Ann. Disaster Risk Sci. 2018, 1, 3-18

CLIMATE CHANGES AND LANDSLIDE HAZARD

Nenad Petrović, Branko Božić and Ivo Lukić

University of Applied Sciences Velika Gorica, Velika Gorica, Croatia

Abstract

Landslides are a significant threat to the critical infrastructures, and this hazard has two type of phenomena: in the first case, the infrastructure is targeted by a sliding material, and in the second case is itself an integral part of the landslide. In both cases, the damage to the infrastructure may be large and accompanied by significant losses of human life and recovery may be long and very expensive. Weather conditions, such as heavy rainfall, due to the increase of groundwater level and soil saturation are common triggers of landslides occurrence. It's expected that the climate changes in the coming decades cause a significant increase in precipitation, which will directly affect the increase in the number of active landslides. This paper provides an overview of the climate changes impact to the dangers caused by landslides. This work is the result of scientific research in the EU-CIRCLE project, financed through the Horizon 2020 program of the European Union.

Keywords: Climate changes, landslides, critical infrastructures, EU-CIRCLE project.

Adress for correspondence: Nenad Petrović, University of Applied Sciences Velika Gorica, Zagrebačka c. 5, Velika Gorica, Croatia, e-mail: neno.petrovic@gmail.com

1. INTRODUCTION

The impacts of climate change may have various potential consequences on critical infrastructures [1]. One of this consequences is an increased number of potential natural hazards that can be threating to critical infrastructures. Among them, landslides are very significant. Landslide is a common name for all earth movements, like landslides, erosions, avalanches, rock falls, soil subsidence, liquefactions, etc.

Landslides may damage infrastructure in two ways: a) if infrastructure in the landslide runout zone is struck by moving debris, b) if infrastructure is placed on unstable ground and is moved suddenly or episodically as the main body of the landslide moves [2].

Downward movement of soil under gravity may be relatively slow (slides) or fast (rockfalls) and may also affect flat ground above and below the moving slope [3]. A slope remains stable while its strength is greater than the stress imposed by gravity. Other factors that determine the risk of landslides include the type of geological material: fractures and joints, the angle of the slope, and the position of the water table.

Landslides occur in areas with certain tectonic predispositions to be activated, as a result of various natural and anthropogenic causes [4]. The failure mechanisms that lead to the slope fault are complex phenomena caused by the reduction of cohesive forces between the soil particles. Groundwater level and infiltration of rainwater into the ground significantly affects the size of the cohesive forces and soil shear strength. Unfavourable weather conditions in synergy with additional load or relief of the slopes, improperly designed or poorly executed, and poorly maintained drainage systems, as well as other anthropogenic causes, significantly affect the overall stability of the slope. The risk of landslide and avalanche is increasing due to deforestation and climate change [5,6]. And at this moment, the frequency of extreme events due to climate change is increased.

Changes in temperature and precipitation are considered likely to have a range of secondary effects, including the extent of glaciers, the distribution and duration of the snow cover, and the temperature and three-dimensional distribution of permafrost [7].

A disruptive event may have impacts on different levels of a system of infrastructures and socioeconomic environments [8]. Most broadly, these impacts can be divided into physical and socioeconomic impacts. Physical impacts are the most immediate ones observed in an infrastructure where the disruption attacks first. Thus, the disruption affects the customers or the users of this infrastructure. However, due to the interdependencies of infrastructures, this disruption will create more effects to other infrastructures dependent on the first infrastructure. Therefore, a sequence of disruptive events will follow with impacts to different sectors. For instance, energy crisis in a region can disrupt many vital services propagated from the initial disruptions created in electric power generation. In addition to that, landslides can affect energy production and delivery facilities, cause supply disruptions and affect infrastructure that depends on the energy supply [3].

In case of heavy rain and floods soil is macerating [1]. Thereby, it loses its stability and gets hazardous. The fall of debris as well as the slipping of earth is activated. The parts of infrastructure, like rail tracks or lanes, located in the active area of those avalanches are threatened. Blocked and buried roads as well as damages in case of fallen debris are a result. Soiled tracks are easily leading to derailments. Road and rail networks are critical infrastructure, vital for ensuring the flow of essential goods and services necessary to maintain a country's economic and national security [9]. Landslides are natural hazards which can seriously affect road and rail networks, so in order to plan mitigation strategies, calculate losses and minimise casualties, it is necessary to know the risk posed by landslides. There are many potential triggers, including precipitation, earthquakes and human activity, with heavy rainfall being the most common trigger.

