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ORIGINAL ARTICLE

Factors triggering landslide occurrence on the Zemun loess plateau, Belgrade area, Serbia

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Abstract

Among the numerous factors that trigger landslide events, the anthropogenic impact caused by inadequate planning and faulty land use in urban areas is increasing. The Zemun settlement on the northern outskirts of Belgrade has experienced a number of landslides in the last three decades, endangering buildings and roads, and claiming human lives, particularly in the case of the 2010/2011 landslides. Selected meteorological parameters were used to calculate rainfall erosivity indices such as Precipitation Concentration Index and Modified Fournier Index over the period 1991–2015. Drought indices, Lang aridity index and Palfai Drought Index were calculated as well. Mann–Kendall trend test was applied to identify potential rising and/or declining trends both in meteorological parameters and calculated indices. Trend analysis of the annual and seasonal scales yielded a statistically significant trend in the spring time series. Stable arid and pronounced drought conditions were recorded. The modified Fournier index based on monthly mean values yields moderate aggressiveness, with several extreme values indicating very high erosivity classes, especially for 2010/2011. The geological substrate is predominantly loess and hence highly susceptible to erosion and slope failure when climatological conditions are suitable. Accelerated urbanization at the end of the last century reduced vegetation cover, intensified pressure on the vertical loess slope, and lacked suitable rain drainage systems so that surface-water runoff was directed into the porous loess, thereby endangering slope stability. We proposed a geomorphic model to describe the nature of the erosional processes on the loess cliffs of the Zemun loess plateau. Results from this study have implications for mitigation strategies.

Keywords Rainfall erosivity · Aridity · Loess · Landslide · Hazard · Zemun loess plateau

Introduction

Natural hazards are generally described as sudden, disastrous events with high possibility to cause harm to various aspects of human life (e.g., Alcantara-Ayala 2002; Bryant 2005; UNISDR 2009; Keller and DeVecchio 2012; Lukić et al. 2013; Mlađan and Kekić 2007). Slope instability is one of the most widespread natural hazards; although it is not generally perceived as being as disastrous as other hazard types, it can have a profound impact on populated

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areas. Natural hazards are not always the result of natural environmental processes, but also result from the interaction between natural and anthropogenic systems. The highest death toll caused by landslides is recorded in urban areas (e.g., 500 people died and another 4,000,000 were affected by landslides in Rio de Janeiro in 1966) (Keller and DeVecchio 2012; Lukić et al. 2013, 2016).

In general, landslides can be regarded as one of the major geo-environmental issues and an important geomorphological feature affected by earth surface processes (Pourghasemi and Rahmati 2018). Natural hazards regarded to land instability can occur in various environments driven primarily by the disruption of slope equilibrium due to the force of gravity. Landslides are a complex phenomenon, comprised most diverse range of processes and factors than any other type of natural hazard. Landslide hazards generally tend to occur in two different types of material: bedrock or unconsolidated sediment. As pointed out by Zhuang and Peng (2014) and Zhuang et al. (2018), the initiation and development of landslides in thick loess terrains is quite peculiar in regard to the main characteristics and features of the given geological strata. Zhuang et al. (2018) indicated that more than 70% of the landslides at Chinese Loess Plateau are shallower than 10 m and have a volume of less than 100,000 m^3. Main contributing factors which lead to the mass movement encompass pore water pressure, steep topography, and thickness of the loess sediments. Secondary factors are regarded to the human activities on the loess plateaus such as cutting slopes, placing an overburden load on them, and pronounced irrigation (Zhuang et al. 2018).

The stratigraphical correlation between loess sections located in south-east Europe and China display many similarities. Most of those involve the palaeomagnetic records of the northern Serbian and central Chinese Loess Plateau (Vasiljević et al. 2014). Also, the records have a closer resemblance on multi-millennial timescales to each other than they do with the globally integrated marine records. Those are consequences of similar controls on deposition in these distant regions and the similar nature of magnetic susceptibility signal acquisition. Numerous loess-paleosol sequences preserved as plateaus in the Vojvodina region reflect a similar style of deposition to the Central Chinese Loess Plateau (Kukla and An 1989). Serbian loess-paleosol sequences have significantly smaller total thickness in contrast to Chinese loess, and thus the dimensions of the loess landforms are also proportionally smaller. Therefore, two distant loess records on the western and eastern sides of Eurasia provide a similar pattern of climatic and environmental changes probably controlled by global increases in ice volume, a progressive aridification initiated in the inner Asian continent, and regional sensitivity to moisture bearing systems (Marković et al. 2012). Hence, the characteristics of loess landslides on Chinese Loess Plateau could be applied to hazardous situations observed for Serbian loess. Therefore, landslides in Serbian loess are also seen as the result of slope instability, which depends on the balance between shear stress and shear resistance (Zêzere et al. 1999; Carson and Kirkby 1975).

Precipitation is one of the most important natural factors responsible for soil erosion in the landslide context (De Luis et al. 2009). The relationship between dry and wet periods is critical since soils with significant clay proportions experience shrinking and swelling under dry and wet periods, respectively. Anthropogenic alteration of the environment is mostly reflected in disruption of ground drainage and modification of vegetation cover (Bryant 2005), and is estimated to contribute to 20% of landslides worldwide (Zêzere et al. 1999). Thereby, Zhang and Liu (2010) pointed out that the geo-environmental conditions are considered as relatively stable, while the precipitation and human activities are subjected to the rapid and dynamical changes.

Although landslides may occur within a variety of geological materials (e.g., Bolt et al. 2013), here we focus on landslides in loess sediments, with an emphasis on the Zemun loess plateau on the northern outskirts of Belgrade in Serbia. Since, loess sediments usually overlay more clayey paleosols, they can be considered as unconsolidated; consolidation is delayed until the combined influence of load and moisture content facilitate particle slip and rearrangement, usually after chemical bonds within the soil minerals become weakened by moisture (Handy and Ferguson 1994). Structural collapse and sudden volume changes represent a major geotechnical issue, particularly in loess (Berisavljević et al. 2014). When moisture content is low, loess generally has sufficient shear strength to resist slope failure (Derbyshire et al. 1994; Gao 1988; Wang et al. 2011; Xu et al. 2013). Heavy and intense precipitation events can reduce loess stability, particularly following drought events. Loess dominates the investigated area, and not only records environmental change over long time scales but is also a particularly valuable agricultural soil, having played a substantial role in the geographic spread of agriculture throughout history (Smalley et al. 2009). The permanent settlements associated with agricultural societies have, therefore, also been developed in loess environments. According to the work of Zhang and Liu (2010), principal triggering factors for the instability of loess slopes result from a joint influence of human activities and precipitation events at the given area. For instance, studies performed on the Chinese Loess Plateau (upper reaches of the Yangtze River) show that about 94% of landslides are triggered by rainfall events and various water processes (e.g., Keqiang et al. 2010).

