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Remote landslide mapping, field validation and model development – An example from Kravarsko, Croatia

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Abstract

The Kravarsko settlement area, in northern Croatia, has multiple landslides and damage to buildings and infrastructure caused by landslides. However, actual landslide investigation data for the wider Kravarsko area (pilot area PA1) is relatively sparse and no landslide inventory or typical landslide model exists. The aim of this research was to develop such a landslide inventory by integrating new approaches in geohazard research such as remote landslide mapping from high resolution digital elevation models (DEMs) and current and historical aerial images with existing and new geological data related to landslides. The conclusion is that detailed DEMs are more than adequate for the development of reliable landslide inventories but field checks are still necessary to account for the specific set of natural and man-made conditions found in the research area. The landslide inventory developed for Kravarsko has been field validated in a smaller validation area (VA1) and a typical simplified landslide model for PA1/VA1 was developed. Within the model, sliding is interpreted as complex with multiple generations of sliding and multiple sliding surfaces. Based on the analysis undertaken and the available field data, around 10-20% of urban structures are endangered in the Kravarsko area and anthropogenic activity was determined as an important landslide triggering factor for landslide activation or reactivation. Still the question remains of how to quantify the anthropogenic influence? The developed landslide inventory for PA1/VA1 could be used for local urban planning/development and endangerment assessment/evaluation.

Keywords: Remote landslide mapping, geology, landslide inventory, model, human factor

1. INTRODUCTION

Geologically, and by engineering geological characteristics, Croatia can be roughly divided into two main areas (Fig. 1a): the northeast continental part with different types of sediments but usually with developed soils on the surface and the southwest karstic landscape with often exposed rocks. This difference is

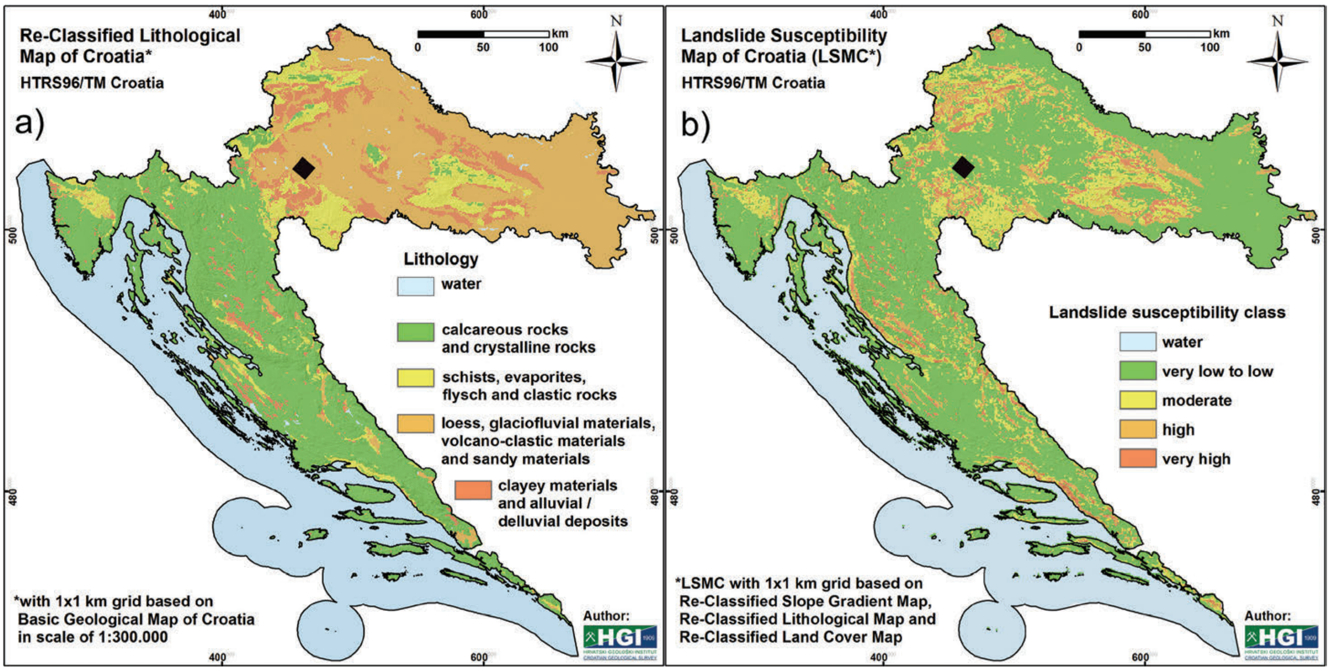

Figure 1. Research area location - in the northern part of Croatia (Kravarsko area - black polygon): a) reclassified and simplified lithological map of Croatia, based on geological map of Croatia in scale of 1:300,000 (HGI, 2009); b) small scale Landslide susceptibility map of Croatia from which the northern part of Croatia can be identified as (generally) prone to landsliding and southern area as prone to rock falls (LSMC HGI-CGS, PODOLSZKI et al., 2015).

Figure 2. Landslide damage in the Kravarsko area: a) destroyed storage in landslide body; b) road mitigated by rock embankment and "fresh" asphalt; c) damaged vineyard in the main body of a landslide; d) landslide main scarp by a house (photos by HGI-CGS, 2019).

also reflected in the type and mechanism of movement (JURAK et al., 1996): the NE is predominantly prone to slides in soils on slopes with variable inclination, while the SW karstic area is predominantly prone to rock falls on steep slopes mainly along the coastline (Fig. 1b). In this research, the focus was on the Kravarsko area in northern Croatia (Fig. 1).

In the northern part of Croatia there is a long history of landsliding (JURAK et al., 2008; PODOLSZKI, 2014) and by these movements houses, roads, water systems and power lines are endangered and locally damaged. Whilst some recent landslide inventory data exist for Zagreb city (MIKLIN et al., 2007; 2018), there is a lack of landslide data and information for the wider Zagreb county area i.e. Kravarsko hilly area, but that is not to say that landslides do not occur in this area. To improve the existing (landslide) data sets the wider Kravarsko area was chosen as one of six pilot areas within the safEarth project (Interreg IPA - CBC program Croatia, Bosnia and Herzegovina, Montenegro) and also as a pilot area (PA1) for the GeoTwinn project (Widespread-05-2017-Twinning project: Croatian Geological Survey – HGI-CGS, British Geological Survey - BGS and Geological Survey of Denmark and Greenland - GEUS). This area was chosen as this area is populated and there are recurring damages caused by landslides (Fig. 2). Also, in the past there has not been systematic landslide research for this area, only the implementation of mitigation measures on an ad-hoc basis. For the wider Kravarsko area a landslide inventory or typical landslide model has not been yet developed. JURAK et al. (1996) provide simplified landslide models at the regional scale but a national landslide inventory for Croatia does not exist.

The aim of the research was to develop a landslide inventory with a typical simplified landslide model for the research area (PA1≈60 km^2) based on available geological and remote sensing data and field validation. The landslide inventory was produced by the integration of existing (Fig. 3) and new geological data with the results of the interpretation of available remotely sensed images of the area (Fig. 4): satellite images, stereo pairs and orthophotos along with mapping on high-resolution digital elevation models (DEMs) derived from airborne Light Detection and Ranging (LIDAR) scanning. The resulting landslide inventory (Fig. 5) was then field validated in a smaller area (VA1≈10 km^2) within PA1. During field work it became obvious that site specific geological and anthropogenic conditions are relevant for landslide development in this area. To support this hypothesis, sedimentary logs developed for the wider area were reviewed and shallow boreholes were drilled in the VA1 area (Figs. 6, 7). After data interpretation and correlation a simplified typical landslide model was developed based on the type example landslide in this area: the landslide on the Miličić Vrh and Kolarci Street intersection, referred to as the LsMVKS (Figs. 8, 9, 10).

1.1. Geographical and geological setting

The research area is situated ~25 km south of Zagreb in the area of Vukomeričke Gorice (Figs. 1, 3). Vukomeričke Gorice is a ~50 km long hilly area between the Sava and Kupa valleys, just before their junction. Kravarsko stands out as the central settlement of this hilly area with an average height of approximately 200 m above sea level with temperate continental climate (ZANINOVIĆ et al., 2008).

The geological development and structure of the investigated area of Vukomeričke Gorice is related to the southwestern marginal part of the Pannonian basin system, a sedimentary basin system located in the central and south-eastern part of Europe. During the Miocene and Pliocene, this area was part of the Central Paratethys (RÖGL & STEININGER, 1984). The most common surface deposits in the Vukomeričke Gorice area are an interbedded mixture of Pliocene sands, gravels, clays, and rarely sandstones and conglomerates (PIKIJA, 1987a). These types of Pliocene deposits are known as the *Viviparus* beds. They represent infill of the Slavonia (Paludina) Paleo Lake which can be up to 0.9 km thick (SAFTIĆ et al., 2003; HARZHAUSER & MANDIC, 2008; CVETKOVIĆ, 2013). Only the northern part of Vukomeričke Gorice is covered with Plioquaternary clays, sands, and gravels (ŠIKIĆ et al., 1978; 1979), and along the NE marginal part of Vukomeričke Gorice, Pliocene deposits are covered with Pleistocene loess-like sediments (PIKIJA, 1987a; 1987b).

According to the development series of gastropods of the genus *Viviparus*, the Pliocene deposits are divided into the lower, middle and upper *Viviparus* beds (NEUMAYR & PAUL, 1875), although in the investigated area there is a visible stratigraphic disconformity with the absence of the middle *Viviparus* beds (PIKIJA, 1987a; MANDIC et al., 2015; KUREČIĆ, 2017). The biostratigraphic units can be roughly correlated to the major lithological members. Lower *Viviparus* beds from the Kravarsko area are composed of plastic "blue" coloured clays (or more rarely multi-coloured), sands and sandstones. The clays are interlayered in places with sand and rarely occur as a matrix in the gravel. The sand is mostly yellow and brown, of various granulations, sometimes turning into fine-grained gravel. In general, clays predominate in the lower *Viviparus* beds. For example, in deep wells (Pliocene of Kravarsko area down to -720 m), the clay:sand ratio varies between 2:1 and 3:1 (ŠIMUNIĆ & AVANIĆ, 1985). Rare occurrences of sandstone, as well as layers of lignite, have been recorded (ŠEBEČIĆ, 2010). The upper *Viviparus* beds are built of grey and yellow-brown sands, yellow, blue and grey clays, and fine-grained gravel. In some places, they contain thin lenses of lignite up to 1 metre thick. The sand/gravel is cemented in places with limonite and turns rarely into limonitized sandstone/conglomerate. Clays are less represented than in the lower *Viviparus* beds, their ratio to sand here is 1:4 to 1:6 (ŠIMUNIĆ, 1964).

