中文摘要

台灣本島係由歐亞板塊和菲律賓海板塊相互擠壓成形，造就出陡峻之地形與脆弱多變之地質環境。近年由於全球氣候異常，頻繁之颱風豪雨及地震活動，受災範圍與程度均遠較過去為烈，以致山崩土石流等自然災害頻傳。因此，如何有效掌握山崩災害之破壞機制與影響範圍，以提供災損評估及作為防災減災之參考，實為今日防災工作上的一項重要課題。雖然導致山崩災害的因素甚多，但降雨是公認誘發山崩的顯著因子之一。一般而言，降雨入滲會導致淺層土壤含水量與基質吸力改變、單位重增加或抗剪強度下降，長期浸潤時則可能造成地層材料弱化或岩層潛變行為，進而導致坡地產生不同類型之災害型態。山崩災害之破壞機制與影響範圍會受地形、地質、地下水位(壓)變化、地層參數等條件而異，因此場址地質及水文特性之調查、現地觀測、數值模型建置及模擬實為釐清破壞機制所不可獲缺的重要工作。

爰此，本計畫共分 5 年，逐年挑選不同場址執行。前年度(106)計畫執行場址編號為 D160 之茶山潛在大規模崩塌地，去年度(107)計畫執行場址編號為 D008 之車心崙潛在大規模崩塌地，今年度(108)計畫場址選擇位於宜蘭縣大同鄉，編號為 D007 之梵梵潛在大規模崩塌地。為能釐清坡地淺層不飽和土體及深層重力變形之破壞機制，本計畫主要工作項目包含：(一) 坡地場址地質調查、(二) 三維水文地質模型建立及驗證、(三) 三度空間坡地活動性評估系統建置、(四) 動態水文條件下之破壞力學分析、(五)車心崙場址持續觀測及回饋分析等。預期透過本計畫於坡地場址之水文地質調查、觀測及數值模擬成果，可整合空間分布之水力條件、變形行為及破壞模式，以探討及驗證坡面淺層破壞與深層滑動之可能情境及模式。

上述工作項目可針對已知的潛在大規模崩塌區域進行全面性的監測系統來探討三度空間坡地活動性，其中包含環境地動與時序反射儀剪動監測、即時動態差分法量測、地下水位及淺層含水量水文觀測。亦可進行地質鑽探、地表地質調查工作、地物測線剖面等工作判釋崩塌體地下構造模型及可能地剪動面深度。進一步，建立三維水文地質模型並利用觀測的水文資料進行率定及驗證分析工作。利用水文地質模型可提供動態水文變化條件下坡地場址可能的變形機制與破壞行為，提供相關案例分析下的山崩破壞門檻值，其中門檻值可包含地震力、地下水位及降雨誘發等相關機制。簡而論述，本計畫將聚焦於提

供監測場址可能的變形機制與同時開發創新之監測技術，並將研究成果落實於相關山崩災害監測。

梵梵場址透過 TDR 觀測出在 108-D007-2T 的剪裂帶觀測到地層滑動，且觀測到兩次降雨事件後數日內出現地層剪動訊號。配合 108-D007 梵梵場址 2T 鑽探孔為觀察到 TDR 有剪動現象。本計畫發現 dv/v 於 TDR 剪動前有增加現象，在 TDR 剪動後 dv/v 先是下降，並於數日後轉為上升趨勢。上述 dv/v 變化皆可在頻率範圍 2-6 Hz 及 6-10 Hz 觀察到。進一步分析，推估可能地剪動深度在 21 m 位置。此外，單站法計算出梵梵場址 1 m 地下水位抬升對應約 1.0 %的震波速度降。數值模擬成果顯示：(A) D007 梵梵場址於常時及高水位情境下，各區所得安全係數皆大於 1.0，初步研判屬於相對穩定狀態；(B) 地震情境(0.32 g)下，坡腹崩滑體的部分塊體恐有崩塌之虞，崩塌量體約為 1,639,650 m^3；(C) 關聯性研究成果顯示當 108-D007-1W 鑽孔水位抬升至地表下 21 公尺或場址 PGA 超過 290 gal 時，均有可能導致坡腹崩滑體產生局部崩滑。本計畫進一步針對坡腹崩滑體進行崩後下坡影響範圍評估，分析結果顯示：(A) 坡腹崩滑體坍滑後，土砂堆積前緣距離 D007 梵梵場址坡趾約 600 m，最大坍滑堆積深度約 46 m，整體崩塌土砂量堆積平均深度約 5.7 m；(B) 初步評估坡腹崩滑體破壞後，對西南側的英士部落無直接之衝擊影響。

