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Combination of close-range remote sensing data (TLS and UAS) and techniques for structural measurements across the deformation zone of the Ionian thrust in Zakynthos Isl.

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Impressive geomorphological structures are quite often interconnected with active tectonics. Most of these cases concern risky steep slopes where the necessity for careful and detailed examination is more than imperative, especially when they are located at areas of high tourist presence and therefore significant economic value. Within this work, a holistic methodology is described, including point-cloud data acquisition from a Terrestrial Laser Scanning (TLS), combined with point-cloud generation from photogrammetric processing of Unmanned Aerial Systems (UAS) imagery. The main scope is to create a reliable methodology for remote measurement of the orientation of structural features (mainly of those hard to be reached) and proceed to their tectonic analysis, as an additional tool for quantifying the surface deformation and improve our knowledge concerning the structural integrity of high-risk slopes that form geologically significant regions.

The area of interest is located at the easternmost part of Laganas beach, at Zakynthos Island, where the Ionian thrust is crosscutting the coastal area normally to the shoreline. It is near the Kalamaki locality, where the Ionian geotectonic unit is found overthrusting the Paxos unit (Papanikolaou, 1997; Papanikolaou *et al.*, 2010), causing deformation at the postalpine sediment succession that lies unconformably on top of the thrust fault. Right next to the beach, a very interesting section is formed consisting of several stratigraphic layers (Fig. 1a), corresponding to eight cycles of depositional gypsum types, which are unconformably capped by the Pliocene Trubi formation (Karakitsios *et al.*, 2017; Kontakiotis *et al.*, 2016). The entire succession consisting of intercalations of shale, limestone and several evaporite facies is tilted towards east with high angles, yielding the degree of tectonic deformation.

The slope deformation due to thrust tectonics in conjunction to the seismic activity of the wider region and the frequent human presence beneath the steep prone, constitute an ultra-high-risk coastal area. We used a combination of close-range remote sensing techniques aiming to construct a detailed 3D model of the geomorphic structure. The orientation of the area of interest was quite challenging as due to the narrow beachfront, there was not enough space on the beach for placing the equipment consisting of the tripod/TLS and establishing the several bases for scanning the steep slopes facing the sea. The shallow waters allowed for a thorough examination of the sea bottom, and we managed to locate hard ground for establishing the tripod for mounting the TLS. Geologically wise the most suitable areas for installing the tripod were at the projection of the harder strata towards offshore. We established 6 bases offshore (Fig 1a), on top of these strata, acquiring the same number of point clouds, which were linked to each other by using 4 targets that were placed along the beach (Fig 1b). Additional targets, alternating at every scan, were also placed offshore, on either side of each TLS base, for keeping the quality of the geometry of the point clouds at the highest possible level. As a result, the bundle error did not exceed 32mm for the unified TLS point cloud of the steep slopes, consisting of 84.5 million points.

The high angle of the steep slopes as well as the antithetic, almost flat, morphology of the hilltop did not allow any data acquisition from the latter. Therefore, a necessity for a different kind of surveying was raised and we used a UAS, with a built-in camera, for acquiring high-resolution, overlapping images, which were used for photogrammetric processing within the structure-from-motion approach (Westoby *et al.*, 2012). An ortho-photo mosaic and a Digital Terrain Model were produced during this procedure, which in turn were used for the extraction of a 50.2-million-point cloud, for the entire hill and not only for the steep slope facing the sea. By using the NRTK solution during the flight we ensured that the accuracy of the dataset was extremely high (27cm) and above all co-registered with the TLS one, since both were projected at the same system.

The overall result of the combination of the described datasets, that were produced based on close-range remote sensing techniques, was a merged point cloud for the entire hilly structure (Fig 1c), which allowed the creation of a 3D model, ideal for visualization and navigation in a user's personal computer. Measuring tectonic features such as strata or lineament dip and dip direction is feasible and practical within the framework of manipulating the 3D model, while using open-source software (e.g. CloudCompare, Girardeau-Montaut, 2011). We used this model for measuring, remotely, the structural orientation of the tilted blocks (e.g. lower unit bedding 55/081 and 'trubi' bedding 40/055) but also tectonic lineaments (hinge, fold axial plane intersections), which have been formed due to the compression caused by the thrust, especially at locations that cannot be reached by humans due to safety reasons, not to mention the statistical analysis of the abovementioned features through stereograms.

