Satellite and UAV-enabled mapping of landslides caused by the November 17th 2015 M_w 6.5 Lefkada earthquake

Cartographie des glissements de terrain causée par le tremblement de terre du 17 novembre 2015 à Mw 6.5 Lefkada, par satellites et UAV

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ABSTRACT: On November 17th 2015 a M_w 6.5 earthquake occurred in the island of Lefkada, Greece. The earthquake resulted in extensive landsliding particularly along the west coast of the island. The landslides were mapped using satellite imagery collected shortly before and after the earthquake event. More detailed mapping also took place using an Unmanned Aerial Vehicle (UAV) equipped with an ultra-high definition optical camera. Using the UAV-based imagery, three-dimensional models of the landslides were created and were used to define the geometric characteristics of the landslides, including area, height and volume. In total, about 240 landslides were mapped from satellite data. Comparisons are made between the data collected from the satellite imagery and the UAV-based imagery. Overall, UAV-based imagery was particularly valuable in quantifying the volume of the landslides, separating amalgamated landslides, and developing cross-sections for subsequent stability analysis. In addition, comparisons between the developed 2015 landslide dataset and pre-existing landslides, showed that although several of the landslides were re-activated, many landslides were new, whereas about 100 pre-existing landslides were not re-activated.

RÉSUMÉ : Le 17 novembre 2015 un tremblement de terre de Mw 6,5 s'est produit dans l'île de Lefkada, en Grèce. Le tremblement de terre a entraîné un grand glissement de terrain, particulièrement le long de la côte ouest de l'île. Les glissements de terrain ont été cartographiés à l'aide d'images satellitaires recueillies peu de temps avant et après le tremblement de terre. Une cartographie plus détaillée a également eu lieu à l'aide d'un véhicule aérien sans pilote (UAV) et d'une caméra optique ultra haute définition. À l'aide de l'imagerie fondée sur les UAV, des modèles tridimensionnels des glissements de terrain ont été créés et ont été utilisés pour définir les caractéristiques géométriques des glissements de terrain, y compris la superficie, la hauteur et le volume. Au total, environ 240 glissements de terrain ont été cartographiés à partir de données satellitaires. Des comparaisons sont effectuées entre les données recueillies à partir de l'imagerie satellitaire et les images basées sur les UAV. Dans l'ensemble, l'imagerie fondée sur les drones a été particulièrement utile pour quantifier le volume des glissements de terrain, séparer les glissements de terrain amalgamés et développer des coupes transversales pour l'analyse de stabilité ultérieure. De plus, des comparaisons entre le jeu de données sur les glissements de terrain de 2015 et les glissements de terrain préexistants ont montré que bien que plusieurs glissements de terrain aient été réactivés, de nombreux glissements de terrain étaient nouveaux, alors qu'une centaine de glissements de terrain antérieurs n'ont pas été réactivés.

KEYWORDS: UAV, unmanned aerial vehicles, satellite, imagery, landslides, earthquakes

1 INTRODUCTION

The island of Lefkada is part of the Ionian complex of islands in Greece and has the highest seismicity in Europe, excluding Turkey. This is because Lefkada is situated in the transition between the Hellenic subduction in the south and the Adriatic collision in the north along the right lateral Kefalonia-Lefkada Transform Fault (KLTF), which runs nearly parallel to the west coasts of both Lefkada and Kefalonia islands, in two segments (Scordilis et al. 1985, Papazachos et al. 1998, Rondoyanni et al. 2012). As such, the area has been subjected to multiple tectonic processes that have led to a complex regional structure and high relief topography.

On November 17, 2015, 07:10 GMT (09:10 local time) Lefkada was struck by a strong, shallow earthquake that is estimated to be M_L 6.0/M_w 6.5 at a depth of 11 km. The epicenter of the earthquake according to the National Observatory of Athens, Institute of Geodynamics (NOA) is shown in Fig. 1, and is located just offshore of the west coast of Lefkada. The causative fault is estimated to be a near-vertical strike-slip fault with dextral sense of motion (Ganas et al., 2015, 2016). The recorded PGA at the town of Vasiliki was 0.37g in the North-South direction, whereas in the town of Lefkada it was 0.10g in the North-South direction and lower in the East-West direction.

The earthquake caused significant landsliding particularly along the west coast of the island. Mapping of the landslides using satellites and Unmanned Aerial Vehicles (UAVs) was executed with the intent to better characterize landsliding patterns on the island. Comparisons between the data generated by the two methods and major observations of landsliding patterns are briefly presented in this contribution.