關於車心崙場址，根據 107 年 7 月開始監測迄今的資料顯示，車心崙場址無論地表或地下均未發現明顯變化與趨勢，然而 107 年 8 月的暴雨事件，淺層土壤含水量有約 8%的變化、地下水位抬升近 2 公尺、並量測到明顯地動訊號增強現象。震波速度變化研究成果亦可以分類為雙站法及單站法成果。雙站法計算之 dv/v 為測站之間傳遞路徑下的平均結果：107-D008 車心崙場址顯示 2 m 地下水位變化對應約 0.5 %的速度變化 (測站對 V02-V03)。單站法計算之 dv/v 為測站下方的材料震波變化: 107-D008 車心崙場址顯示 2 m 地下水抬升對應約 1.0 %的震波速度降。成果上已確認單站法用於監測地下水位優於雙站法，其 dv/v 變化與特定深度地下水位變化呈現高度相關。數值模擬成果顯示：經破壞行為分析可判釋出關鍵塊體 A 及關鍵塊體 B，其崩塌體積分別為 1.14 及 2.74 百萬立方米。主要受到地下水位與地震力誘發條件主導，地下水位與地表加速度震動門檻值分別為 18 米與

300 gal。目前在計畫執行期間並未觀察到地表及地下有位移的情形。相對震波波速變化受到強降雨影響最多可降 0.5%。

計畫關鍵詞：水文地質調查、地下水、坡地觀測、變形機制

ABSTRACT

Taiwan is an active mountain belt created by the oblique collision between the northern Luzon arc and the Asian continental margin. The inherent complexity of geological nature creates numerous discontinuities through rock masses and relatively steep hillside on this island. In recent years, the increase in the frequency and intensity of extreme natural events due to global warming or climate change brought significant landslide and debris flow hazards in the mountain area of Taiwan. The causes of landslides are attributed to a number of factors. Notably, rainfall is well-known one of the most significant triggering factors for landslides. In general, the rainfall infiltration could result in changing the suction and the moisture of soil, raising the unit weight of soil, and reducing the shear strength of soil for the shallow colluvium. Long-term infiltration may result in weakening or creeping of slope formation material. The stability of slope is closely related to the geological and topographical conditions, the groundwater pressure change in response to rainfall infiltration, and the physical and mechanical parameters of slope formation. Detailed site investigation and observation using the state-of-the-art technology will be performed on active landslide from the study area to clarify the occurrence of landslides induced by the change of hydrologic conditions during heavy rainfall.

This study is aimed to better understand the mechanism of triggering landslide hazards so that casualties and property damages can hopefully be reduced in the occurrence probability of natural disasters in the future through the appropriate disaster prevention planning we proposed. The project is a 5-year integrated study and the site investigation in the past year focuses on the Chashan and Chexinlun potential large-scale landslide (D160 and D008). The Fanfan potential large-scale landslide (D007) is selected as the study site in 2019 year. The work scopes of the project contain: (1) hydrogeological investigations on the site; (2) establishment and verification of the three-dimensional hydrogeological model; (3) construction of slope activity evaluation system; (4) deformation mechanism analysis under dynamic hydrological condition; (5) continuation observation and refined analysis of Chexinlun site. It is expected that the complex phenomenon between the stability of landslides and hydrogeological conditions can be revealed and clarified

through the detailed study on the hydrogeological investigation, observation and the numerical simulation.