The Zemun loess plateau within the Danube basin, while preserving biological and cultural diversity (Marković et al. 2016), is also highly urbanized. Many examples report on slope instabilities in populated loess terrains induced by anthropogenic activities, ranging from small superficial landslides to heavy landslide events (e.g., Dijkstra et al. 1994, 1995; Dijkstra 2001; Kwong et al. 2004; Choi and Cheung 2013; Derbyshire et al. 2000; Derbyshire 2001). According to Michoud et al. (2012), the boundary changes between natural and anthropogenic landslide triggers should be considered as a consequence resulting from an increase in human activity. The Zemun loess plateau has experienced a number of landslides and other mass movements during the last decades, which have affected parts of the settlement and road infrastructure on the northern periphery of Belgrade. To improve engineering methods which can provide protection and useful mitigational approaches relating to these events, some case studies have been carried out by Serbian researchers (e.g., Lukić et al. 2016; Milošević et al. 2006, 2010; Berisavljević et al. 2014; Samardaković and Samardaković 2007; Šipetić and Kuzmić 2016).

The objective of this study of the Zemun area is to analyze the relationship between selected meteorological parameters, their trends, and temporal distribution in an environment susceptible to landslides due to the specific sedimentological and human land use characteristics. In doing so, we identify triggers relating to climate variability, geology, and human activity. Landslide hazard mitigation generally involves landslide mapping, control structures, warning systems, local, and regional planning (Gori et al. 2003). The approach that has shown to have the best results includes a combination of these strategies along with good coordination between the scientific, engineering, and planning communities. A potential solution for the landslide hazards in loess terrains lays in preparedness, requiring officials to introduce and conduct qualitative mitigation strategies by implementing a long-term cliff reinforcement programme near endangered human settlements. Examples of good practice are evident in the slopes recultivation worldwide (e.g., Abramson et al. 2002; Kwong et al. 2004; Choi and Cheung 2013; Lukić et al. 2016). Results from this study could facilitate the promotion of mitigation strategies and risk education, leading to vulnerability reduction and increased resilience.

Data and methods

Study area

The investigated area is situated on the Zemun loess plateau (44°50′27″N and 20°24′02″E), on the northwest periphery of Belgrade in northern Serbia. This area adjoins the larger Srem loess plateau which lies to the northwest and lies on the southwest bank of the Danube River and northwest of the Sava River (Fig. 1). The highest points of this loess plateau are Kapela (114 m.a.s.l.), Gornji grad (103 m.a.s.l.), Bežanija (114 m.a.s.l.) and Surčin (103 m.a.s.l.) (Šarić 2009).

The climate of this area is moderate continental, experiencing hot, humid summers (maximum average 23.1 °C), and cold winters (minimum average 1.1 °C). The mean annual temperature is 12.4 °C (Gavrilov et al. 2015, 2016), and mean annual precipitation is 630 mm, falling mostly in June (> 180 mm); minimum precipitation occurs in February (120–150 mm) (Tošić et al. 2014). According to the De Martonne aridity index, this corresponds to a semi-humid climate (Hrnjak et al. 2014).

There are many factors that influence the occurrence of landslides besides the precipitation factor (e.g., prevailing climatic conditions, soil type, vegetation cover, and slope). Loess is characterized with high cohesive strength when the moisture content is low. But when the moisture content increases the cohesive strength reduces significantly (Derbyshire et al. 1994). Furthermore, under the continuous shaking induced by earthquakes or human activities loess can liquefy due to its high silt content. It becomes unstable, collapsible, and could travel long distances causing long-term damage and loss of human lives (Zhang and Wang 2007; Wang et al. 2014). The highest precipitation amounts during the years 2009, 2010, and 2011 were recorded in May and June (more than 130 mm). Since loess has a very low permeability, the percolation of rain water is mainly through vertical joints on the top of loess slopes. The sink holes and open fissures that form due to the erosion along the joints allow a large amount of rain water to infiltrate. As the water meets a relatively impermeable bed, such as paleosol or bed rock, it accumulates on the bed, softens the soil, and induces landslides. However, the Palfai Drought Index indicates that for Surčin station, for the same period, the extremely drought conditions prevailed, but the extreme daily and monthly precipitation led to favorable landslide conditions. This environment along with the human activities enhanced the already pronounced dynamical processes along steep loess cliffs of the Zemun loess plateau.

The terrain in the Belgrade area consists of two complexes: silty Quaternary loess and alluvium overlying Tertiary clays and marls (Hadzi-Niković 2009). A thorough research regarding geological, engineering-geological and hydro-geological features of the Belgrade area have been performed by Šipetić and Kuzmić (2016) and Berisavljević et al. (2014). The respective authors distinguished construction conditions regarded to the natural soil characteristics and works required by urban development. According to these studies, Zemun loess plateau can be classified as area with unfavorable and exceptionally unfavorable urbanization conditions. Furthermore, these conditions can additionally contribute to development of landslides.

Hence, at the end of the twentieth century (70–80's), urban development intensified in and around Belgrade.

Fig. 1 Study site and landslide of the Zemun loess plateau (Source: ESRI)

Urbanization at Zemun began at this time. Most of the construction occurred on loess, presenting opportunities for increased slope instability and landslides (Milović and Djogo 2013; Berisavljević et al. 2014). The landslide event investigated here occurred in 2010 in the vicinity of the Zemun kindergarten and surrounding residences, on the edge of a natural loess cliff 9–12 m high and with an original slope angle of 70°–80° (Secretariat for child protection and Geological Institute of Belgrade 2011).

Meteorological factors

Monthly and annual values of temperature and precipitation were obtained for the Surčin meteorological station (44°49′N, 20°18′E and elevation of 96 m.a.s.l.) from the Republic Hydrometeorological Service of Serbia (http://www.hidmet.gov.rs) for the period 1991–2015. Meteorological observations are in accordance with World Meteorological Organization (WMO) standards. The time series of temperature and precipitation data for Surčin are homogenous according to the Alexandersson (1986) test.

The Precipitation Concentration Index (PCI) (Table 1a) characterizes rainfall variability through space and time (e.g., Apaydin et al. 2006; De Luis et al. 2009, 2011), and has previously been used to identify potential patterns of climatic interaction with geological substrate that may trigger landslide events (e.g., Lukić et al. 2016). It is also the basis for calculating the rainfall erosivity index, the Modified Fournier Index (MFI) (Table 1b), which has been used to analyze rainfall aggressiveness and its correlation with other climatic variables contributing to catastrophic erosion (e.g., Gabriels 2001; De Luis et al. 2010; Khorsandi et al. 2010; Mello et al. 2013; Lukić et al. 2016). Two aridity indices were calculated. First, the Lang (1915, 1920) aridity index (AI_{Lang}) compares mean annual precipitation (MAP, in mm) and mean annual temperature (MAT in °C) (Table 1c). This index is based on the hypothesis that warmer temperatures lead to soil and air dryness if there is not enough precipitation and/or groundwater recharge (Lang 1915, 1920). Second, the Palfai Drought Index (PaDI) (Table 1d) emphasizes monthly temperature and precipitation as more precise indicators of the evolution of drought (Pálfai and Herceg 2011).