Through the current project of lithostratigraphic mapping of the Republic of Croatia at a scale of 1:50,000, most of the sediments previously described as *Viviparus* beds are now classified as an informal lithostratigraphic unit the Vrbova fm. In this unit there are multiple records of landslides on existing maps (ČUBRILOVIĆ et al., 1967; PIKIJA, 1987a; HALAMIĆ et al., 2019) and multiple landslides were mapped during the safEarth project.

1.2. Site specific geohazards

According to the widely used classification of landslides (VARNES, 1978, 1984; CORNFORTH, 2005; BOBROWSKY & HIGHLAND, 2008) and geohazards (BELL, 2003; GUZZETTI, 2006) and available landslide data, the most common geohazards in PA1 are slides in soil i.e. clay/silt rotational, planar or compound slides or gravel/sand debris slides (HUNGR et al., 2014). Although in PA1 other processes are also present, for example: soil creep, erosion, small scale torrential flows and fluvial processes, the focus of this research is on soil slides which will be referred to simply as landslides.

The 1:500,000 scale Engineering geological map of Yugoslavia (ČUBRILOVIĆ et al., 1967, Fig. 3a) indicates that three units are present in PA1: (i) sandstones, marly clays, marls and sands – Upper Neogene lacustrine bedded sedimentary complex with very variable porosity and permeability, prone to erosion and sliding (brown on map); (ii) sands, gravels and clays, poorly to medium settled and sporadically cemented, with well pronounced bedding – Upper Neogene lacustrine complex with great variability of porosity and permeability, prone to erosion and sliding (yellow on map); and (iii) sandy gravels, sporadically clayey – Pleistocene-Holocene fluvial sediments, mostly covered with loam, poorly settled and bedded, rather porous (white on map).

The 1:100,000 scale Basic geological map (PIKIJA, 1987a, Fig. 3b) indicates that two units are present in VA1: (i) Sands,

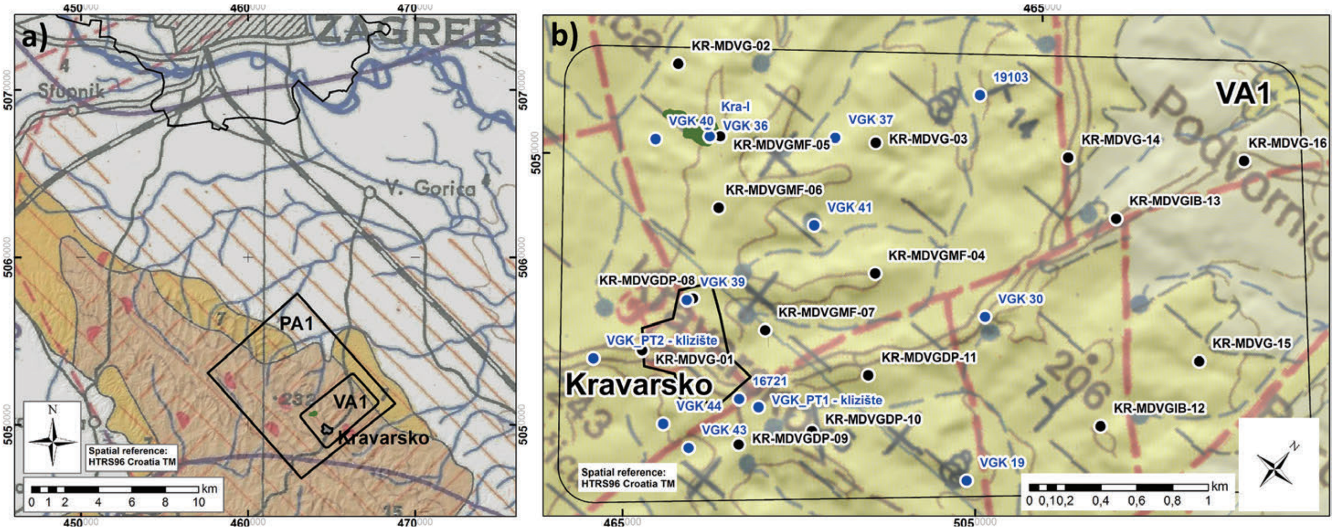

Figure 3. Pilot area setting overview: a) detail from the Engineering geological map of Yugoslavia at (original) scale of 1:500,000 (ČUBRILOVIĆ et al., 1967; see text for explanation). Even at this scale landslides are identified in the (wider) area (red polygons): b) detail from the Basic geological map - Sisak sheet at (original) scale of 1:100,000 (PIKIJA, 1987a; see text for explanation). Green polygon indicates the location of the example landslide for this area (LsMVKS), blue points mark the locations for the *Viviparus* beds research (KUREČIĆ, 2017), and black points show the location of 16 shallow boreholes from the safEarth project (HGI-CGS field data from 2019). Landslides are also indicated on the Basic geological map with red lines with arrow (wider area).

Table 1. List of reviewed and analysed main data sets for the Kravarsko study site (PA1/VA1).

Data type	Short description
Maps, sedimentary logs, landslide inventory	Small scale Landslide susceptibility map of Croatia (LSMC HGI-CGS, PODOLSZKI et al., 2015)
	1:500,000 Engineering geological map of Yugoslavia (ČUBRILOVIĆ et al., 1967)
	1:300,000 Re-classified lithological map of Croatia (internal HGI-CGS)
	1:100,000 Basic geological map – sheet Sisak with Guide (PIKIJA, 1987a; 1987b)
	1:5,000 Developed Geological map for VA1 (internal HGI-CGS 2019)
	1:5,000 Topographic map (National Geodetic Administration of Croatia)
	11 Sedimentary logs developed for wider area (KUREČIĆ, 2017)
	Developed Landslide inventory for PA1 with 1,430 landslides (internal HGI-CGS 2019)
Remote sensing images	Satellite images – Sentinel 2 (10 m pixel size, Copernicus Open Access Hub, free access)
	Orthophotos from 2011 (National Geodetic Administration of Croatia, NGA-DGU)
	Orthophotos from 2014-2016 (National Geodetic Administration of Croatia, NGA-DGU)
	Orthophotos from 2017 and 2018 (National Geodetic Administration of Croatia, NGA-DGU)
	Orthophotos from 2018 (safEarth)
	Stereopairs from 1977 (HGI-CGS archive)
	Stereopairs from 2018 (safEarth)
LIDAR and developed DEMs for PA1/VA1	20 points per m^2, airborne LIDAR scan, early spring 2018 (safEarth)
	0.5x0.5 m cell size DSM – digital surface model
	0.5x0.5 m cell size DTM – digital terrain model
	0.5x0.5 m cell size DTMh – digital terrain model hillshade
Field data	16 shallow boreholes (100-350 cm) for VA1
	443 field pocket penetrometer tests for VA1
	29 field shear vane tests for VA1
	676 field points (geological and engineering geological) for VA1
	113 field points (geological) for wider area
Laboratory data	~200 different laboratory tests for wider area: granulometry, mineralogy, XRD, $CaCO_3$ content, etc.
LsMVKS re-activation estimation – witness based	In April 2014 during field sedimentary mapping (KUREČIĆ, 2017) the "fresh" head scarp was clearly visible - indicating "winter time" movement (end of 2013 - beginning of 2014) i.e. landslide re-activation coincide with unusually high precipitation values (above average) during winter of 2013-2014 (eye witness account).

gravels, clays, conglomerates, sandstones (Pliocene, dark yellow on map); (ii) Loess (Quaternary, light yellow on map). The prevailing Pliocene sediments (sands, gravels, clays, conglomerates, sandstones) are known for landslide phenomena.

2. METHODS

Data used in the Kravarsko research (PA1/VA1) consisted of existing and new data in different forms: maps, remote sensing data, field research, laboratory data with associated interpretation and eye witness accounts. The main datasets are listed in Table 1.

2.1. Remote landslide mapping

Landslide inventory development based on remote sensing data is possible if there are distinct features which can be mapped (MIYAGI et al., 2004; GUZZETTI et al., 2012; PAINE & KISSER 2012; PODOLSZKI 2014; MIHALIĆ et al., 2016). The following information is gained from a detailed examination of remote sensing data for PA1/VA1 (Figs. 4, 5): (i) aerial photo interpretation (stereo pairs and orthophotos) can be a source of otherwise unavailable historical data and can give an understanding of the temporal evolution of a landslide. (ii) analysis of high resolution DEMs can provide very useful and accurate data on the morphology of landslides and a usable and reliable landslide inventory can be developed; (iii) results of the medium resolution (10 m pixel size) Sentinel 2 satellite images interpretation are not conclusive.

2.1.1. Satellite image and aerial photography analysis

For PA1 Sentinel 2 images were acquired from the Copernicus Open Access Hub. The analysis was performed in Sentinel Application Platform (SNAP) software at the British Geological Survey. The SNAP architecture is ideal for Earth Observation processing and analysis due to its technological innovations, however for PA1, the resolution of the images is too coarse for landslide delineation (Fig. 4a).

Available stereo pairs of aerial photographs covering the Kravarsko area from 1977 at a scale of 1:26,000 (Fig. 4b) and from 2018 at a scale of 1:2,500 (Fig. 4c, both from HGI-CGS archive) were analysed on 3D photogrammetric workstations at the Geological Survey of Denmark and Greenland. Indications of landslides (deformations, cracks, damages to structures) and affected areas were reviewed for the selected locations areas/landslides (also for the LsMVKS area).

Orthophotos and topographic maps at a scale of 1:5,000 available from the National Geodetic Administration of Croatia (https://geoportal.dgu.hr/) from 2011, 2014-2016 and 2018 were further implemented in analysis to better constrain the temporal evolution of the landslides and development of the area ("urbanization") i.e. for LsMVKS area (Fig. 4d-4g).