In conclusion, there are quite a few ways to use close-range remote sensing data and techniques for extracting geological information, but it is very crucial to take under consideration the maximum accuracy that should be succeed during the fieldwork, especially when combing data from different sources and equipment.

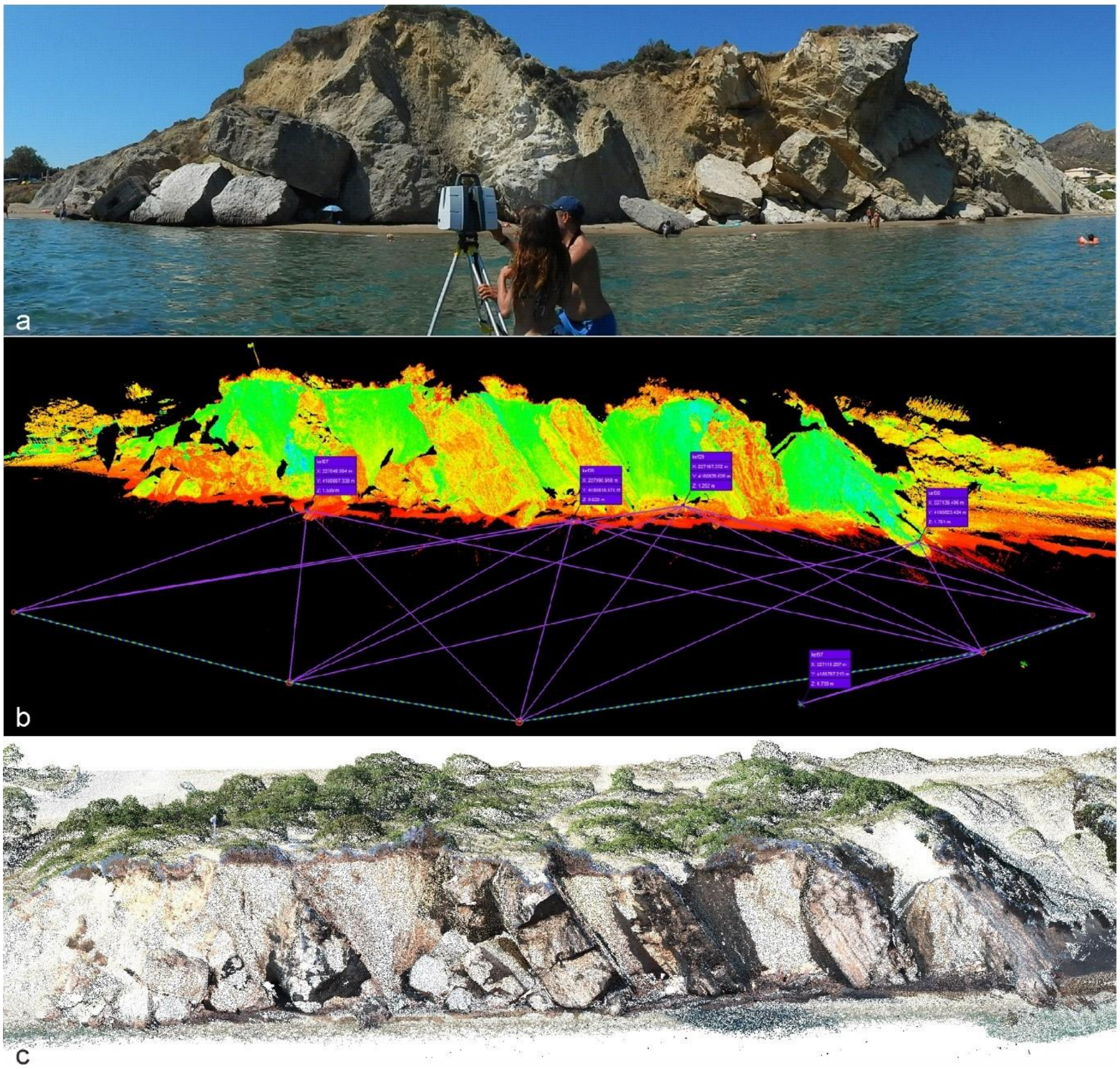

Figure 1. Using the TLS for the point-cloud data acquisition of the steep slope (a). Construction of the 3D model after the alignment of the six datasets and registration with the ground control targets (b). Combination of the two datasets of pointclouds (from TLS and UAS).

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