Table 1 Meteorologically based parameters calculated for investigated area

Index	Equation	Classification		Literature overview
(a) PCI	PCI seasonal $= \frac{\Sigma_{i=1}^{3} p_i^2}{\left(\Sigma_{i=1}^{3} p_i\right)^2} \times 25$ Here, p_i is mean monthly precipitation in mm for month i	Uniform Moderate Irregular Strongly irregular	≤ 10 $> 10 \leq 15$ $> 15 \leq 20$ > 20	Oliver (1980) Michiels et al. (1992) Lujan and Gabriels (2005) Apaydin et al. (2006) De Luis et al. (2011) Lukić et al. (2016)
(b) MFI	$\mathrm{MFI} = \sum_{i=1}^{12} \frac{p^2}{P}$ Here, p is mean monthly rainfall amount, P is annual rainfall amount (all in mm) and i is mark for the month	Very low Moderate High Very high	0–60 60–90 90–120 120–160 > 160	De Luis et al. (2010) Khorsandi et al. (2010) Mello et al. (2013) Lukić et al. (2016) Bjelajac et al. (2016)
(c) $\mathrm{AI_{Lang}}$	$\mathrm{AI_{Lang}} = \frac{\mathrm{MAP}}{\mathrm{MAT}}$ Here, MAP is mean annual precipitation in mm and MAT is mean annual temperature in °C	Arid Humid Perhumid	< 40 40–160 > 160	Lang (1915, 1920) Lalić et al. (2002) Quan et al. (2013)
(d) PaDI	$\mathrm{PaDI} = \left[\sum_{i=\mathrm{apr}}^{\mathrm{Aug}} T_i/5 \times 100\right] \Big/ \sum_{i=\mathrm{Oct}}^{\mathrm{Sept}} P_i \times w_i$ Here, T_i is monthly average temperature in °C, P_i is monthly average precipitation in mm and w_i is weighting factor	Droughtless Mild Moderate Heavy Serious Very serious Extreme	< 4 4–6 6–8 8–10 10–15 15–30 > 30	Pálfai (2002) Pálfai and Herceg (2011), Blanka et al. (2013) Mezősi et al. (2014, 2016)

Rainfall erosivity indices were used because they represent not only the higher percentages of the annual total precipitation in a few very rainy days, but also the time and degree of concentration of the yearly total precipitation within a year. They have the potential to indicate and characterize possible floods, droughts and in this case wet mass movement events (Zhang and Qian 2003; Zhang et al. 2009). On the other hand, drought indices, especially PaDI (designed primarily for the Carpathian Basin climate conditions), were used to evaluate the relation of air temperature, precipitation, and possible groundwater conditions (Spinoni et al. 2013).

Established statistical approaches were applied to identify trends in the meteorological data. The Mann–Kendall (MK) non-parametric test was used to evaluate long-term trends of selected parameters (Mann 1945; Kendall 1976). The MK test compares the relative magnitudes of data rather than the data values themselves (Gilbert 1987), and are often used in the field of natural hazards (e.g., Basarin et al. 2016, 2017; Bačević et al. 2017; Gavrilov et al. 2010, 2013; Hrnjak et al. 2014; Lukić et al. 2016, 2017; Radaković et al. 2017). To prevent false positive results in the MK trend test (von Storch and Navarra 1995), the Yue-Pilon pre-whitening test (Yue et al. 2002) was applied. Finally, the identified trend and the modified residual series were combined, and then the MK test was applied (e.g., Basarin et al. 2016, 2017) using the *R* package ZYP (http://www.r-project.org).

Geological substrate

The Zemun plateau is typical geomorphic unit of northern Serbia since it is dominated by wind-blown dust (Fig. 2), or loess, a common facies in the mid-latitudes (Smalley et al. 2001, 2011). The formation of loess in the Danube basin is associated with glacial expansion and river transport during Pleistocene glacial phases (e.g., Marković et al. 2008, 2015). During warmer, more humid interglacial periods, loess accumulation decreases, and soil formation intensifies (buried soils are known as paleosols), resulting in interstratified loess-paleosol deposits (e.g., Kukla 1977; Pecsi 1990).

The Zemun lowlands between the Sava and the Danube Rivers lie at the southern end of the Srem loess plateau. The plateau sediments comprise five loess and four paleosol horizons. Several characteristics of the loess dictate the erosional processes affecting it. High porosity (30–50%) and carbonate content (10–35%) (Marković et al. 2004, 2005, 2006, 2007, 2008; Bokhorst et al. 2009; Lukić et al. 2009, 2016) results in high permeability and moisture absorption capacity (Leger 1990; Lukić et al. 2009, 2016). Porosity increases with clay content in loess paleosols, with the most porous being loess with an aggregate structure. Shear strength in loess decreases substantially under wetter conditions (Derbyshire et al. 1994; Gao 1988; Lin and Wang 1988; Xu et al. 2013; Lukić et al. 2016). Heavy and intense precipitation events affect loess stability by causing instantaneous disaggregation under its own weight (Derbyshire et al. 1995)