Additionally, the aviation and the maritime sector are not disrupted by landslides significantly. ICT sector is at risk from landslide effects in cases where the telecommunications infrastructure (i.e. lines) is located in vulnerable areas.

Landslides are an increasing problem [10]. Multiple landslides can be triggered by heavy rainfall resulting in loss of life, homes and critical infrastructure. The costs of disruption to road networks can be several orders of magnitude higher than direct clean up and repair costs. Such disruption can limit the ability of a country to respond to the disaster. In many cases it is possible to reduce this risk by investigating the underlying risk drivers and investing in appropriate slope management and stabilisation measures prior to disasters.

This paper is developed as part of an ongoing collaborative project titled „Pan-European framework for strengthening Critical Infrastructure resilience to climate change (EU-CIRCLE), which is funded by European Union´s Horizon 2020 research and innovation programme. The paper provides an overview of the climate changes impact to the dangers and damages caused by landslides.

2. METHODS

This research is based on an intensive review and systematization of existing literature. The authors reviewed over 100 relevant scientific papers related to landslides and the consequences of the earth movement. The criteria for selecting papers and appropriate cases are as follows:

1. The main triggers of the landslides occurrence should be necessarily climate related,
2. Secondary triggers don't need to be climate related (e.g. earthquaqe, tsunami, etc.),
3. Papers should include the following information: location and time of events, triggers and direct consequences of events, impact of hazard on the environment (such as damage, cost, recovery time, casualities, etc.) In accordance with the above criteria, the authors identified 25 events, which are described below.

3. CATASTROPHIC LANDSLIDESCAUSED BY CLIMATE CHANGE

3.1. Electric power generation & transmission

Kulekhani watershed (124 km^2) is located in the Lesser Himalayan region of the Himalayan belt in the central region of Nepal [11]. The area has elevations ranging from 1500 m to 2600 m. This region is highly populated and most prone to landsliding. The average annual rainfall is about 1600 mm. The area is drained by the Palung River, which empties into the Kulekhani reservoir. The reservoir received a tremendous amount of sediments (thirty times the average annually) during the debris flow disaster in July 1993. This is the only reservoir in Nepal and supports one third of the total electric power generation of Nepal; consequently, landslide hazard assessment is critical for effective watershed management.

On 29 March 1993, a massive rockslide dammed the Rio Paute, ~20 km northeast of Cuenca in the Inter-Andean Basin of south-central Ecuador [12]. This 20-25 x 106 m^3 translational slide occerred in igneous rocks overlain by colluvial deposits. The slide was probably caused by heavy rainfall (March rainfall was approximately double the March average for the region) and by a 160-m-deep open-pit mine excavation at the base of the slope. The regions upstream and downstream from the landslide were densely populated. The economic losses incurred by landslide were devastating, as were the terrain and environment. The slide formed a 100-m-high natural dam of the Rio Paute at its junction with the Rio Jadan. The impoundment behind this dam flooded the upstream valley for a length of 10 km, submerging agricultural land, homes, and industries. The final stored water volume of the natural dam was 200 x 106 m^3, corresponding to a depth of 83 m. After 33 days, the dam failed, resulting in a peak discharge of 10 000 m^3/s. The resulting debris flow and mudflow flooded the valley downstream for a distance of 50 km, where 3 hours after failure of the natural dam, the flood entered Amaluza Reservoir, the impoundment behind Amaluza Dam. This dam is a part of the Paute Hydroelectric Plant, which generates 65% of the electric power consumed by Ecuador. Before the landslide dam failed, the reservoir, which had a total capacity of 120 x 106 m^3, was lowered 31 m to provide a storage volume of 51 x 106 m^3 for the expected flood. In spite of these precautions, the powerhouse turbines suffered damage due to high concentrations of suspended solids in the water.