2 GEOLOGIC SETTING

The Ionian islands, including Lefkada, is a region known for the generation of frequent M_w 5-6.5 earthquakes, as well as larger (up to 7.5) earthquakes that occur less frequently. The island has experienced a number of earthquake events in its recent history. There is reliable detailed information for at least 23 events since 1612, which induced ground failures at the island of Lefkada (Papathanasiou et al 2005), which is an average of a damaging earthquake every 18 years. More recently, on August 14 2003 a M_w 6.2 earthquake occurred offshore the NW coast of Lefkada and caused significant damage, particularly in the town of Lefkada where a PGA of 0.42g was recorded (Fig. 1). Liquefaction was also observed and rockslides and rockfalls on the western coast occurred (Papadopoulos et al. 2003, Karakostas et al. 2004, Papathanasiou et al. 2005, 2012), but landsliding was far less extensive than observed in 2015.

Fig. 1 overlays the neotectonic map by Rondoyanni et al. (2012), with the epicenters of the 2003 and 2015 events. The southwest coast of Lefkada is part of the Triassic to Eocene age Paxos zone and consists of limestones and dolomites that are covered by Neogene clastic sedimentary rocks, mostly sandstones and marls. Landslides were also observed further to the north along the west coast in an area with Neogene sediments that consist of conglomerates, sandstones, marls and marly limestones, as well as Triassic to Eocene age rocks of the Ionian zone, which consists of evaporites, dolomites, limestones, siliceous schists, and flysch. The geodynamic history is dominated by compressive stresses, which are expressed by numerous thrusts and folds. Recent tectonic deformation is associated with the NE-SW striking transpressive stresses associated with the KLTF and have resulted in the island's most recent phase of mountain building (Bornovas 1964, Rondoyanni et al. 2012).

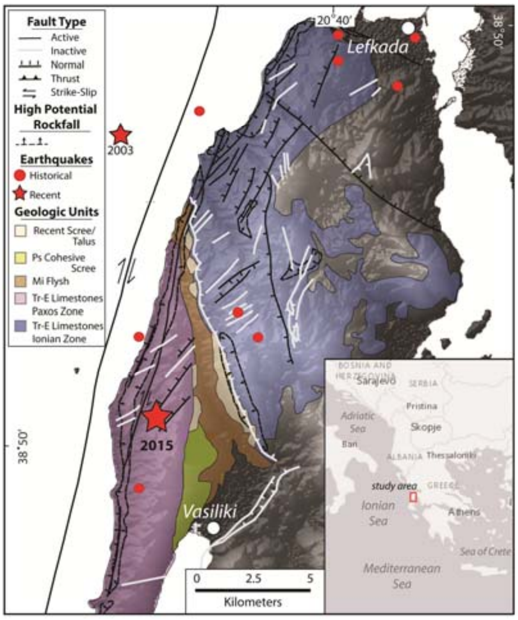

Figure 1. Neotectonic map of Lefkada Island, Greece (Rondoyanni et al., 2012). Recent earthquakes (stars) in 2003 (M_w6.2) and 2015 (M_w6.5) produced widespread landsliding along the western coast of the island. Several other historic earthquakes (red circles) have also affected the island (Kassaras et al., 2015).

3 MAPPING METHODS

Landslides were mapped using optical imagery collected by satellites and Unmanned Aerial Vehicles (UAV). Satellite photography was collected by the Worldview-2 and Worldview-3 satellites by Digital Globe Inc. before (May 30st 2015) and after (December 28th 2015) the earthquake. The resolution of the imagery was 30-50 cm allowing for identification of landslide features that are at least 10 m^2 in average dimension.

Unmanned Aerial Vehicles were also used to map landslides in higher resolution. Specifically, the DJI Phantom 3 Professional© platform equipped with f/2.8 lens with a 94^0 field of view camera capable of collecting 12 MP Ultra High Definition (UHD) imagery and 4k video at 30 frames per second, was used for this work.

Members of the team deployed in the area two days after the event. During that time, many of the roads towards the west coast of the island were closed due to heavy landsliding. The UAV was able to bypass these obstacles and collect imagery of some of the affected areas. A second deployment took place in April 2015 with the goal to map in more detail larger areas affected by landslides. In total, 6.45 km^2 (in plan view) were mapped by the UAV as shown in Fig. 2. By April (5 months after the earthquake), it was observed that much of the landslide debris that covered beaches immediately following the earthquake had been removed by wave action. An example is shown in Fig. 3 for the Egremnoi beach, which was severely affected by the earthquake. The orthophoto generated by the UAV two days after the earthquake (November 19th 2015) shows significant amounts of debris that was progressively eroded with time. Already significant erosion had taken place by December 28th 2015, as observed by satellite imagery and additional erosion occurred by April 13th 2016 during the second UAV deployment in the area. This dataset highlights the importance of collecting perishable data as soon as possible.