The LsMVKS landslide has a history: the landslide is present on stereo pairs from 1977 (Fig. 4b). It was probably reactivated during the 2013-2014 winter due to high rainfall and hence water content: the "fresh" head scarp was clearly visible in the field in April 2014 during sedimentary log mapping, (indicating "winter time" movement), which is in accordance with orthophoto data (visible changes on available orthophotos from 2011, 2014 and 2018, Fig. 4d-4f). Also the upper part of the slope is becoming more urbanized: the road has been expanded, objects have been built (on Fig. 4g there is only one house on landslide area).

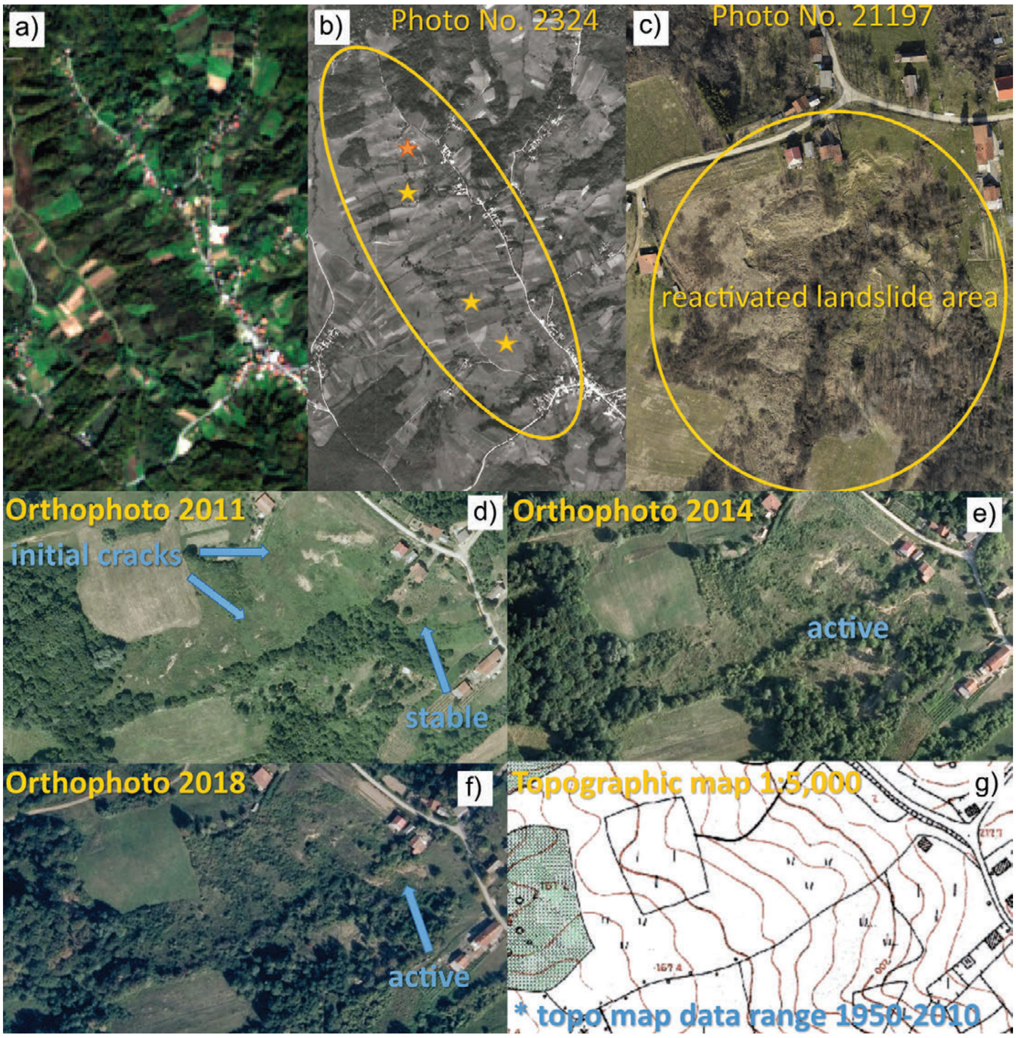

Figure 4. Satellite image and aerial photography analysis: a) Sentinel 2 images downloadable from Copernicus Open Access Hub – the resolution is too coarse for landslide delineation on this area – PA1 (BGS Training room, GeoTwinn 2020); b) Stereo pairs for the Kravarsko settlement from 1977 (only Photo No. 2324 is shown) – inspected slope (yellow ellipse), LsMVKS landslide location (orange star), probable landslide locations (yellow stars); c) Stereo pairs for LsMVKS landslide location from 2018 (only Photo No. 21197 is shown) - main scarp is just below the houses and deformation and fissures are also visible in the landslide body (GEUS Training room, GeoTwinn 2020). Reviewed and analysed orthophoto data from National geodetic administration of Croatia for LsMVKS landslide location – reactivation and development: d) visible initial movement and stable area (Orthophoto 2011); e) active landslide area (Orthophoto 2014); f) active main scarp zone (Orthophoto 2018); g) topographic map with one house above the landslide area (probably data from 1990's): can be used as information source for human activity on landslide area – in 2011 there are more houses built on landslide area.

2.1.2. Airborne laser scanning (LIDAR data) and landslide inventory development

Landslide inventories based on high resolution DEMs can be accurate and also periodically updated if the mapping criteria remains the same and there are available data of the same level or better (SLAUGHTER et al., 2017; JAGODNIK et al., 2020). Based on aerial LIDAR scanning from early spring 2018, with point cloud density of 20 points per m^2, high resolution DEMs (0.5 m cell size) were created and interpreted for the ~60 km^2 area of PA1 and 1,430 landslides were mapped on DEMs. The developed landslide inventory was field validated for the ~10 km^2 area of VA1 (Fig. 5). These mapped landslides were rated with a score from 1 to 10 according to the Confidence of LandSlide Identification (CoLSI), based on SLAUGHTER et al. (2017). The score/confidence of landslide identification is based on landslide features which are present, visible and can be mapped on the DEM: head scarp, flanks, toe and internal deformation. For a landslide to have a high score (CoLSI of 8-10, Table 3) all of the landslide features (head scarp, flanks, toe and internal deformations) must be present, visible and identifiable on the DEM. For a landslide to be assigned a middle CoLSI score (4-7, Table 3) some of the landslide features (head scarp, flanks, toe and internal deformations) cannot be identified on the DEM. For low scoring landslides (1-3, Table 3) most of the landslide features (head scarp, flanks, toe and internal deformations) are not present, or visible and can't be mapped on DEM. The scoring system is subjective, but it is based on the system which is in use by the Washington Geological Survey, USGS (SLAUGHTER et al., 2017). As the score is given based on the presence of landslide features it also reflects the relative age of landslides as features degrade and become more obscured as the landslide ages (MCCALPIN, 1984). Thus, a low score does not necessarily mean that there is an uncertainty whether it is a landslide or not but more probably reflects that it is an old degraded landslide or alternatively a juvenile, poorly developed landslide.

On the LIDAR derived 0.5 m cell size digital terrain model hillshade (DTMh) landslides can be mapped very precisely with sub metre precision. From detailed orthophotos land cover and manmade objects can easily be distinguished. With a combination of orthophoto, LIDAR DTMh, slope map and contour lines,

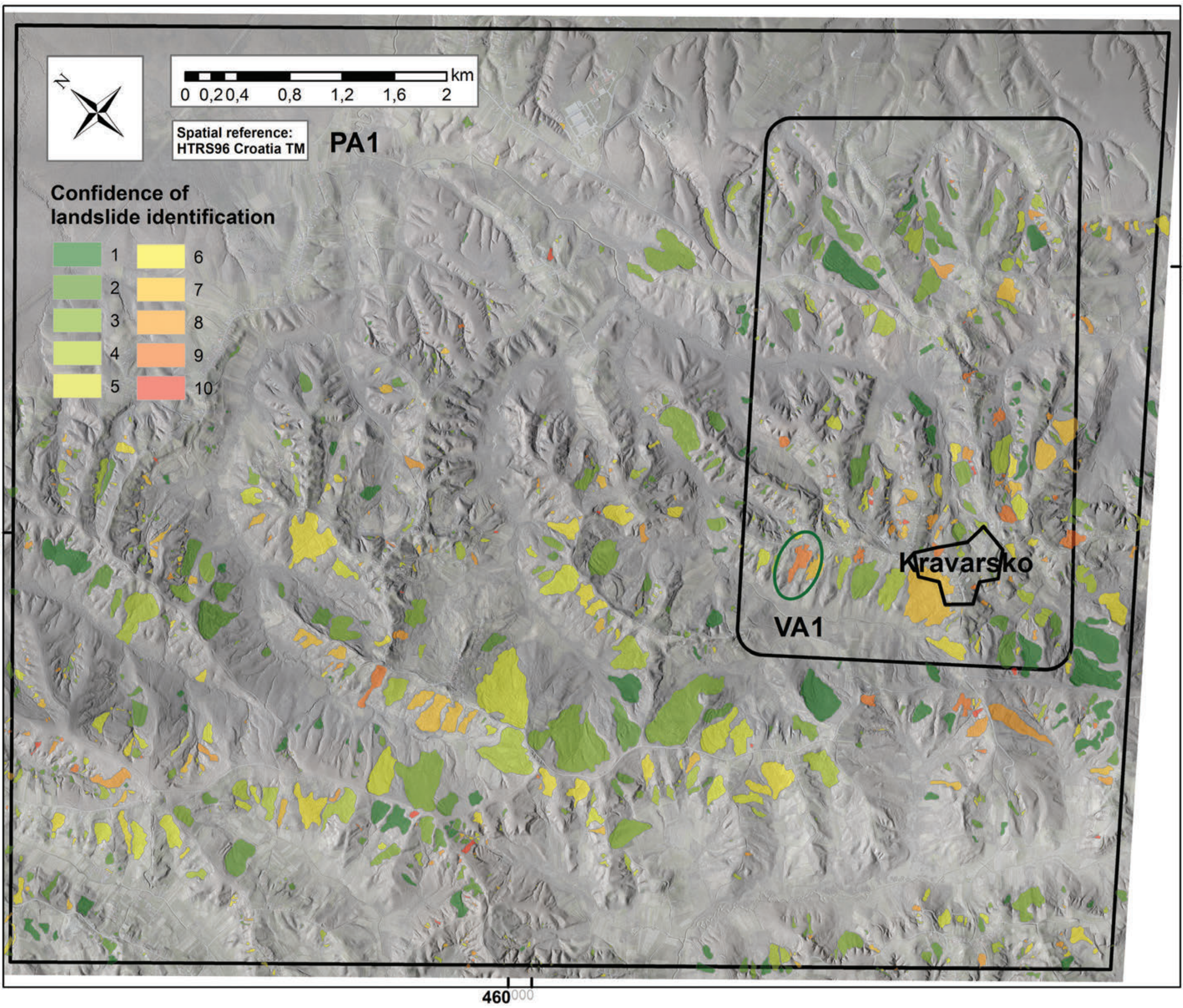

Figure 5. Developed landslide inventory for PA1 with 1-10 Confidence of landslide identification (CoLSI) based on landslide features (head scarp, flanks, toe and internal deformations) which are present, visible and can be mapped on the DEM (HGI-CGS cabinet data from 2020). The green ellipse indicates the location of the type example landslide for this area - LsMVKS landslide.

landslide mapping can be completed with varying degrees of confidence for the entire area of PA1/VA1. The resulting landslide inventory is of high quality and represents a reliable product as exemplified by the mapping of the LsMVKS landslide (Fig. 8). With the use of "extra" data, such as available historical images (stereo pairs, orthophotos) and 3D visualization tools (for example ArcScene, GeoVisionary), the developed landslide inventory can be enhanced.