Figure 1. Landslides effects on electric power facilities [1]

The flood of debris caused very serious damage in the Rio Paute valley between the natural dam and Amaluza Reservoir. Hundreds of private homes and several industrial complexes on the Rio Paute plain were devastated. Because the flood was anticipated and people and livestock had been evacuated, the flood caused no casualties. While the water level was decreasing in Lago (Lake) Josefina because of failure of the landslide dam, several landslides occurred on the surrounding slopes due to the rapid drawdown; the most important of these was the Zhizhio slide, which occurred on the slope facing the original La Josefina failure.

On 29 November 1987, a catastrophic debris flow on the Rio Colorado in Chile destroyed the campsite, access roads, bridges, and equipment that were supporting construction of the El Alfalfal 160 MW hydroelectric power plant, causing 29 deaths and considerable damage not only to El Alfalfal, but to the preexisting 25 MW Maitenes hydroelectric power plant (Figure 1) [12]. The economic impact was estimated at more than $65 million (U.S.). This landslide resulted in considerable public alarm in Chile because it affected an area only a few kilometers from Santiago, the capital city. The debris flow originated as a massive rockslide or rockfall and/or avalanche in sedimentary rocks at an elevation of 4700 m on the Estero Parraguirre (Parraguirre Creek), a tributary of the Rio Colorado. The volume of rock involved in the initial landslide has been estimated at between 2.5 x 106 and 5.5 x 106 m^3. The ensuing debris flow traveled ~50 km down the Estero Parraguirre and the Rio Colorado to within 50 km of Santiago. The sedimentary rocks involved in the original rockfall and/or avalanche were steeply dipping limestones, shales, and calcareous sandstones of the Lo Valdes Formation and conglomerates, sandstones, and siltstones of the Rio Damasa Formation; these rocks form the high mountains along the border with Argentina in this area. The nearly vertical dip and open subvertical fractures have resulted in unstable large-dimension rock blocks. The strength of the rock may have been further reduced by hydrothermal alteration, which is evident at the site. Triggering of the initial failure appeared to have been caused by significant water infiltration trough the fracture system due to extreme snow melt. The catastrophic, high-velocity slope failure probably combined fall, toppling, and avalanching of unstable large-dimension blocks and sliding of others. The rock mass suddenly fell from a maximum elevation of 4700 m to ~3500 m at the toe of the slope. Because of the large mass involved and the considerable height of fall, the energy generated was significant. The Institute of Seismology of the University of Chile noted that a M = 3 earthquake was registered at precisely the time of impact of the rockfall. The kinetic energy of the rock mass at the toe of the slope led to an estimated velocity of 100 km/h at the head of the debris flow in the Estero Parraguirre. According to witnesses, the flow occurred as an enormous wave, which often reached a height as great as 20 m. Impressive evidence of the power of this wave and the debris flow was a boulder, more than 10 m in diameter, that was transported ~ 14 km along the bed of the Rio Colorado. The El Alfalfal hydroelectric power plant was finally completed in 1990, after a one-year delay caused by the debris flow and after modification of the design of the water intakes to minimize the possibility of damage due to future debris flows. The Maitenes power plant returned to operation in 1992. A rock embankment was built around the power house in order to protect it from future debris flows.

3.2. Oil plants

In Ecuador in May 2013, the Trans-Ecuador pipeline is ruptured in a landslide. The volume of oil released to the environment was reported to have been about 11500 barrels. The oil flowed into the Coca River making its way downstream. The initial impact was on the city of Coca, which has 80.000 inhabitants, which had to shut down its drinking water supply [13]. Over the years, engineering and design standards have improved and are generally seen within the oil and gas sector to be more ro-

Figure 2. Landslide impact on Trans-Ecuador pipeline [13]

bust in the face of current landslide risks. However aging infrastructures are at risk, particularly linear infrastructures such as pipelines (Figure 2) [14].

Storm-wave loading and under-consolidation became recognized as major factors in causing submarine landslides following the failure of or damage to several offshore drilling platforms when Hurricane Camille struck the Mississippi Delta in August 1969 [15]. Bubble-phase gas charging can degrade sediment shear strength and contribute to slope failure. Existence of gas hydrates underlying many submarine slopes. Such hydrates are ice-like substances, consisting of natural gas and water, which are stable under certain pressure and temperature conditions that are common on the seafloor. When temperatures increase or pressures decreases, the stability field changes and some of the hydrate may disassociate and release bubble-phase natural gas. Unless pore water flow can occur readily, this gas charging leads to excess pore pressures and degrades slope stability. Worldwide lowering of sea level during glacial cycles could lead to numerous slope failures because of gas hydrate disassociation. Of more immediate interest, warming of the seafloor through changes in current patterns or global warming could potentially cause a similar effect. The impact of oil and gas offshore production in areas where gas hydrates are present poses difficult questions regarding the effect of these activities on the gas hydrate stability and its link to slope instability or the potential reactivation of older mass movements.