Figure 2. View of landslide affected areas mapped by Unmanned Aerial Vehicles (UAVs) in April 2016.

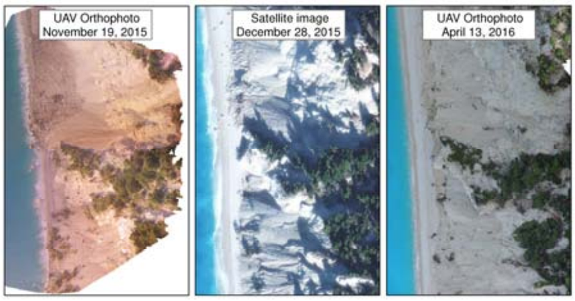

Figure 3. View of Ekgremnoi beach mapped by UAV on November 19 2015, by satellite on December 28 2015 and on April 13 2016.

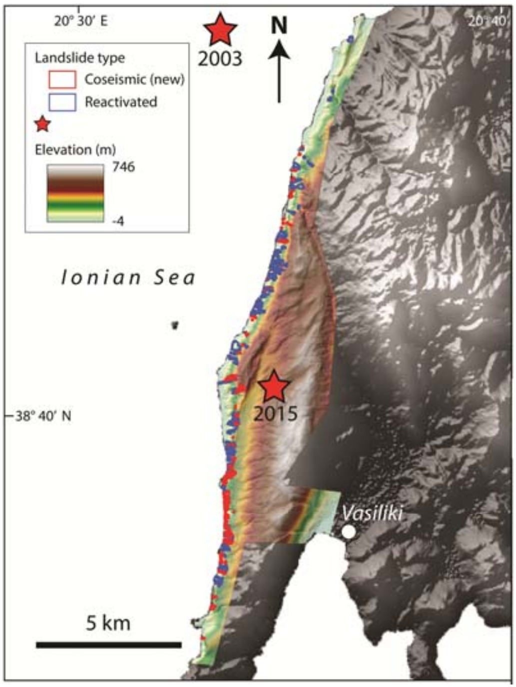

Figure 4. Satellite-based mapping of landslides.

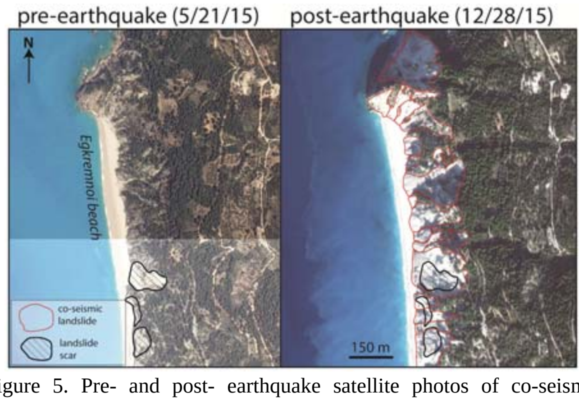

Figure 5. Pre- and post- earthquake satellite photos of co-seismic landsliding that took place in Lefkada island during the November 17th 2015 earthquake at Egkremnoi Beach. Prior to the earthquake (left), a few remnant landslide scars are visible.

4 DATA ANALYSIS & RESULTS

Pre- and post- earthquake imagery was used to identify the co-seismic landslides. In total ~240 landslides were identified using this approach as shown in Fig. 4 and additional 100 pre-existing landslides along the coastline that were not reactivated. An example is shown in Fig. 5. The landslides were found to be concentrated on the steep slopes of the west coastline. The intensity of landsliding resulted in many adjacent and overlapping landslides and landslide complexes, which are likely comprised of many smaller individual features. This is attributed to the higher ground motion intensity on that side of the island, the steepness and height of slopes, as well as the rockmass conditions. The trend of decreasing landslide density from west to east was also observed during the 2003 earthquake (Papathanasiou et al. 2012). In general, this earthquake appears to have affected mostly the west coastline and especially its south and central portion where new landslides were generated. Further north, landslides that failed in 2003, failed again in 2015. The size distribution of the landslides is shown in Fig. 6.