2.2. Geological investigations

Existing relevant geological data was revised for the whole area (PA1) and for the VA1 area new geological data was acquired. These include new mapping along with borehole and sedimentary log data and sampling (Table 1).

2.2.1. Field mapping and site specific shallow borehole data

For the VA1 area sixteen shallow boreholes were drilled within the safEarth project and a new geological map at 1:5,000 scale was compiled (Fig. 6). Due to the vegetation coverage of the terrain, a combination of methods was used during the field geological mapping, mainly based on KORBAR et al. (2012). The average density of observation points was ~60 points/km^2. Most of the mapped units in VA1 consist of the (informal) Vrbova fm. (previously described as the *Viviparus* beds, Pliocene, Pl$_{1-3}$). In the field, three units can be differentiated (Fig. 6): VRV-P sands, silty sands and sandy silts (no colour on map); VRV-G clays, silty clays and clayey sits (grey on the map); VRV-Š gravel, gravely sands and sandy gravels (yellow on map). Near river beds, creeks and streams, alluvial sediments (al, Quaternary, Q$_2$) can be differentiated (gravels, sands and silts, al, blue on map). Eleven "new" typical sedimentary logs for the PA1 and wider area were developed as of a result of field mapping and point observations with sedimentary log Kra-I in the VA1 area (KUREČIĆ, 2017, see the following section 2.2.2). Based on the data the landslide on the Miličić Vrh and Kolarci Street (LsMVKS) intersection on the western part of the slope was chosen as the type example for this area because:

1. The new 1:5,000 scale lithostratigraphic geological map (internal HGI-CGS 2019) covers this landslide location and the wider slope (Fig. 6).
2. Remote sensing interpretation of this slope using the stereo pairs from 1977 and 2018 has been completed along with a review of topographic data and orthophotos (2011-2018) giving a remote sensing data background (Fig. 4).

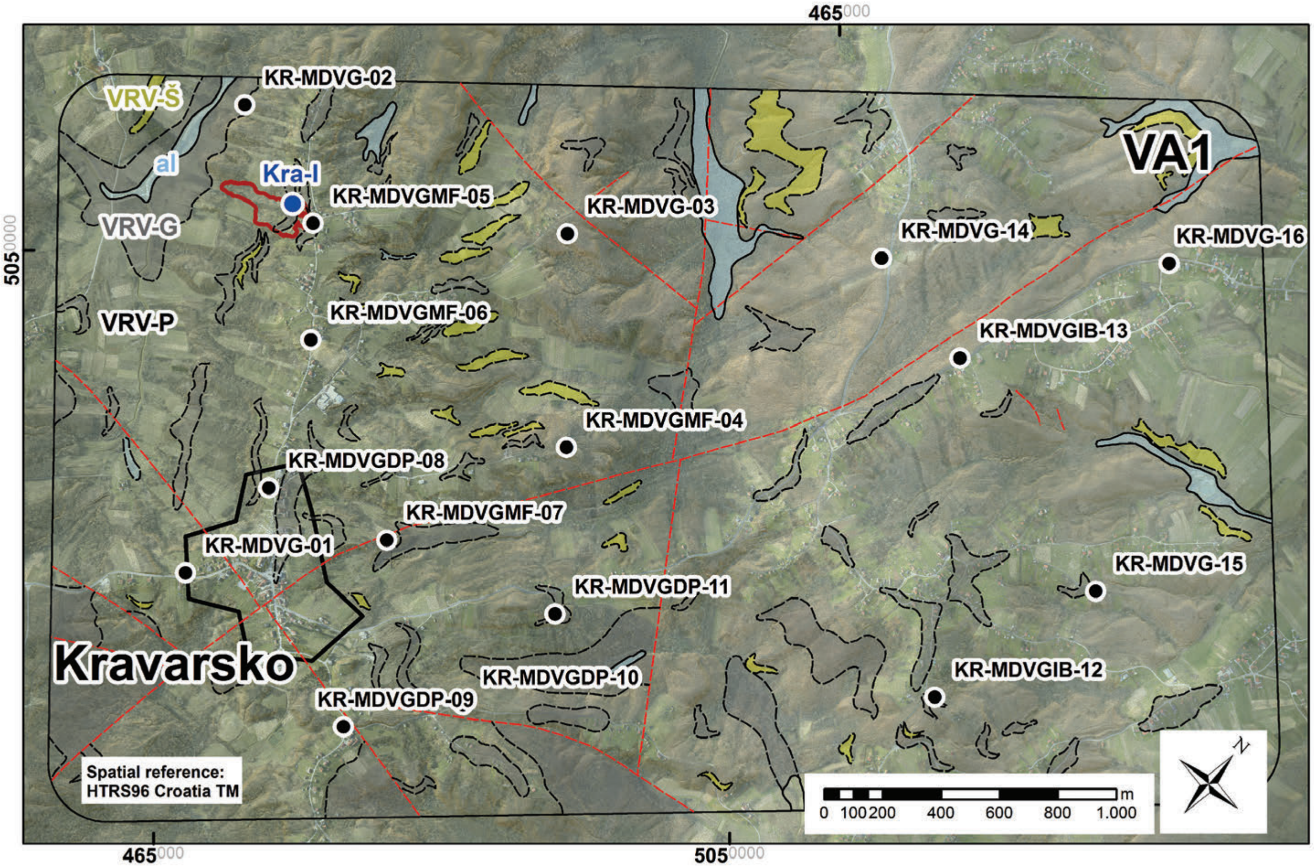

Figure 6. VA1 area. Mapped units indicated by colours: alluvial sediments (al-blue), sands with silts (VRV-P-no colour/orthophoto background), clays with silts (VRV-G-grey) and sands with gravels (VRV-Š-yellow). Locations of shallow boreholes shown by black points (HGI-CGS field data from 2019) and sedimentary log Kra-I by blue point (KUREČIĆ, 2017). The red polygon marks the location of the type example landslide – LsMVKS. The black polygon marks the Kravarsko settlement and interpreted faults are marked with red dashed lines.

3. A sedimentary log has been developed for this location - Kra-I (Fig. 7).
4. Field mapping of the landslide has been completed in the period of 2014-2019 (Fig. 8).
5. A shallow borehole was drilled (KR-MDVGMF-05, shortened to KR-05) on this location (Figs. 6, 7).

The shallow borehole KR-05 (Fig. 7) has the following composition: humus (0-15 cm); brown to grey clay and silt with roots and moisture content (15-65 cm); brown to grey clay and silt with sand in the upper part of the horizon and with debris in the lower part of the horizon (65-225 cm); and grey clay with silt (225-250 cm). The borehole location is by the road on the upper part of the slope, this is above the main scarp of the landslide, on the undisturbed part of the slope (Fig. 8). Generally the borehole is in "clayish" materials and is representative of the VRV-G unit (clays with silts), also described as facies of clayey silt (see the following section 2.2.2.).

2.2.2. Sedimentary log development

The Sedimentary log Kravarsko – Kra-I (Fig. 7) was logged within the area of active landsliding, at the northern end of the LsMVKS. Sedimentary log development was based on the recording of all lithological changes by measuring "layer by layer", whereby all layers and packages of layers with similar lithological characteristics were measured and isolated. Samples for granulometric analysis were taken at each lithological change, and carbonate content analysis was performed at 0.2 m and 1.8 m from the base of the log. The lower sequence of sediments consists mostly of grey clayey silts and clays at the base of the log with a total carbonate content below 12%, this is described as a clayey silt facies. Within that package there are visible discontinuities marked by minor granulometric differences and changes in colour. The upper part of this sequence consists of grey clay. In the central part of the log a 25 cm thick package of medium-grained brown sand interbedded with grey clay occurs. It is described as a heterolithic facies. The upper boundary of the heterolithic package is marked by a limonite crust up to 0.5 cm thick. At the top of the Kra-I log is a 180 cm thick package of clayey silt with limonite crusts occurring in the middle part of this interval, it is also described as a clayey silt facies. The top of this sequence is pedogenetically altered. Carbonate content in the lower 180 cm of the column is below 20%. Both hetherolithic and clayey silt facies are widely widespread in the Pliocene sediments of surrounding area (KUREČIĆ, 2017).

3. ANALYSIS AND RESULTS

For PA1/VA1 a combination of approaches were applied: (i) available remote sensing data was analysed in the context of geohazards i.e. landslides; (ii) geomorphological (landslide) features were identified (on digital elevation models and field) and a landslide inventory was developed; (iii) available and new geological data was analysed with a field data collection (mapping and drilling of shallow boreholes) and with field landslide inspection and verification of the developed landslide inventory for chosen sites/locations; and (iv) a simplified typical landslide model for the area was developed based on the LsMVKS landslide.