In the early morning hours of 28 November 2003, a low gradient extremely rapid, liquefaction earth flow occurred on the Khyex River, 35 km east of Prince Rupert, northwest British Columbia, Canada [16]. The earth flow severed a natural gas pipeline of Pacific Northern Gas (PNG) leaving the communities of Prince Rupert and Port Edward without a gas heat supply for a period of 10 days. Consequently, over $300.000 in emergency food and shelter were spent by the City of Prince Rupert. Moreover, costs incurred by PNG exceeded $1M to install a temporary gas line.

3.3. Drinking and Waste Water Systems

Natural hazards and disasters cause more than 70 percent of all “blackouts”, about 20 percent of breakdowns in heat and water supply systems, 16 percent of water transport accidents; more than seven percent of pipeline ruptures, and about three percent of air crashes, automobile, and railway accidents [17]. Water transport accidents triggered by storms, cyclones, typhoons, and other weather effects sum up to another five percent. In case of oil and fuel releases such accidents can lead to water pollution and hurt the coastal (riverside) and water ecosystem. About 15 percent of accidents at drinking water and heat supply systems caused by hard frost, rainfalls or subsidence of ground; air crashes caused by windstorms, snowfalls, icing or fogs come to about two percent.

On 7 March 1983, a catastrophic landslide occurred in Dongxiang County, Gansu Province, in the Loess Plateau of China [18]. The peak and the steep south slope of Sale Mountain slipped suddenly: after sliding, the peak had dropped from 2283 m elevation to 2080 m, a vertical displacement of approximately 200 m. The toe of the displaced mass pushed forward across the more than 800 m wide valley of the Baxie River and climbed 10 m up the opposite bank before stopping. Three villages on the second river terrace level just under the foot of the mountain, and near the toe of the rupture surface, were completely destroyed, and 237 people were killed. A farmer on the mountain slope survived by holding the trunk of a nearby tree and traveling with it for 960 m without injury. The length of the landslide is 1600 m, the width is 1100 m, and the area is 1.3 km^2. According to geophysical profiling and drilling, the maximum and the average depth of the landslide debris are 70 m and 24 m, respectively. The landslide volume is estimated to be 30 x 106 m^3. Although its volume is large and its travel distance long, the entire sliding process lasted less than 1 min. The velocity of movement was thus extremely rapid, estimated as 20 m/s. No trigger for this huge landslide is evident. The Loess Plateau of China is a semiarid region and spring is a dry season. No rainfall or earthquake was associated with the sudden catastrophe.

On 18 June 1991, after unusually heavy rain, Antofagasta, a coastal city of Chile 1300 km north of Santiago, was hit by several debris flows [12]. The flows and associated flash floods killed 101 people and resulted in another 48 missing. They destroyed 402 houses and damaged more then 2.000. In addition, Antofagasta´s water-supply system, roads, and railway lines were damaged, affecting a total of 21.000 people. Total losses were estimated at $27 million (U.S.). The debris flows came from a dozen normally dry ravines that drain the western edge of the Cordillera de la Costa. The ravines cut through Antofagasta before reaching the Pacific Ocean. The estimated velocity of the flows along the Quebrada El Jardin (Jardin Creek) was 30 km/h. Erosion caused by the flows affected streets, culverts, and construction along the courses of the ravines. At the same time, debris transported by the flows destroyed many houses. The total mass of detrital material in the flows was estimated at 500.000-700.000 m^3. These debris flows were triggered by precipitation that ranged from 14 to 60 mm in 3 hours. Historical records indicate that this was the equivalent of a 100 yr storm. These records also indicate the occurrence of similar flows at least five times since 1940 in this area; however, none of these previous flows caused as much damage to Antofagasta because the city was smaller at that time. It will be difficult to prevent similar damage in future occurrences of debris flows in Antofagasta and other coastal cities in northern Chile because of their particularly susceptible locations and the practice of constructing low-income housing in ravines in the narrow strip of land between the western edge of the Cordillera de la Costa and the Pacific Ocean. At present, a series of studies is under way to determine proper designs for diversion and retaining structures intended to minimize the effects of future debris flows in Antofagasta and nearby cities. These studies are being complemented by more appropriate land planning and zoning than have been used in the past.