The UAV provided the opportunity to map in three dimensions large portions of the landslide affected areas at a much higher resolution than is possible from the satellite data. In addition, structure-From-Motion (SFM) photogrammetry was used to develop 3-D point cloud models of landslide sites using the imagery collected by the UAV (Westoby et al., 2012, Greenwood et al. 2016, Manousakis et al. 2016). Sufficient overlap, of at least 60%, between successive images is required for 3-D model generation. Ground control point (GCP) targets were used, when possible, to develop reliable digital elevation models (DEM) at cm-level resolution. Specifically, the average point cloud density of the various 3D models was 20-70 points/m^2. An example of the data generated is shown in Fig. 7. Fig. 7 shows an oblique view of the Egremnoi beach in 2D, and as a 3D point-cloud that can be used for such analysis. Point cloud data enables identification of individual landslides within larger landslide complexes, which cannot be easily recognized from satellite imagery alone, mostly because the imagery lacks resolution in 3D. Segregation of landslide complexes into their component parts is expected to significantly affect commonly used frequency area statistics such as shown in Figure 6.
Such segregation is expected to be achieved using the higher resolution UAV imagery.

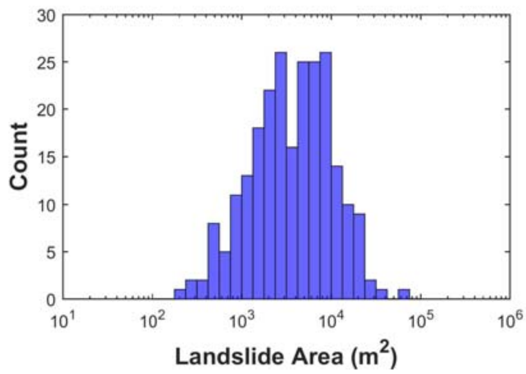

Figure 6. Landslide size distribution based on satellite imagery.

The 3D models allowed for an assessment of the volume of the landslides within landslide complexes as component parts, and a derivation of a relationship between landside area (actual, sloped area) and volume, as shown in Fig. 8. For the interpreted landslides in Lefkada, the derived relationship is:

$$V=0.13*A^{1.4} \quad (1)$$

Note that in Eq. 1, A is the actual sloped landslide source area, (not plan view area). Volume is calculated by measuring the (air) volume outlined by the source area scarp, assuming a planar surface measured across the scar in an orientation parallel to the scar slope. In addition, cross-sections, as shown in Fig. 9 were drawn through the affected areas and can be used in stability analyses of the rock masses for back-analyses and risk assessment of further movement as well as subsequent erosion.

Figure 7. UAV-based 2D imagery (top) and 3D point cloud geom etry (bottom) for an example site in Lefkada

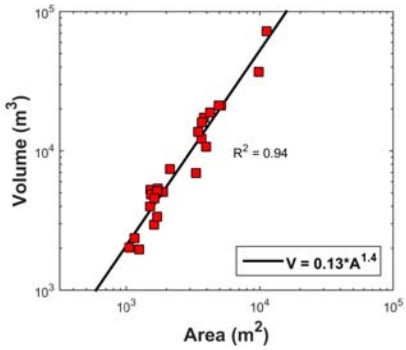

Figure 8. Volume to Area relationship for Lefkada landslides base d on UAV imagery analysis.

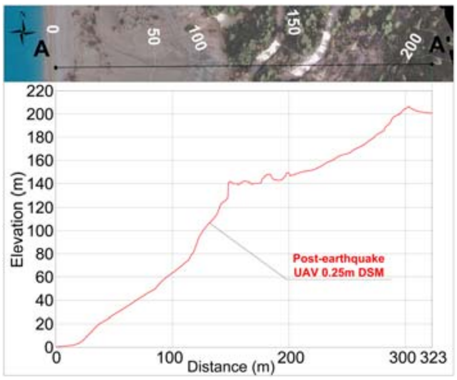

Figure 9. Example cross-section through a landslide affected area based on 3D model derived by UAV imagery.

5 CONCLUSIONS

The landslides that occured during the November 17th 2015 earthquake in Lefkada were mapped using imagery collected by satellites and Unmanned Aerial Vehicles. The landslides affected primarily the west coast, and especially its central and south portion. The geometry of the landslides, and especially the landslide debris was observed to change significantly due to wave action during subsequent months. UAV imagery allowed mapping of landslides at higher resolution than feasible from satellite imagery and creation of 3D models that enabled identification of individual landslides within larger landslide complexes, derivation of area-volume relationships and development of cross-sections for 2D stability analysis.

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