This study deploy a comprehensive monitoring network consisting of seismic, geotechnical (time domain reflectometer, TDR), geodetic (real-time kinematic measurement, RTK) and hydrological (ground water level (GWL), shallow water content) instruments on a slow-moving landslide site. The borehole drilling, geological and geophysical (seismic reflection profile and resistivity images) investigations provide the surface-to-subsurface structure and movements of landslide area, and can also be used to find possible sliding surface. With the available knowledge of landslide structure, we further built the hydrogeo-conceptual model and validated the model by fitting the observed GWL and shallow water content, which are the crucial input parameters to analyze the possible triggered factors of landslide failure. A series of the scenario testing can quantify the safety factor of landslide based on different conditions, including earthquake forcing, ground water level and precipitation. A main purpose of this five-years project is not only to illustrate the possible failure mechanisms for the specific landslide areas, but also to develop innovation-monitoring technique for landslide hazards.

In Fanfan site, TDR slope monitoring system has successfully observed the slope deformation at the 108-D0072T site. The slope deformation was found to be located within the shear zone of the 108-D007-2T borehole. The peak reflection coefficient of the TDR signal reflected the trace of slope deformation within several days after two relatively heavy precipitation events. Based on the dv/v resulting and TDR measurements observed at the 108-D007-Fanfan site, Our study noticed that the dv/v increasing before the TDR movement, and then decreasing after sliding movement. Finally, the dv/v value recovers a few days later. Aforementioned pattern of temporal changes in dv/v can be clearly observed in the frequency bands of 2-6 Hz and 6-10 Hz. The origin of such dv/v measurement is inferred at the depth 21 m as the basal sliding interface. The results of shallow sliding analysis show that: (1) in the normal and high water level scenarios, the safety factor obtained in each zone is greater than 1.0, and the initial judgment belongs to the relatively stable state; (2) in the earthquake scenario, the A1 mass in LM may slide, the volume of A1 slide is about 1,639,650 m^3; (3) when the water level of the 108-D007-1W rises to 21 meters below the surface or the PGA

exceeds 290 gal, it may cause the local landslide. Based on the above analysis results, this project further evaluates the influence zone of the potential sliding mass of A1 on the downslope. The analysis shows that after the destruction of potential sliding mass of A1, there is no direct impact on the YingShih village.

In Chexinlun site, according to the observations (the monitoring began in July 2018), no significant changes or trends have been found in the Chexinlun site. However, in the August 2018 rainstorm event, the shallow soil water content increased by about 8%. The groundwater level was raised by nearly 2 meters, and the apparent signal enhancement was measured. Results of the relative seismic velocity variations (dv/v) can be derived from the methods of station pairs and/or single station. Resulting of dv/v of two stations represents the mean value along the wave propagation path: for the 107-D008-Chexilun site, there is the GWL of 2 m changes, coinciding with the 0.5 % of dv/v variance (station pairo f V02-V03). The dv/v results derived from single station indicate the changes of subsurface medium beneath single station: for the 107-D00-Chexinlun site, the dv/v reduction of 1.0 % can be measured during the GWL of 2.0 m increasing. Our study concluded that the method of single station can provide better understanding the relation between dv/v and GWL. For the Chexinlun landslide site, the large-scale landslide regions with collapsed volumes of 1.14×10^6 m^3 (region A) and 2.74×10^6 m^3 (region B) would be probably triggered by the GWL and seismic forcing. The triggered thresholds of GWL and ground shacking are 18 m and 300 gal, respectively. Based current observations of comprehensive monitoring system, there is no movement during the monitoring period. The dv/v measurements exhibited the largest reduction of about 0.5%, coinciding with the intense rainfall.

KEYWORDS: hydrogeological investigation, groundwater, slope observation, deformation mechanism