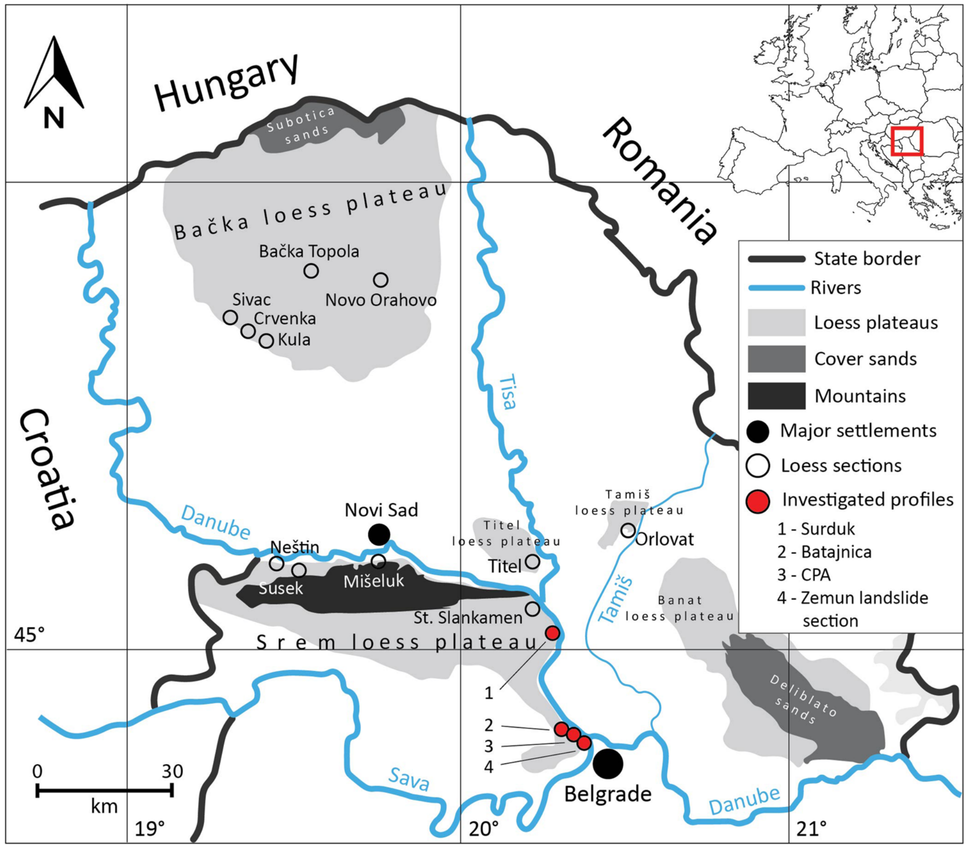

Fig. 2 Map of the Northern Serbia region with geographical position of the main loess sections (modified after Marković et al. 2004, 2014, 2015)

and leaching of finer particles, increasing packing density and facilitating mass flow. Hydrocompaction is an important cause of slope failure in loess (Derbyshire et al. 2000; Derbyshire 2001).

A permanent aeration zone at least 20-m-thick occurs at Zemun in the vicinity of the Danube River (110–114 m.a.s.l.). Loess above the groundwater table preserves a primary, loose structure characterized by spherical aggregates which increase porosity between grains and aggregates. The pores are capillary to super-capillary, vertically elongated and tubular. The dominant grain-size fraction (~70%) lies between 0.06 and 0.002 mm; the fraction > 0.06 mm increases with depth. For macroporous and paleoelluvial loess sediments it ranges between 10–20 and up to 90% for sandy loess soil. The < 0.002 mm fraction contributes 10–20% to the macroporous and paleoelluvial loess sediments. Pore space contributes 45–55% to the total loess volume; 22–32% of the total volume is water. Gravimetric water content varies between 15–18% and the degree of saturation varies from 45% for macroporous loess, to 55% for sandy loess and up to 80% for paleoelluvial loess soil (Hadzi-Niković 2009). The unit weight with natural water content varies between 16.0 and 19.0 kN/m^3. The sediments of the aeration zone are clayey with low plasticity, CL, with a liquid limit wl = 24–35%, a plastic limit wp = 13–20%, a plasticity index of Ip = 7–15% and a colloidal activity of Kp > 1.25. Deeper horizons are either sandier, more compressed with many concretions or have greater clay content (Hadzi-Niković 2009).

In this study, the authors used the pedostratigraphic and sedimentologic data for reference profiles of the Srem loess plateau [Surduk, Batajnica and Criminalistic Police Academy (CPA) exposure—Fig. 2] to aid interpretation of the morphological evolution of landslides in the Zemun area (Antoine et al. 2009; Marković et al. 2009; Gavrilović et al. submitted).

Results and discussion

Climatic parameters and trend analysis

Temperature and precipitation variability are important elements concerning the implications of erosion intensity in the investigated area. The regression analysis was used to estimate the tendencies of selected meteorological parameters as well as rainfall erosivity and drought indices. This approach was used so that the evolution of potential geomorphological agents could be estimated with potential implications for the future. The MK trend test indicates that there is an increase in mean annual values of air temperature, precipitation as well as rainfall erosivity indices and drought index with air temperature showing the statistically significant trend ($p < 0.05$). Only an aridity index exhibits declining trend which can also be observed on regression equations coefficients. Sen's slope estimator indicates that mean annual air temperature is rising 0.075 °C per year (0.073 °C according to the regression equation), while precipitation amounts were increasing by 3.959 mm per year (4.449 mm according to the regression equation) (Fig. 3a).

According to MK trend test no statistically significant trend is observed for PCI over the time series. PCI values are moderate and vary from < 9.7 (1996) to 14.1 (2003). Based on MK trend test results the PCI is rising every year by 0.054 (0.051 based on regression equation) On seasonal scales, PCI values are uniform during the winter (9.6), spring (10.1), and summer (10.2). Higher PCI (10.7) values were observed for autumn. In general, the seasonal PCI values suggest a uniform distribution of rainfall concentration (Lujan and Gabriels 2005). Analysis of the seasonal PCI indicated a statistically significant positive trend only for the spring period ($p < 0.037$). Every spring the PCI is rising for 4.360.

MFI values average 91.3 (Fig. 3b) and generally display moderate aggressiveness for the study area. Several extreme values were observed in 1999 (148.4), 2001 (141.8), 2010 (131.2), and 2014 (271.3). These values correspond to high and very high erosivity, although there is no indicative trend during the observed period. According to MK trend test statistically significant rising trend was not detected. On the other hand, regression equation implies that every year MFI rises by 1.914.

The aridity/drought indices, AI_{Lang} and PaDI, yield no statistically significant trend over the period of interest. AI_{Lang} multiannual average values (4.3) indicate pronounced arid conditions overall (Fig. 3c), with a declining tendency shown on a regression equation (every year it declines for 0.018). This is in agreement with the observed rising tendency of precipitation sums. The average PaDI values varied between 12.03 in 2006 and 21.67 in 2003 (Fig. 3d). These PaDI values indicate the occurrence of a very serious drought in 58.3% of the observed cases. Trend analysis display positive tendency (with increase of 0.115 per year), but without statistical significance.