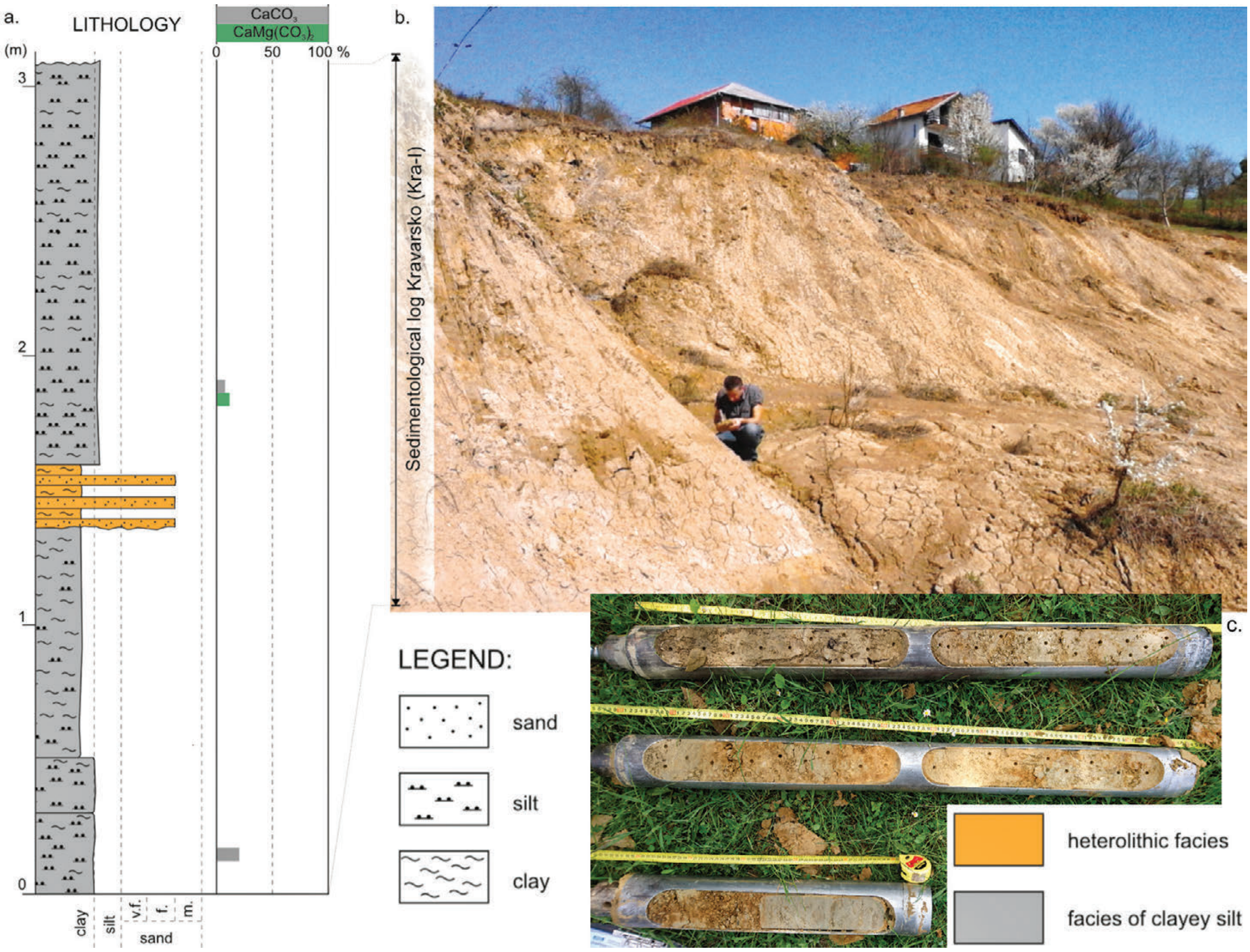

Figure 7. Sedimentary log at LsMVKS: a) Sedimentary log Kravarsko (Kra-I) within the landslide (modified after KUREČIĆ, 2017; MANDIC et al., 2015); b) Panoramic photo of the main scarp of the landslide from 2014 with indicated position of log Kra-I (KUREČIĆ, 2017); c) KR-05 shallow borehole core sample with visible locations of field pocket penetrometer tests (HGI-CGS field data from 2019).

3.1. Comparison of remote landslide mapping techniques

Sentinel 2 satellite images do not have adequate spatial resolution to identify the size of landslides found in PA1. Historical aerial photos from 1977, at 1:26,000 scale can be used to identify landslide prone slopes by the convergence of evidence, for example the main scarp can be visible, as can deformations in the landslide body and "damages" in vegetation (PAINE & KISSER 2012). It is also possible to map some landslides on these slopes using stereo pairs from 1977. However, given the geology, geomorphology and visible landslide features in PA1 the ideal scale of the photos for reliable landslide inventory development would be 1:10,000 scale or better (PODOLSZKI, 2014). The 1:2,500 scale stereo pairs from 2018 therefore allow detailed features such as cracks in landslide bodies to be mapped (Fig. 4).

Orthophotos from the National geodetic administration of Croatia have proven to be a very good landslide data source to constrain the temporal evolution of landslides. In some cases even the development of landslides can be observed on these orthophotos, for example the LsMVKS landslide (Fig. 4). From these orthophotos the following was concluded: (i) on the 2011 orthophotos (same inspected slope as on the stereo pairs from 1977) potential landslide locations can be depicted based on the cracks in grass areas or cultivated areas; (ii) on the 2014 orthophotos a "newly" formed active landslide is visible on the area where the 2011 cracks were developed and on the neighbouring area; (iii) on the 2018 orthophotos the landslide is still visible and has retrogressed up-hill.

For accurate and dependable landslide inventory creation based on remote sensing data, airborne LIDAR scanning data and derived high resolution DEMs (0.5x0.5 m pixel size) in combination with detailed orthophotos (10x10 cm pixel size) proved to be optimal: Fig. 8 shows the expression of a typical landslide (LsMVKS) in this area in the LIDAR DTMh and orthophoto – landslides features can be identified and mapped with high confidence. A short comparison of remote sensing data used for landslide mapping and data analysed for the Kravarsko area with its applicability is presented in Table 2.

3.2. Landslides in relation to geomorphological indicators

From the high resolution DEMs a landslide inventory was developed for PA1 with 1,430 remotely mapped landslides representing a total area of landslides of 6.5 km^2 (10.5 %) out of the total 61.7 km^2 area. In the VA1 area 446 landslides were remotely mapped with a total area of 1.6 km^2 (15.5 %) out of the total 10.3 km^2 area and also for VA1 field verification of the developed landslide inventory was carried out with geological and landslide field

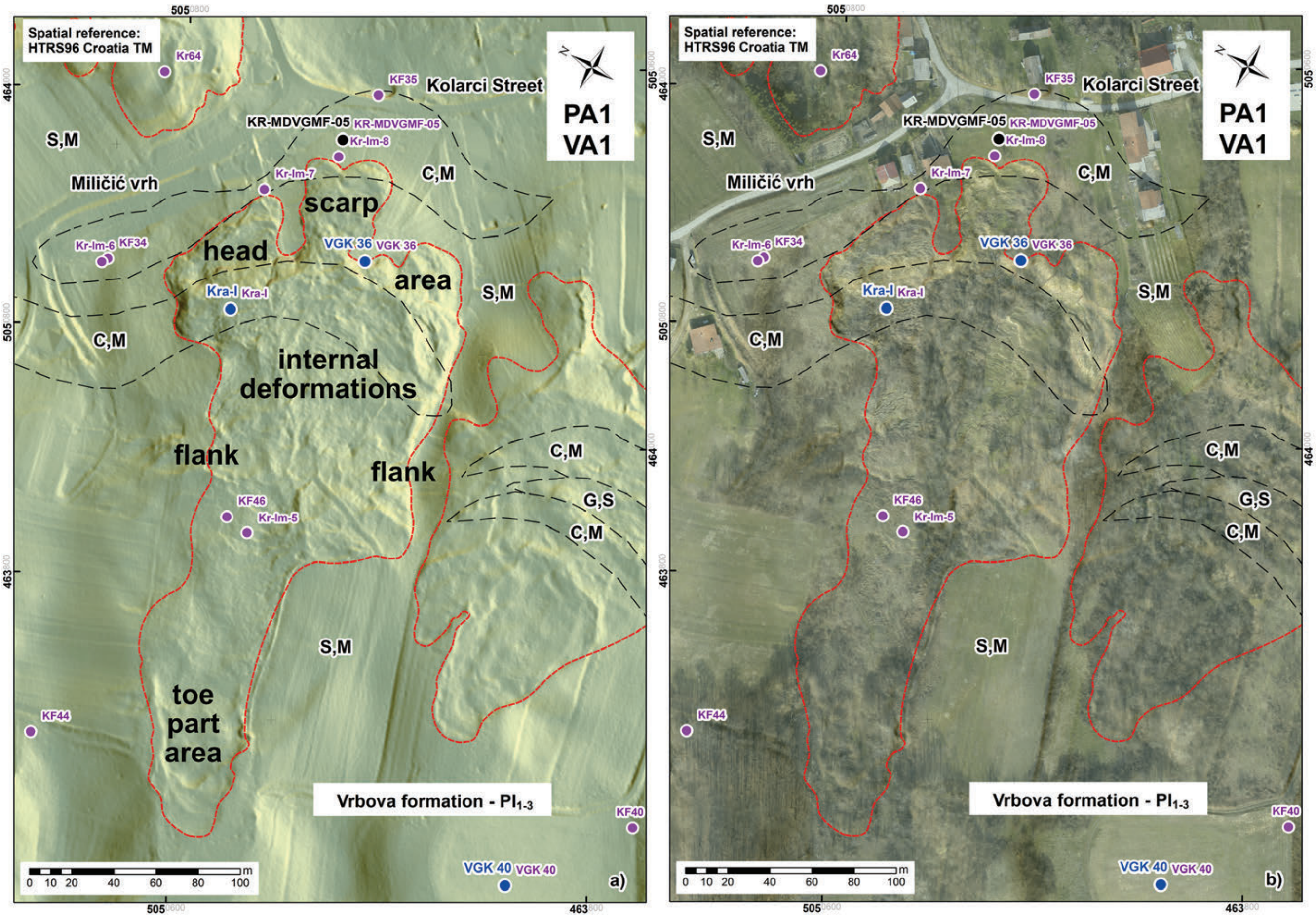

Figure 8. Overlapping different data sets for the LsMVKS landslide: a) hillshade of the LIDAR Digital Terrain Model as a base background with marked elements for CoLSI scoring system; b) orthophoto from 2018 as a base background. Mapped units from the geological map at a scale of 1:5,000: sands with silts (S,M; VRV-P), clays with silts (C,M; VRV-G), gravels with sands (G,S; VRV-Š), locations of field observation points, sedimentary log location (Kra-I) and shallow borehole location (KR-05).

