of groundwater on the stability of rock slopes and other mine constructions, especially in limestone quarries, are crucial because calcite, the major mineral component of limestone, is moderately soluble in water. In Chapter 2, evolution of groundwater in the limestone quarry located in Chichibu city of Saitama prefecture, Japan was monitored to understand the geochemical processes occurring within the rock strata of the quarry and changes in chemistry of groundwater, which suggests zones of deformations that may affect the stability of rock slopes. There are three distinct geological formations in the quarry: limestone layer (covering), interbedded layer of limestone and slaty greenstone, and slaty greenstone layer (basement). Although the hydrochemical facies of all groundwater samples were Ca-HCO_3 type water, changes in the geochemical properties of groundwater from the three geological formations were observed. In particular, significant changes in the chemical properties of several groundwater samples along the interbedded layer were observed, which may be attributed to the mixing of groundwater from the limestone and slaty greenstone layers. On the rainy day, the concentrations of Ca^{2+} and HCO_3^- in groundwater fluctuated notably, and the groundwater flowing along the interbedded layer was likely to be dominated by groundwater from the limestone layer. These suggest that groundwater along the interbedded layer may affect the stability of rock slopes.

Water-rock interaction and groundwater mixing phenomena are important in understanding hydrogeological systems and the stability of rock slopes especially in limestone quarries consisting largely of moderately water-soluble minerals like calcite. In Chapter 3, water-rock interaction in the open-pit limestone quarry was evaluated using PHREEQC, while hierarchical cluster analysis (HCA) and principal component analysis (PCA) were used to classify and identify water sources responsible for possible groundwater mixing within rock layers. The results showed that the water-rock interaction within the quarry was distinguished by individual layers, all of which were geochemically involved in calcite dissolution. The changes in Ca^{2+} and HCO_3^- concentrations of several groundwater samples along the interbedded layer found to result from mixing groundwater from the limestone layer and that from slaty greenstone layer. Based on the HCA and PCA results, groundwater samples were clas-

sified into three types depending on their origin: (1) groundwater from the limestone layer (Lo), (2) mixed groundwater flowing along the interbedded layer (e.g., groundwater samples L-7, L-11, S-3 and S-4), and (3) groundwater originating from the slaty greenstone layer (So). These results suggest the necessity of continuous monitoring of groundwater.

Estimation of groundwater mixing ratios and tritium analysis are the crucial tasks in groundwater management especially for identifying sensitive zones affecting rock slopes, while tritium, a radioactive isotope, is effective in predicting groundwater age. In Chapter 4, Geochemist's Workbench was applied to estimate the mixing fractions to clarify sensitive zones that could affect rock slope stability. The mixing fractions of 41%Lo:59%So, 64%Lo:36%So, 43%Lo:57%So and 25%Lo:75%So on the normal days corresponded to groundwaters L-7, L-11, S-3 and S-4, respectively, while the mixing fractions of groundwaters L-7 and L-11 (61%Lo:39%So and 93%Lo:7%So, respectively) on rainy days became the majority of groundwater originating from the limestone layer. The tritium concentration of groundwater sample L-7 was lower than those of L-2 and LP-10 but higher than that of S-2, which explained the mixing phenomenon along the interbedded layer. The groundwater age seems relatively young, younger than 1953, by considering the water balance and topographical condition of the quarry. Regarding overall evaluation for rock slopes, the groundwater along the interbedded layer has significantly affected the stability of rock slopes by enlarging multi-breaking zones in the layer through calcite dissolution and inducing high water pressure, tension cracks and potential sliding plane along this layer, particularly during intense rainfall events.

Chapter 5 describes the overall conclusions and the suggestions for future works to develop the related studies. The geochemical survey of groundwater should be paid attention in the study of rock slope issues. Mass balance of calcite including estimation of limestone dissolution rate in the multi-breaking zones or fractures along the interbedded layer would further appear to be significant for rock slope stability. Further tritium analysis is required and ^{3}H-^{3}He analysis method should be conducted to obtain more precise groundwater ages.