Instability of the geological substrate

The area most susceptible to slope instability is located on a 10- to 15-m-thick vertical section forming the southeastern margins of the Zemun loess plateau. The absolute height of the plateau is 99–100 m.a.s.l. and the base of the vertical section lies at 85–89 m.a.s.l. The undulating slope is built upon by households and traffic infrastructure. Regarding the surface development, area is partially asphalted over, with inadequate rain drainage system directed to run toward the vertically exposed loess

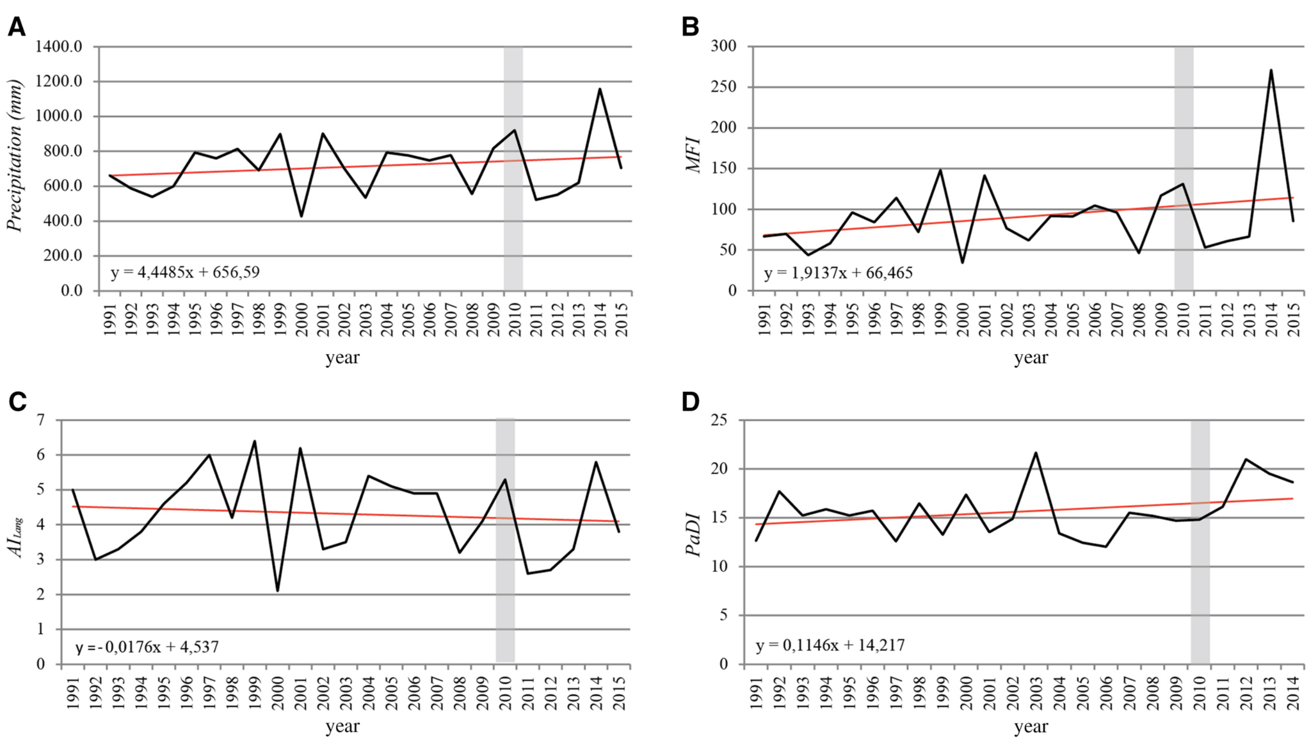

Fig. 3 Temporal variability of selected meteorological parameters (gray bars highlight the largest landslide event)

sediments. Analysis of the geological strata indicate that investigated profile consists of the recent Holocene soil (S0) overlying a sequence of last glacial loess with a sandy component at the base (L1) and interglacial–early glacial soil complex unit (S1). Such lithological conditions have profound impact on the development of landslide hazard at the investigated area. Detailed data on sediment thickness and stratigraphic distribution are presented in the geological map (Fig. 4).

The loess deposits of the study area are characterized by complex tubular, primrose and intergranular porosities, allowing surface water to infiltrate vertically down existing cracks. The contrast in grain size and corresponding hydrological properties between silty primary loess and more clay-rich paleosols leads to accumulation of rainfall in the form of a hanging aquifer (e.g., Lukić et al. 2009, 2016).

The Zemun area is prone to surface-water runoff exacerbated by the absence of an urban rain drainage system. This leads to unregulated water discharge directly into the loess substrate, resulting in rapid dissolution of readily soluble carbonic salts which provide a stable matrix for the loess soil and its slope stability. Field observations show an increase in slope angle of the endangered slope following heavy rain events (Secretariat for child protection and Geological Institute of Belgrade 2011).

Decoupling major factors in slope instability at Zemun loess plateau

At Zemun settlement, multiple episodes of collapse and slope instability have occurred since urbanization of the area, endangering buildings and transport infrastructure. The most significant event occurred following drought conditions in 2010 which created suitable conditions for the most severe landslide event at the end of summer 2011. This landslide resulted in loss of four human lives and one heavily injured casualty. Loess slope stability is strongly influenced by climatic conditions (Lukić et al. 2016); under-saturated dry loess can sustain nearly vertical slopes, which become unstable following precipitation or intensified drainage as cohesion is lost (Derbyshire 2001). Hence, the triggering factors (TF) of this event can be found in joint climatological characteristics of the investigated area, properties of the geological substrate, and human activity that further accelerated slope instability (Fig. 5).

Landslides are usually triggered by several factors affecting slope stability and shear stress (Alimohammadlou et al. 2013; Bolt et al. 2013). Soil erosion resulting from a combination of climatic factors, and exacerbated by human land use unsuitable to the geological conditions, is considered the major trigger for landslides (Gobin et al. 2004). Water erosion is primarily driven by the intensity and seasonal