In May 2005, heavy rain has resulted in a landslide that severely damaged the main sewer line entering the Cascade shores Wastewater Treatment Plant [19]. The plant serves 80 homes in the Cascade Shores subdivision, located east of Nevada City (USA). The plant normally treats approximately 35 to 60 m^3 of wastewater per day, with the treated effluent being discharged into Gas Canyon Creek. In December 2005, at the same place, rainstorms have caused the bluff adjacent. An estimated 300 – 400 tons of material slide down the bluff. The damage was a broken water line that resulted in 35 m^3 of treated effluent not receiving disinfection.

3.4. Road and Railway network

In course of heavy rain and floods, the ground is macerating and becoming unstable and hazardous. The movement of a mass of rock, earth or debris is triggered off. Falls, topples and flows are summarized as landslides and threatening public infrastructure. They are blocking or even damaging roads easily by burying them. In October 2014 heavy rains brought down debris from the surrounding hillside and blocked the Scottish motorway A82 thereby [1]. In March 2016 boulders fell down from a height of 40 metres on the Via Aurelia, Milan, Italy. Detours and the possibility of personal damage caused by debris avalanches have to be incurred. Landslide patrols and reforestation to fix slopes as well as the setting up of automatic warning and alarm systems should be initiated to reduce landslide caused damages.

On 9 September 1987, an unusually heavy rainfall of 174 mm in <5 h occurred in the Rio Limon drainage north of the city of Maracay, 100 km west of Caracas, in Aragua State, Venezuela [12]. This heavy rain saturated the residual soils on steep slopes (commonly >40°), which triggered thin slips and slumps that were soon transformed into very rapid debris avalanches and debris flows. These debris flows resulted in the worst landslide catastrophe in the history of Venezuela: ~20 000 people returning from a weekend at the beach were trapped on several sections of the highway; many were killed by debris flows. The debris flows continued down to the city of El Limon and to the small towns of Cana de Azucar and El Progreso, destroying houses and killing or injuring people. The event damaged or destroyed ~ 1500 homes, 500 vehicles, three bridges, and 25 km of roads; ~210 people were killed, 400 were injured, and more than 30 000 people were temporarily stranded. The characteristics of the Rio Limon debris avalanches and debris flows can be summarized as follows: (1) The intense rain saturated the soil, causing thin, elongated, shallow slips or slumps (thickness <1.5 m) to occur on the upperparts of steep slopes in the Rio Limon watershed - this process continued until the residual soils had been stripped to the underlying gneissic bedrock. (2) As the saturated soil masses moved downslope, they soon were transformed into very fluid debris avalanches and then to debris flows. (3) The debris flows, including boulders, trees, and other vegetation, moved down stream channels, forming temporary natural dams or plugs that inundated some areas. The area denuded by the landslides was ~140 ha. Based on an average thickness of residual soil of 1.4 m, the total volume of material removed from the upper Rio Limon basin has been estimated at 2 x 106 m^3.

On 26 March 1983, during the wettest year of the century, a major landslide occurred in the vicinity of the town of Chunchi, ~60-70 km north of Cuenca, on the western slope of the Andes in south-central Ecuador [12]. Although we have little information on this catastrophic mass movement, it involved ~1 x 106 m^3 of geologic material that slid ~3000 m, blocked the Pan-American Highway, buried vehicles on the highway, and killed more than 150 people.

Unusually heavy rains fell in mid-southern Brazil during the summers of 1966 and 1967 [12]. In 1966, the area most affected was the city of Rio de Janeiro and Vicinity. Total loss of life from floods and landslides in the area may have reached 1000. In 1967, the area most affected was 100 km^2 along the escarpment of the Serra das Araras, 50 – 70 km west of Rio de Janeiro; deaths from floods and landslides were estimated to be as high as 1700. Property and industrial damage was described as inestimable. The slides, avalanches, and flows resulted in immense human and material losses in the Serra das Araras mountain region along the most important highway, which had not suffered any previous landslide damage in its 39 years of existence. In addition, much damage was done to important hydroelectric installations in the area. Hillsides were devastated by thousands of thin debris slides and avalanches.