Table 2. Comparison of remote sensing data used for landslide mapping and analysed data for the Kravarsko area (PA1/VA1).

Remote sensing data for landslide mapping and analysed data for Kravarsko area (PA1/VA1): 1-not applicable; 2-somewhat applicable; 3-applicable and recommended									
Data type: Remote sensing images					Data type: airborne LIDAR scan (2018) and developed digital elevation models				
Satellite images	Orthophotos (NGA-DGU, safEarth)		Stereo pairs (HGI, safEarth)		DEMs*: digital surface, terrain and hillshade model (0.5x0.5 m)			LIDAR based and developed contour map and slope map	
Sentinel 2; 10 m pixel size	2011; 2014-16; 2017-18	2018; 10x10 cm	1977; 1:26,000	2018; 1:2,500	DSM	DTM	DTMh	Contour map (1 m)	Slope map (1°)
1	2	3	2	3	2	3	3	3	3

* Digital surface model (DSM) is useful for interpretations in vegetation changes and for identifying anthropogenic objects. Digital terrain model (DTM) is useful for "bare-earth" geomorphology interpretation and for identifying landslide features in general. On digital terrain model hillshade (DTMh) the sun azimuth and altitude angels can be varied and that may assist the analyst to visualize landslide deposits, cracks and other deformations with higher confidence.

mapping. Data about the Confidence of LandSlide Identification (CoLSI, see also section 2.1.2), landslide numbers and landslide areas are shown in Table 3. In Table 4 the range of landslide areas and the percentage of the total area covered by landslides is shown.

Landslides with a low confidence level (low score, 1-3) are still regarded as landslide areas and generally they can be considered as old extinct or dormant landslides where the morphological features have degraded. Landslides with medium confidence levels (medium score, 4-7) can be considered as dormant landslides (old dormant landslides, medium score, 4-5 and young dormant landslides, medium score, 6-7). Landslides with high confidence levels (high score, 8-10) can be considered as active landslides. The landslide activity in relation to landslide relative age classification is based on MCCALPIN (1984) while the landslide scoring system is based on SLAUGHTER et al. (2017). The CoLSI number/score can be considered as an indicator of relative landslide age. Still "new and active" landslides are much easier to identify on remote sensing data (for example high resolution DEMs) and while with available (remote sensing) data the confidence of the landslide identification can be defined, assessment of the relative landslide age is much harder/more uncertain.

The small difference in percentage of landslide classes (1-10, both for number of landslides and for landslide areas) for PA1 and

VA1 indirectly indicate that the mapping criteria for the whole area was the same during landslide inventory development. Generally, the areas covered by landslides are smaller as the CoLSI is higher due to the used mapping criteria: the low and middle classes of CoLSI also include larger areas of mapped soil creeps (long lasting shallow and slow movements). Due to the nature of its movement soil creep boundaries or features are harder to map with a high level of confidence. Higher percentages of landslide areas for VA1 (15.5 %) than for PA1 (10.5 %) is to be expected due to the local geological conditions on VA1 (Fig. 3) i.e. the area is more prone to landsliding.

3.3. Landslides in relation to site specific conditions

According to the 1:100,000 Basic geological map (PIKIJA, 1987a) the typical sediments in PA1/VA1 area are Pliocene sands, gravels, clays and sandstones (see section 1). Generally, the landslides in this area occur in this chronostratigraphic unit, but local conditions can vary, for example sand layers can be interbedded with clay layers or different variations and mixtures can locally be present: sands with clays, sands with gravels, clays with silt, silt with clays and sands or sandstones. Following lithostratigraphic and engineering geological field mapping two relevant observations were made:

1. in the Kravarsko area (VA1) there are multiple locations where the rhythmic exchange of sand/clay/sand layers is generating small springs at the contacts of permeable coarser grained layers and non-permeable clayey layers and these local geological conditions can precondition landslides;
2. also in multiple cases slopes appear to be in a state of stability, however human activity (usually at the top of the slopes) in the form of inadequate drainage and sewerage systems or slope loading and road cuts can serve as anthropogenic preconditions or even in some cases as landslide triggers, (when disturbance by human activities initiate landslides).

These field observations lead us to conclude that for the wider Kravarsko area (PA1/VA1) the important landslide preconditioning factors are:

1. material ratios (clays: silts: sands: gravels),
2. water content and
3. anthropogenic influence (settlements, roads, drainage and sewerage networks).

When "unfavourable" change occurs in landslide preconditioning factors landslides can be initiated. Most often landslides are triggered by rainfall, snowmelt, changes in water level, stream erosion, changes in ground water, earthquakes, disturbance by human activities, or any combination of these factors. The landslide preconditioning factors and triggering factors are site specific for landslide locations in Kravarsko area but usually it is a combination of natural conditions and anthropogenic influence.

Nearby, in the LsMVKS area there are numerous field points investigated during the geological mapping within the safEarth project and also during previous detailed research which revealed how there are dynamic changes in the lithology of the Kravarsko area. For example, points VGK 36 and VGK 40 (KUREČIĆ, 2017, Fig. 8) close to Kra-I sedimentological column show sandy silt rich with micas and fossil remains of mollusc macro fauna (VGK 36), and sand interbedded with sandy silt and grey clayey silt (VGK 40). The general impression is that it is a change of lenticular sedimentary bodies as shown on the geological map (Fig. 6). It is therefore important to point out that the sediments (material ratios) can change often locally, both laterally and vertically.

Table 3. Landslide inventory data comparison for PA1 and VA1: classes, number and areas.

CoLSI (score)	PA1 No. of LS	PA1 % of LS	VA1 No. of LS	VA1 % of LS	PA1 LS area (km^2)	PA1 % of LS area	VA1 LS area (km^2)	VA1 % of LS area
1 (low)	111	7.8	37	8.3	0.91	14.0	0.23	14.3
2 (low)	253	17.7	76	17.0	0.93	14.3	0.28	17.4
3 (low)	231	16.2	74	16.6	1.39	21.4	0.22	13.7
4 (middle)	198	13.8	61	13.7	0.89	13.7	0.26	16.1
5 (middle)	151	10.6	40	9.0	0.72	11.1	0.08	5.0
6 (middle)	166	11.6	47	10.5	0.66	10.1	0.10	6.2
7 (middle)	133	9.3	44	9.9	0.55	8.4	0.27	16.8
8 (high)	110	7.7	35	7.8	0.26	4.0	0.07	4.3
9 (high)	55	3.8	24	5.4	0.17	2.6	0.09	5.6
10 (high)	22	1.5	8	1.8	0.03	0.5	0.01	0.6
Sum(s)	1,430	100	446	100	6.51	100	1.61	100

Table 4. Landslide areas range and percentage of area covered by landslides for PA1 and VA1.

LS areas range and percentages	Smallest (m^2)	Largest (m^2)	Sum (km^2)	% of ls area*
PA1 (1,430 landslides)	20	178,000	6.5	10.5
VA1 (446 landslides)	25	130,000	1.6	15.5

* The 5 % difference of landslide area is expected as PA1 has more area covered with less landslide prone Quaternary loess sediments than VA1. Also the overall percentage of landslide area is also in accordance with expected, based on previous knowledge and engineering judgement (expected range 10-20 %).

Table 5 Overview of mapped units on VA1 area

Research area VA1	Vrbova fm. (Pl_{1-3})			Alluvial sediments (Q_2)
Mapped ≈ 10 km^2 (100%)	VRV-P sands ≈ 8.5 km^2 (85%)	VRV-G clays ≈ 1.1 km^2 (11%)	VRV-Š gravels ≈ 0.2 km^2 (2%)	al - gravels, sands, silts ≈ 0.2 km^2 (2%)

Table 6. VA1 area landslide analysis: areas, percentages and Confidence of LandSlide Identification (CoLSI) for mapped units.

VA1 area LS	LS Area km^2	LS Area %	LS No.	LS No. %	CoLSI 1-3	CoLSI 1-3 %	CoLSI 4-7	CoLSI 4-7 %	CoLSI 8-10	CoLSI 8-10 %	Sum(s)
Sands (silts)	1.335	83.2	305	68.4	129	42.3	132	43.3	44	14.5	305 *100*
Clays (silts)	0.236	14.7	94	21.1	35	37.2	39	41.5	20	21.3	94 *100*
Gravels (sands)	0.032	2.0	34	7.6	18	52.9	14	41.2	2	5.9	34 *100*
Alluvial (mixture)	0.002	0.1	13	2.9	5	38.5	7	53.8	1	7.7	13 *100*
Sum(s)	1.605	100	446	100	187	-	192	-	67	-	446

All the described characteristics of the investigated sediments around Kravarsko, and especially the heterogeneity of the lithological composition with frequent lenticular changes, are in accordance with the characteristics of the Vrbova fm.

In most of the VA1 area "sandy" layers were mapped (~85%) but "clayish" layers are also present in significant parts (~11%). This raised the question of whether the landslide inventory could be correlated with clays i.e. permeable/non-permeable contacts based on available data for VA1 area? Landslides data analysis is shown in Table 6.

The majority of the mapped landslide areas in VA1 are in sands (~83%) and the majority of the mapped landslides (number) are in sands (~68%). In clays there are ~15% of mapped landslide areas and ~21% of the mapped landslides (number). Landslides in gravels are (generally) relatively smaller and "local" with "not significant" landslides areas (~2%) and they are relatively rare with only ~8% of the mapped landslides (number). Landslides in alluvial materials are small and local with "disregarding" landslides areas (~0.1%) and they are rare and local (stream shores) with only ~3% of the mapped landslides (number).

The landslides in sands and clays (or their mixtures) are significant for this area and for the Vrbova fm. The ratios of mapped landslides in sands and clay in comparison to CoLSI simplified classes (low, medium, high) are similar *(~37-42%: ~42-43%: ~15-21% i.e. 40: 40: 20).* The highest percentage of high scoring landslides are in clays *(~21%)* which is indicative of this lithology being important in landslide development but other than that the developed landslide inventory and analysed data show no real correlation regarding permeable/non-permeable mapped contacts. One explanation could be that the clay (inter bedding) layers are thin and vary through depth and spatial location i.e. it is hard to map the contacts in the field even though more than 650 field points were noted for VA1. Within those 650 field points also more than 230 locations of field landslide inventory checks were performed in the VA1 area and the field impression is that the typical landslide in this area is associated with clay.