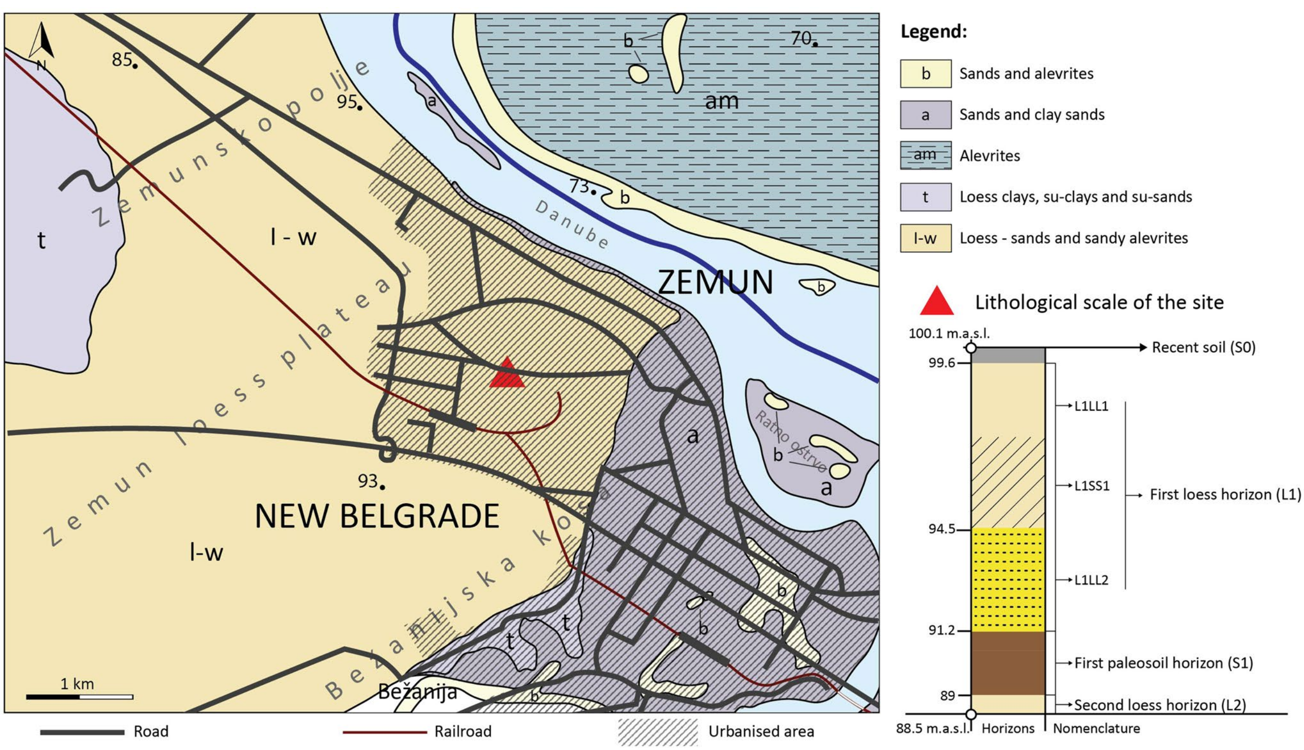

Fig. 4 Geological map and lithological description of the site derived from Base geological map of Serbia 1:100,000—Beograd sheet. After Dimitrijević et al. (1985a, b)

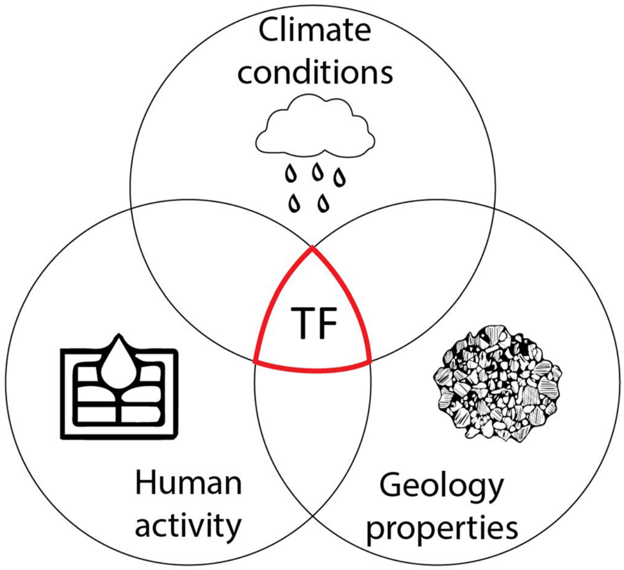

Fig. 5 Triggering factors for the landslide activation in Zemun settlement

distribution of precipitation events (Wischmeier and Smith 1978; Mello et al. 2013).

One of the highest precipitation years at Zemun for the investigated time period fell in 2010 (921.1 mm), just prior to the largest landslide event. The corresponding MFI value (131.2) falls within the high erosivity class (Fig. 4b). Consistently arid and drought conditions over 2010 are respectively indicated by AI_{Lang} (5.3) and PaDI (14.1). These suggest that the high precipitation recorded in 2010 occurred in a few torrential events over a short period of time, thus increasing the susceptibility of the geological substrate to erosion and landslides. It is important to note, that activation of the landslide event in 2011 was additionally backed up by mishandled rehabilitation activities preformed at the cliff's base.

Hydrological compaction is a key process in slope failure in loess terrains. Over the long term, the pore space of the Zemun loess is under saturated (Hadzi-Niković 2009) and mostly subject to matric suction or negative pore-water pressure. Matric suction in soil decreases the lateral active earth force and increases the critical height of a slope, its bearing capacity and slope stability. Following intense rainfall events, short-term oversaturation, causes the loess to disaggregate instantaneously under its own weight, particularly in the more porous and weakly cemented uppermost Late Pleistocene loess.

Loess is highly susceptible to water erosion even at a 5–10% slope gradient (Abramson et al. 2002). The loess cliff at Zemun has a slope gradient 275–567.1%.

The loess stratigraphy and sedimentological characteristics of northern Serbia are consistent despite variable thickness of the sedimentary packages across the region (Antoine et al. 2009; Marković et al. 2009, 2015; Gavrilović et al. submitted). This consistency is assumed to apply to the loess at Zemun and therefore informs us about the grain size, porosity, and cohesiveness of the landslide deposit (Fig. 6).

Figure 7 summarizes the likely development of conditions facilitating slope failure at Zemun. The contact between the relatively porous, unconsolidated primary loess, and underlying buried soil (paleosol) likely played an important role in accelerating erosion from the base of the slope, following models examined in Derbyshire (2001) and Lukić et al. (2016). Geomorphological model presented by Lukić et al. (2016) suggests the morphogenesis of the Zemun landslide is closely related to the sedimentological characteristics of the loess-paleosol sequences. Under normal conditions (Fig. 7a), the length of wet and dry climatic cycles is relatively uniform; during this phase primary loess develops higher permeability and porosity than the more clay-enriched paleosol, forming hanging aquifers (Ma et al. 2017). Under sustained dry conditions, loess is subject to vertical cracking (Fig. 7b) and erosion. When drought is followed by extreme rainfall events, precipitation percolates downward through the vertical cracks and develops a hanging aquifer in the relatively sandy primary loess layer (L1LL2) immediately overlying the less permeable paleosol (S1; Fig. 7c). The contact between the saturated primary loess and less permeable paleosol intensifies erosion as groundwater discharges toward the base of the cliff face (Fig. 7c). This process is further exacerbated by the dissolution of calcium carbonate which occurs within the matrix of the primary loess, accelerating erosion and cliff collapse in the final stage (Fig. 7d).

