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Mechanisms and activity of deep-seated landslides at Tienchih and Yakou (S Taiwan) revealed by structural geology and remote sensing

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Deep-seated gravitational slope deformations (DSGSD) gained increasing attention in Taiwan due to their catastrophic impacts on lives and infrastructures during Typhoon Morakot in 2009, when over 2700 mm of rainfall in 5 days were recorded. As the main Taiwan island is located on a complex convergent plate boundary, available data suggest that the island's strong tectonic activity has contributed, along with its subtropical climate and intense human activity, to the onset and destabilization of deep-seated landslides. These are widespread in high-relief mountain areas where Miocene to Eocene meta-sandstone and slate successions outcrop. Slopes at Tienchih (Lalong River of Kaohsiung) and Yakou (few km east in Taitung County) were affected by significant slope collapses and impending instabilities after the heavy precipitation of Typhoon Morakot. This led to severe damages and closure of the South Cross Island Highway No.20, a critical roadway connecting the western and eastern sides of S Taiwan, where continuing slope instability has been observed after 2009. At Tienchih, 240 mm of displacement over an area of 6.7 ha were recorded in 2016 by continuous GPS measurements after a heavy rainfall event. At Yakou, the middle slope sector including the road experienced a major collapse in 2018. At both sites, morpho-structural evidence identified in 1-m resolution LiDAR DEMs suggest that long-term slope deformations occurred well before catastrophic slope destabilization. This is supported by spectacular gravitational deformation structures (i.e. kink folds and shear zones), well exposed at Yakou, and by continuous slow movements detected at Tienchih by multi-temporal TCPInSAR analyses on ALOS/PALSAR images (2007-2011). On the other hand, dense vegetation and limited rock outcrops make an accurate assessment of the geometry, controls, mechanisms and style of activity of these landslides difficult. To overcome this difficulties, we carried out a systematic geomorphological mapping of the two areas through ortho-photos and HRDEMs derived from aerial LiDAR (2012 and 2019), and field surveys to characterize the local structural geology (ductile and brittle features), rock mass strength and gravitational morpho-structures. We performed a local-scale analysis of displacement patterns and rates by combining traditional radar interferometry (D-InSAR on ALOS and Sentinel-1 imagery), improved TCPInSAR analyses, GPS data, Digital Image Correlation between DEMs and change detection analysis of LiDAR point clouds. Our results suggest that long-term progressive failure of slopes was promoted by high tectonically-forced erosion rates and constrained by inherited ductile structures. These preconditioned the location, size and mechanisms of slope sectors more prone to catastrophic failure due to intense rainfall and river

bank erosion. A systematic characterization of long-term slope deformation can thus provide key information to assess the hazard related to deep-seated landslides in Taiwan.