The field research was mainly oriented to the verification of the developed "remote" landslide inventory. Numerous landslide locations were field validated and the main conclusions are listed below:

- Landslides are easier and much quicker to map on a detailed DEM than in the field due to vegetation cover (bushes), field configuration (gullies) and anthropogenic factors (fences).
- Soil creeps and their extents are extremely difficult to map in the field. General areas of long lasting shallow and slow movements can be estimated in the field and can be mapped based on convergence of evidence (undulating slope, tilted elements on slope, minor damages, etc.) but a detailed DEM is generally better for mapping the extent of these.
- The landslides mapped with low Confidence of LandSlide Identification (CoLSI) on DEMs are sometimes hard to map in the field, in some cases landslide features can't be seen in the field (usually old dormant landslides covered with vegetation).
- The landslides mapped with medium or high Confidence of landslide identification (CoLSI) on DEMs are identifiable in the field, but the general impression is that the landslides look "fresher and more recent" on DEMs than is actually the case in the field. In some cases the high confidence scoring landslides with clearly visible features on the DEMs are estimated to be more than 10 years old, or even more (corroborated by field verification, surrounding artificial objects, age and damages on them and orthophotos).
- For the high scoring (active) landslides, the "traces" of activity are mostly easily recognisable in the field (head scarp area, cracks, areas of deformation, fresh collapses without vegetation, damages, etc.) and usually (almost as a rule) also clearly visible on detailed orthophotos. The detailed orthophotos (multiple generations) can also be used on a case by case basis to indirectly determine the hazard posed to structures (houses, objects, roads, etc.) or at least to assess endangerment.
- The overall conclusion of the research team was that the detailed DEMs are more than adequate for the development of reliable landslide inventories but field checks are still necessary for "landslide scoring system calibration", as every area has its specific set of natural and man-made conditions which has to be taken into account.

The analysis of anthropogenic influence for the Kravarasko pilot area (PA1/VA1) was undertaken based on available data i.e. local management digital data acquired within safEarth project as shp files (Tables 7, 8): settlement areas (polygons), roads (lines), water systems (lines) and power lines (lines).

In PA1 and VA1 ~10% of the area is built upon. Also ~10% of the mapped landslide areas in VA1 are within that built area. There is ~142 km of linear structural elements in the PA1 area and ~41 km of linear structural elements in the VA1 area (roads, water systems, power lines). Roughly ~13% of the built area in VA1 is endangered by landslides and ~10% of the linear structural elements in VA1 area are endangered by landslides (Table 7). This is only an estimation based on available data but it still provides planning numbers for the local community: around 10-15% of urban structures are directly endangered in this area (VA1). This estimation is in accordance with field observations but with "lower and conservative" estimated field values.

Table 7. Anthropogenic influence – settlements, roads, water system and power lines network analysis, with landslide areas and percentages influencing the artificial structures.

Anthropogenic structures	PA1 area ~60 km^2	VA1 area ~10 km^2	LS VA1 area ~1.6 km^2	Endangered by LS on VA1 area
Settlements (km^2)	5.7 (9.5%)	1.1 (11%)	0.14 (8.8%)	12.7 %
Roads (km′)	85.4	24.6	1.99	8.1 %
Water systems (km′)	34.7	7.3	0.51	7.0 %
Power lines (km′)	21.7	8.6	1.56	18.1 %

Table 8. Wider area anthropogenic influence – settlements with 500 m buffer influence analysis; roads, water system and power lines networks with 100 m buffer analysis, with landslide areas, numbers and percentages influencing the artificial structures.

Anthropogenic structures	PA1 ~60 km^2	VA1 ~10 km^2	LS VA1 area ~1.6 km^2	Endangered by LS on VA1 area	Number of LS on structure area buffer
Settlements with 500 m buffer (km^2)	37.8	6.3	1.17	18.6 %	309
Roads with 100 m buffer (km^2)	10.1	2.5	0.34	13.6 %	113
Water systems with 100 m buffer (km^2)	7.0	1.4	0.16	22.4 %	57
Power lines with 100 m buffer (km^2)	3.6	1.4	0.27	19.3 %	75
*Total number of LS is 446 for VA1 area. LS No. of 554 is higher than 446 due to analysis type undertaken i.e. 1 LS can endanger more structures, for example house, road and power line, but every structure type was evaluated separately.					Σ=554*

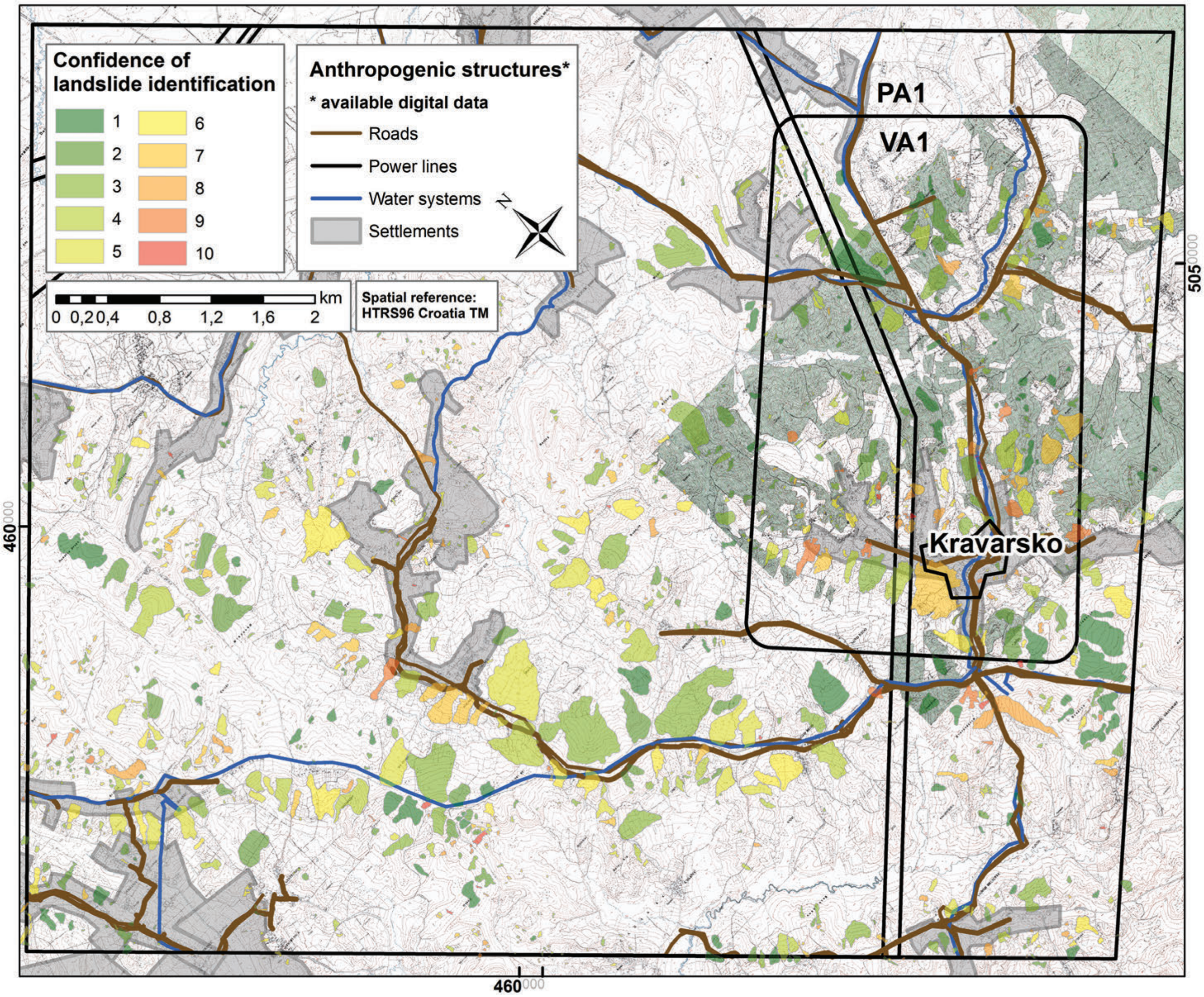

Figure 9. Overview map of developed landslide inventory with CoLSI and anthropogenic structures (according to available digital data): roads, power lines, water systems and settlements.