Slope failure at Zemun has been enhanced by the lack of vegetation and intensive urbanization. In particular, the absence of an adequate rain drainage system has exacerbated erosion at the site; surface drain pipes are directed into the porous sediments. While soil erosion is primarily driven by the sedimentological characteristics of the loess and the climatic factors, anthropogenic land use has acted as an amplifier to these processes at Zemun loess plateau. Urban development in the area is poorly regulated. Faulty handled excavation in natural slopes can disturb its equilibrium resulting with deformation of the ground, thus leading to the landslide events (Zhang and Liu 2010). Following the loss of four lives and significant damage to a kindergarten and nearby residences (Fig. 8a, b), measures were taken to mitigate further slope failure, such as reinforcement of building supports and retaining walls (Fig. 8c, d). The

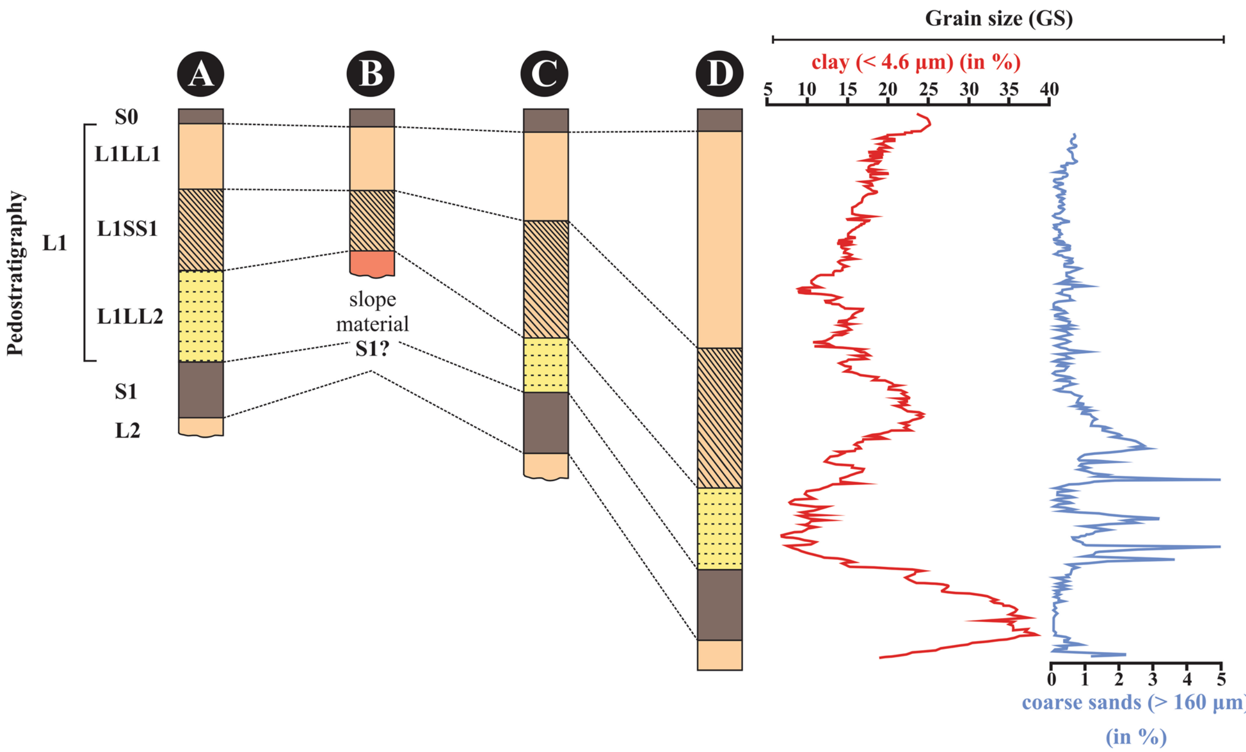

Fig. 6 Pedostratigraphy and sedimentology of the Zemun landslide (A), CPA (B), Batajnica (C), and Surduk loess sections (D) with grain-size distribution (GS), clay and coarse sand content [The authors designate the "L" (loess) and "S" (palaeosol) stratigraphic units, numbered in the order of increasing age as the standard Pleistocene loess-paleosol stratigraphic units of the Northern Serbia] (modified after Antoine et al. 2009; Marković et al. 2009, 2015; Gavrilović et al. submitted)

damage inflicted by 2010 landslide event and rehabilitation of the unstable slope (at the end of 2011) cost c. 0.3 M Euros (Secretariat for child protection and Geological Institute of Belgrade 2011).

Future recommendations and conclusion

Landslides along the loess cliff at Zemun will remain a real risk for its inhabitants. So far, inadequate regulation of urban development and post-landslide mitigation has resulted in adverse economic impacts on all levels. To reduce future infrastructure damage and prevent development of landslide events, it is necessary to introduce and conduct qualitative mitigations strategies by implementing a long-term cliff reinforcement programme. Apart from upgrading, the supporting wall requires regulatory enhanced maintenance. Sections in need of maintenance should be identified by regular inspections due to the dynamic hazardous nature of the terrain. Utilizing consultancy services will ensure wider professional resources as well as faster cliff mitigation processes (e.g., Kwong et al. 2004). If the investment in cliff safety is not maintained, cliff deterioration over time will increase the landslide risk and the vulnerability of the settlement itself. Furthermore, this can cause significant economic losses and social disruption, thereby compromising public safety (Choi and Cheung 2013; Berisavljević et al. 2014; Lukić et al. 2016).

Trend analysis of air temperature and precipitation data for the Zemun loess plateau in northern Serbia yields moderate variability, yet minimal overall change, over the period 1991–2015. Rainfall aggressivity (MFI) correlates with precipitation concentration, indicating moderate aggressiveness and several instances of extreme values despite consistent aridity which are likely to have been a major contributor to erosion at the Zemun site (Bjelajac et al. 2016; Lukić et al. 2016). This is in large part due to the inherent sedimentological characteristics of the loess substrate at Zemun loess plateau.

