深層邊坡變形運動學的構造限制

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摘要

作者首次在意大利 Rhaetian 阿爾卑斯山的 Bormio 東部 Valfurva 中部發現了一個顯著的袋狀（sackung）深層邊坡重力變形（DSGSD）。通過對其形態學、地質力學和構造特徵的詳細描述，重建了其運動學、年代和活動狀態。為了更清晰地理解該現象，採用了綜合多學科的方法。進行了現場調查和航空照片解讀，以明確 DSGSD 發生的構造、地質和地貌背景。通過對形態構造及其與岩性標記和第四紀沉積物的關係進行分析，建立了邊坡變形的運動學概念模型。在對邊坡變形有關的岩體進行地質力學特徵描述後，進行了數值建模，以驗證關於運動學和現象驅動因素的假設。袋狀變形影響了屬於 Campo Nappe Austroalpine 上層基底的前二疊紀變質泥岩、變質基性岩和大理岩，以及晚更新世和全新世的冰川和岩石冰川沉積物。這種變形始於晚 Wurmian 期（距今 15,000 – 11,000 年），並持續到幾個世紀前，不排除當前仍有低速活動的可能性。變形表現為沿深層滑動面的大規模斜向下陷，與先前存在的脆性構造重力再活化相關，導致 N-S 和 WNW-ESE 趨向重力型態構造的形成。WNW-ESE 趨向系統不對稱溝槽的演化，導致了過去 10,000 年下坡部分逐漸破壞，這從大型古山崩堆積物中得到了證實，且該過程仍在進行中。數值模擬表明，冰川消退後的卸載是引發坡地變形的主要因素。這一深層邊坡變形的重要性因發生在坡地下部的 30 Mm^3 活躍 Ruinon 山崩的存在而加強。該山崩正在快速發展，威脅到山谷底部，對人類生命和社會經濟活動構成了重大風險。

關鍵字： 深層重力變形、邊坡穩定性、阿爾卑斯山中央、工程地質、構造地質、數值模型。

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Structural constraints on deep-seated slope deformation kinematics

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Abstract

A significant sackung-type deep-seated slope gravitational deformation (DSGSD) was recognised for the first time by the authors in the middle part of Valfurva, east of Bormio (Rhaetian Alps, Italy). The reconstruction of its kinematics, age and state of activity is presented, through a detailed description of its morphological, geomechanical and structural features. An integrated multi-disciplinary approach was performed to achieve a clear comprehension of the phenomenon. Field surveys and aero-photo interpretation were carried out in order to clarify the structural, geological and geomorphological setting in which the DSGSD developed. A kinematic conceptual model of the slope deformation was developed through the analysis of morpho-structures, of their significance and relationships with lithological markers and Quaternary deposits. After a geomechanical characterisation of the rock mass involved in the slope deformation, numerical modelling was performed to verify the hypotheses made on kinematics and driving factors of the phenomenon. The sackung affects pre-Permian metapelites, metabasites and marbles belonging to the Upper Austroalpine basement of the Campo Nappe, as well as Late Pleistocene and Holocene glacial and rock glacier deposits. The deformation started after the Late-Wurmian age (15,000–11,000 years B.P.), and continued until few centuries ago, not excluding a present-day low-rate activity. Deformation consists in a large oblique "sagging" along a deep confined sliding surface, associated with gravitational reactivation of pre-existing (late-Alpine and recent) tectonic brittle structures, leading to the formation of N–S and WNW–ESE trending gravitational morpho-structures. The evolution of the WNW–ESE trending system, resulting in asymmetric trenches, led to progressive failure of the lower part of the slope during the last 10,000 years, as testified by large paleo landslide accumulations, and it is still in progress. Numerical modelling indicates post-glacial unloading as the main triggering factor of the slope deformation. The importance of this deep-seated slope deformation is enhanced by the occurrence of the 30 Mm^3 active "Ruinon" landslide in the lower part of the slope. Such landslide is subjected to rapid evolution and threatens the valley floor, establishing an important risk factor connected to human lives and socio-economic activities.

Keywords: Deep-seated gravitational deformations; Slope stability; Central alps; Engineering geology; Structural geology; Numerical modelling