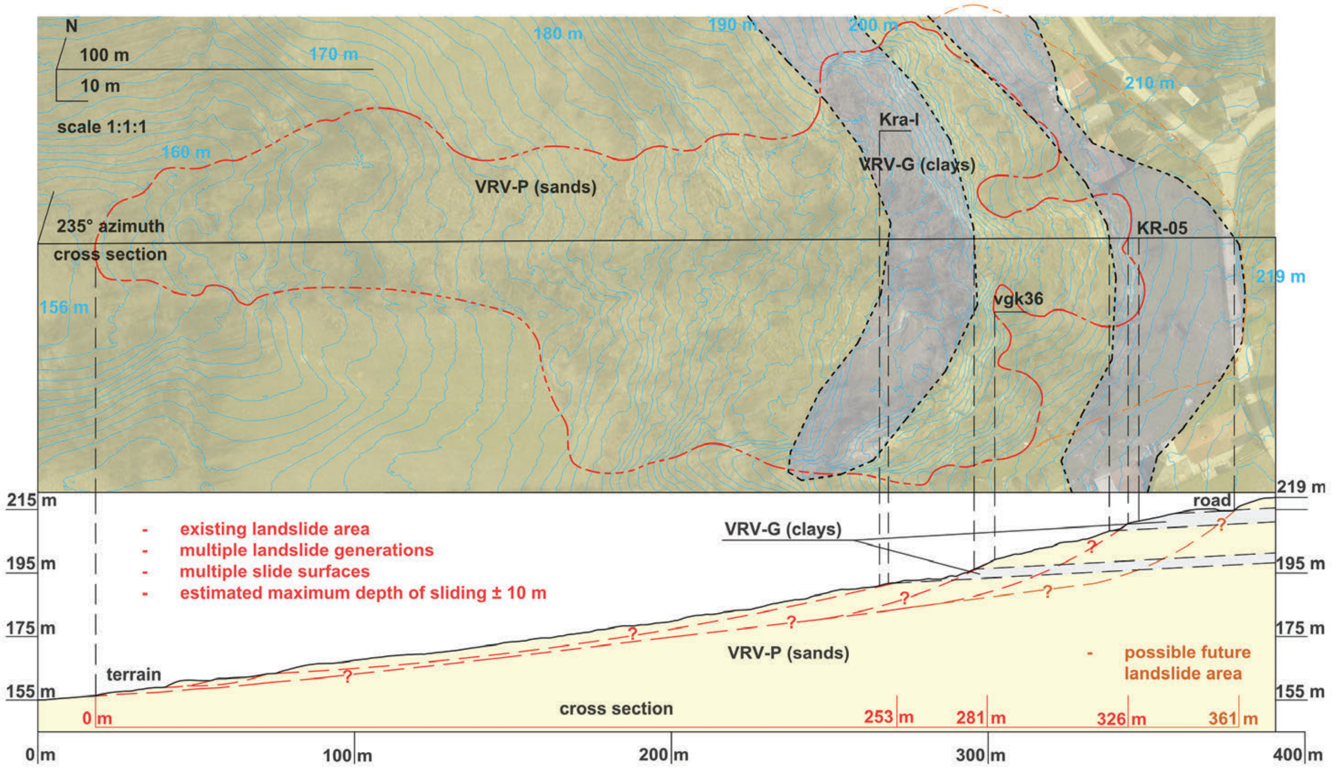

Figure 10. Idealized and simplified LsMVKS landslide cross section: existing and interpreted movement features (red lines) with possible new movement prediction (yellow lines) with 1 m contour lines (blue lines).

It is important to understand that in the VA1 area: (i) the local houses don't have a built sewerage network. Therefore, they usually let the sewerage drain down-slope a couple of metres (variable) away from the houses; (ii) the majority of the local roads don't have drainage systems; (iii) the existing water systems locally can be permeable; and (iv) the existing cuts for power lines locally can be unstable. Because of these reasons, analysis for anthropogenic structures with implemented buffers was performed (Table 8). The buffers applied were: a 500 m buffer to settlements and a 100 m buffer was applied to roads, water system and power lines networks.

Endangered areas values/percentages are, of course, somewhat higher when analysis with buffered areas are considered. Roughly ~19% of the built area in VA1 is endangered by landslides and ~15% of the linear structural elements areas in VA1 area is endangered by landslides (Table 8) i.e. around 15-20% of urban structures are endangered in this area (VA1). This estimation is in accordance with field observations but is in line with the "high-end" estimated field values.

For VA1 these values (~10-15% built area and structural elements directly endangered and ~15-20% built area and structural elements areas proximally endangered) seem to be realistic (according to past data, experience, field observation and assessment based on the buffers applied i.e. undertaken analysis). Also this type of simple analysis gives the local community the opportunity to sort out the "relevant" landslides from "irrelevant" landslides i.e. for them the relevant landslides are those which are endangering local houses, roads, water systems and power lines (Fig. 9). The landslides "in the woods" are not important from this view point.

The importance of scale must be kept in mind as it determines the applicability of developed data/maps (FELL et. al., 2008). Lack of basic landslide information (i.e. the extent of landslide phenomena in an area) undermines the possibility to develop quality landslide zoning maps (VAN WESTEN et al., 2008), as landslide inventory maps are only the first but a very needed step toward development of quality landslide susceptibility, hazard and risk maps (GUZZETTI et al., 2012). Still, the developed landslide inventory for PA1/VA1 could be used for the purpose of local urban planning/development and endangerment assessment/evaluation as a first "step" data and base line for further landslide zoning analysis (Fig. 9), as some authors have already suggested (LOPARIĆ & PAHERNIK, 2011).

3.4. Simplified landslide model

The LsMVKS landslide could be considered as a type example for landslides in this area (see also section 2.2.1): based on available data and field mapping. The bedding is horizontal or near horizontal (up to 5°, with slight dipslope). The sandy layers are interbedded with thinner clay layers (with variable thickness, often in range of 1-5 m) which serve as a barrier to water flow and at contacts water seepage and multiple small springs were noted in the field. The trend of the movement development is retrogressive with multiple generations of sliding. A simplified cross section with field mapping data, KR-05 shallow borehole and sedimentary log Kra-I is shown in Fig. 10 for the LsMVKS. Even though the landslide is relatively long (~400 m) the estimated deepest sliding surface is relatively shallow (~10 m). The estimation is based on head scarp height, landslide body morphology, terrain geomorphology and experiences with other landslides in the area. Sliding is interpreted as complex with multiple generations of sliding and multiple sliding surfaces: on the lower part of the slope the movements are interpreted as almost creep to translational movements ("along bedding") in weathered zone materials, while on the upper part of the slope, above the clay layer, the movements are interpreted as progressions of rotational sliding (at the contact of permeable/non-permeable layers). If the observed and interpreted movement features are applied to the cross section with the same geological and engineering judgement, a possible new up-hill movement prediction can be assumed and even the road on the top of the hill can be endangered. Of course the heterogeneity of geological/lithological units i.e. locally changes in material ratios in the Vrbova fm. are the source of the uncertainty in this movement estimation together with coexisting anthropogenic factors which still need to be quantified more precisely. For reliable estimation much more data is needed (for example borehole data from landslide body and water content data) but still the general trends can be assumed even from this available data level.

The following observations are thought to be general for active landslides in the area:

- on the site there are (usually) a combination of sand (with silt) layers interbedded with clay (and silt) layers,
- on the contacts of these layers water can be present, observed as seepage and small springs and these are the critical locations for new movements,
- the sliding areas are relatively large but relatively shallow and the movement is retrogressive, developing up-hill,
- multiple generations of sliding and sliding surfaces are present as a result of long term (several decades) seasonal activity cycles (snowmelt/rainfall/sliding/erosion) on the slopes,
- on the upper part of the slope un-favourable anthropogenic activity is (usually) present: road cuts with no drainage, extra loads from objects and in-adequate water and sewer drainages/networks,
- the landslide activity varies (through time) due to natural and man-made conditions.

4. CONCLUSIONS

For the Kravarsko pilot area (PA1) previously published landslide data is relatively sparse. The main aim of the research was to produce a high quality landslide inventory based on the review of geological data and mapping in remotely sensed areas. For the subarea VA1 field mapping and verification of the developed landslide inventory was undertaken. Based on existing and new data a typical simplified landslide model for the area was developed.

The landslides in the research area are mainly found in one informal lithostrathigraphic unit (Vrbova fm.). This formation is characterised by Pliocene sands, gravels, clays, conglomerates and sandstones, however the ratios of clay vs. silt vs. sand vs. gravel are site specific and are highly variable both laterally and vertically. Sliding seems to be predominantly in sands but associated with clay intervals. The sliding is often complex with multiple generations of sliding and multiple sliding surfaces as a result of long term (several decades) seasonal activity cycles (snowmelt/rainfall/sliding/erosion) on the slopes. It is the site specific combinations of such material (sand/clay/sand) and human activities (cuts, loads and in-adequate water and sewer drainages/networks on slopes) which can trigger landsliding. Based on undertaken analysis and available field data around 10-20% of urban structures are endangered in this area. As a first step mitigation method establishing drainage/sewage systems is suggested to the local stakeholders. The developed landslide inventory for PA1/VA1 could be used for local urban planning/development and endangerment assessment/evaluation.

The following has been achieved for PA1/VA1:

- Remote sensing data analysis was performed. Available historical photos (stereo pairs, orthophotos) and new data (stereo pairs, orthophotos, LIDAR data) were analysed and compared. For a typical landslide (LsMVKS) the temporal evolution of the landslide was constrained (mainly) based on remote sensing data.
- A rating of available remotely sensed data for its suitability for landslide mapping has been established for the area. Recommendations have been made concerning the scale of imagery and resolution of derived DEMs.
- Analysis of geological data was performed. Available maps and relevant research results were taken into consideration. New detailed lithological geological mapping was undertaken and shallow boreholes were drilled for VA1 in order to sub-divide the lithology in the area into smaller units with different main characteristics resulting with new geological map at 1:5,000 scale.
- A landslide inventory was developed for the larger area (PA1) mainly based on mapping in the detailed DEMs (0.5x0.5 m pixel size). The remote mapping was mainly based on USGS recommendations (SLAUGHTER et al., 2017) and it can be repeated for any area which has similar data availability. Following field verification of the subarea (VA1) the developed landslide inventory proved to be precise (sub metre) and reliable. Some of the landslide areas and features are even more visible on the high resolution DEMs, especially for large landslides with dense vegetation, than in the field.
- A simplified typical landslide model for the area was developed based on the landslide at the Miličić Vrh and Kolarci Street intersection (see sections 2.1.1, 2.2.1 and 2.2.2). This LsMVKS landslide has a history of over 40 years with multiple phases of reactivation and stagnation and as the upper part of the slope is becoming more urbanized the landslide is developing up-hill, endangering the buildings and road on the hilltop.

What still needs to be done for PA1/VA1?

- During field mapping anthropogenic activity was determined as an important landslide influence factor. Still the question remains of how to quantify this influence?
- Also during field mapping it was apparent that on the contacts of permeable (sandy/silty) layers and non-permeable (clayish/silty) layers there are usually small springs or water seepage which in some cases can also be important landslide conditioning factors or landslide reactivation factors. Still the question remains of how to determine the spatial layout of these contacts and how to quantify them?

Future monitoring recommendations for PA1/VA1:

- Periodic LIDAR data acquisition and analysis – comparisons and changes through time could be analysed.
- With implementation of InSAR (Interferometric Synthetic Aperture Radar) monitoring of the area, the temporal evolution of landslides could be observed.
- Water content can also be an important landslide triggering or reactivation factor and the critical water content needs to be determined. The installation of rain gauges and pore water pressure monitoring on specific sites could prove useful for local community.

- Monitoring of deformations on specific landslide locations could enable an improvement to the simplified typical landslide model.

The presented research and approach could be applied for the wider hilly area where landslides are common but existing landslide data is scarce. The development of a reliable and accurate landslide inventory based on high resolution LIDAR data is possible for the wider (regional) area and the developed landslide inventories could be comparable if the same mapping criteria would be used. The suggested monitoring recommendations could also be applied to the wider area and could provide valuable data for landslide hazard research and to raise awareness and inform public and authorities i.e. stakeholders about landslide risk.

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