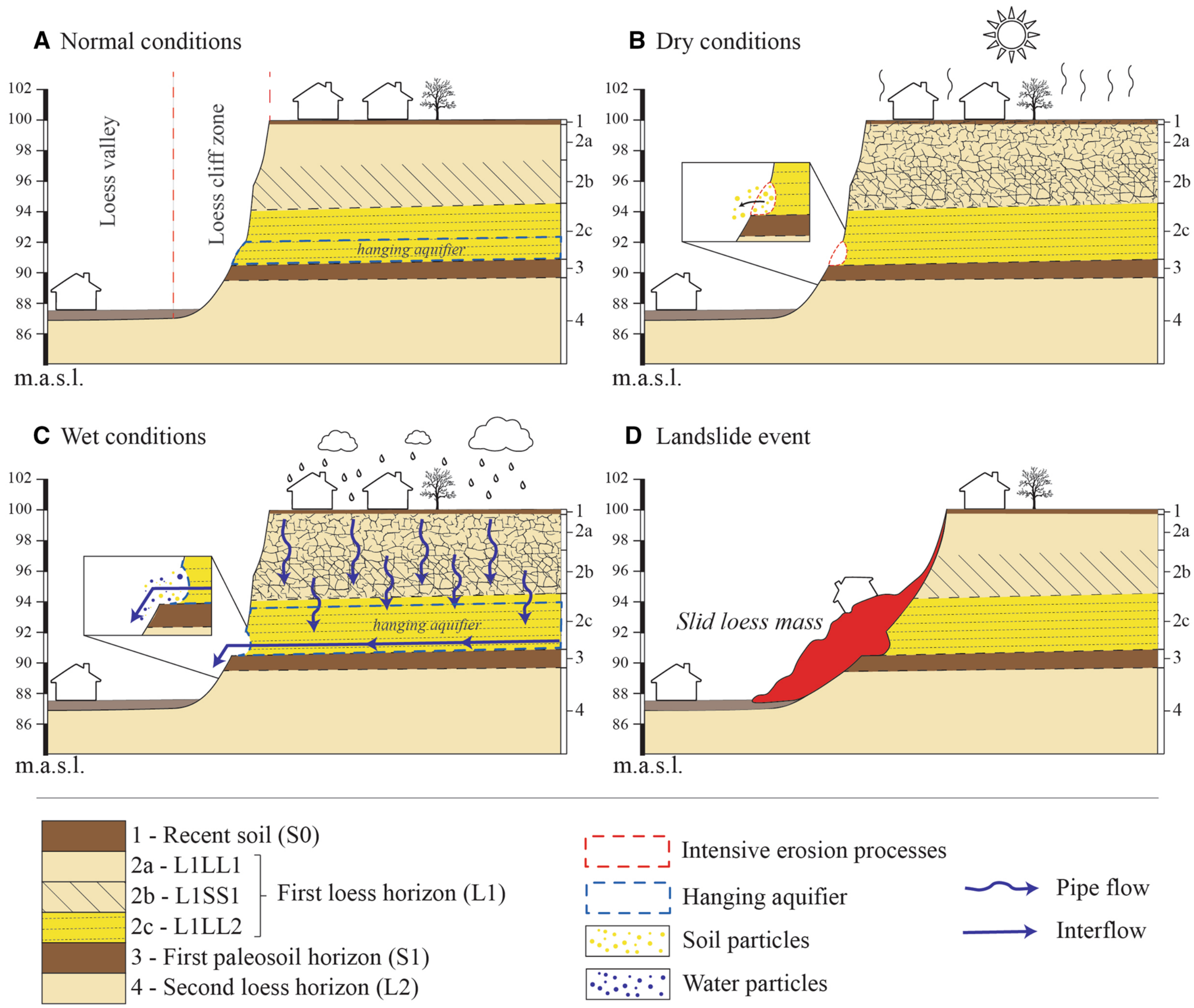

Fig. 7 Four stages of landslide development on the Zemun loess plateau following the models of Derbyshire (2001) and Lukić et al. (2016)

Urban development at Zemun settlement, largely unregulated, has exacerbated the landslide risk and can be regarded as a "hidden hazard". While engineering a safer, more stable slope is a challenge in thick loess terrain, careless water management such as direction of urban runoff directly into the loess, so exacerbating sediment saturation and development of a soluble, erodible hanging aquifer, is a practice which could easily be avoided through better regulations in Serbia. Increasing population pressure and associated urban development on the edge of the Zemun plateau will continue; prevention of future slope failures can only be achieved only through careful management of land and water in urban areas. A successful strategy is dependent on a combined scientific and engineering approach and management of natural resources at both local and national levels (Larsen 2008). The results presented in this study contribute to an improved understanding of factors triggering landslides in loess regions generally.

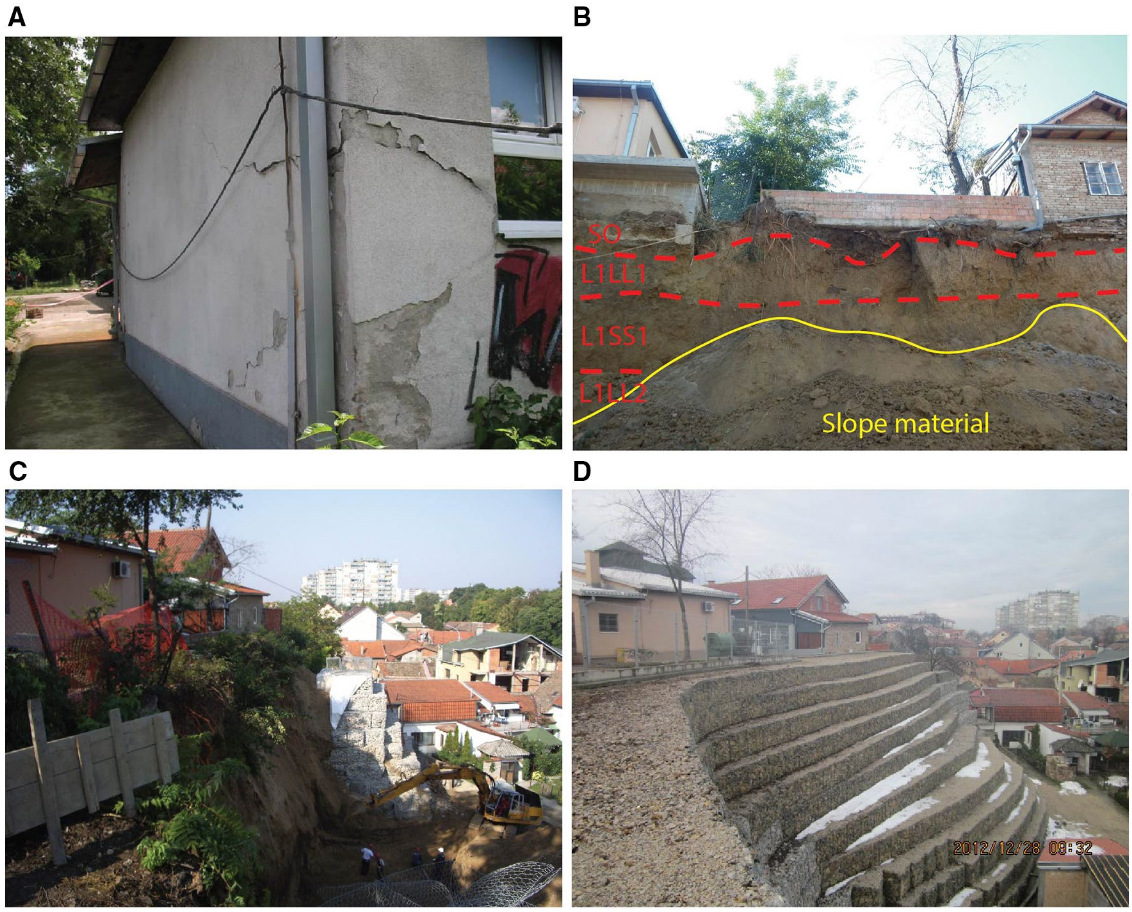

Fig. 8 **a** The kindergarten facility before the 2010/2011 landslides. **b** View from the base of the slope after landslide event in 2010. **c** Rehabilitation works following the landslide event in 2010. **d** Installation of retaining walls at the end of 2012 (Photo: Mlađan D)

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