Figure 3. The impact of landslides onto the highway [1]

Rapid snow melting and intense precipitation triggered and reactivated tens of mostly shallow landslides in the eastern part of the Czech Republic at the turn of March and April 2006 [20]. This area is build up by highly fractured flysch rock units with variable content of sandstones and claystones. The landslide complex at Hluboce (Brumov-Bylnice town) is composed of shallow translational (up to 10 m thick) as well as deep-seated (up to 20 m thick) rotational landslides, which generated a catastrophic earthflow at their toe. During the main movement activity (3–4 April 2006), this earthflow destroyed three buildings, the access road and caused total loss of about 350 000 EUR. The immediate triggering factor of the April 2006 Hluboce landslide complex was water saturation of its material due to mutual effect of snow melt water and high cumulative precipitations at the last days of March and beginning of April 2006. Abnormally cold winter 2005/2006 was characterised by very thick, long-lasting snow cover, which abruptly melted after sudden warming at the turn of March and April 2006. Maximal daily temperature varied between 14.4–18.6°C through 28 March and 2 April 2006. Additionally, total precipitation amount (75 mm) in March 2006 was 67% higher than the long-term average (45 mm). These climatic conditions produced exceptionally high values of total cumulative precipitation (143 mm at the nearest meteorological station) during the 2006 snow thaw period which was responsible for widespread occurrence of landslides. According to local residents, the sliding activity itself started 5 to 6 hours after the main precipitation event.

A 2-km-long landslide occurred at Pink Mountain in late June or early July 2002 [21]. The Pink Mountain landslide is a rock slide-debris avalanche. This landslide may have been triggered by the delayed melt of an above-normal snowpack, followed by a week of intense rainfall. The landslide destroyed 43 ha of non-commercial forest, covered an access road, and came to rest within a few kilometres of a ranch house (Figure3).

As a consequences of the rainfall event on

18th/19th September, 2010, landslide and flooding disasters have affected the Himalayan region, in Almora District, India [22]. A late Monsoon downpour deposited 277 mm of rainfall in just 48 hours at intensities that peaked at 33 mm/hr. Falling on land that was already saturated, not least because of heavy rains on the previous two days, the result was a swarm of landslides and debris flows, and a spate of surface water runoff and mobilised debris that swept, downslope, into the river network, creating a major flood surge in the region's main drainage channel, the River Kosi. River discharge rose from its pre-Monsoon level of $0.07 m^3/sec$ to a peak of $618.1 m^3/sec$. The flood surge caused severe bank erosion and, where it swept against the steep Himalayan hillsides, caused toe erosion that triggered further landslides. Inevitably, Almora's infrastructure, especially its road network, was badly disrupted. People were killed when their homes became engulfed in landslide debris and hundreds of trucks were trapped on roads that were, variously, blocked by landslides, undercut by landslides or washed out by river erosion. A month after the disaster, much of the network remained impassable. The disaster had affected around 80 % of the district's people and the total damages exceeded US $ 125 million.

Caracas, the capital of Venezuela, is situated in a narrow valley surrounded by hills composed of weathered Jurassic-Triassic metamorphic rocks [12]. The pressing need for housing at the outskirts of the city has resulted in the development of unstable hilly areas. Many cuts and fills have been constructed without an adequate understanding of the geology and behavior of the weathered rocks. An excellent example of a catastrophic landslide in Caracas on the September 29, 1993, landslide that completely destroyed seven expensive homes and a 150 m section of street in a high-cost residential area. This landslide caused no casualties, but residents had only a 15-30 minute warning in which to abandon their homes. The slide blocked the main access to the suburban development, adversely affecting 20,000 families. Total damage was estimated at $2 million (U.S.), and engineering remedial measures cost another $6 million. The slide originated in a fill that had been placed on phyllites and schists that dip toward the slope face. The site had been subject to preexisting stability problems. The cause of failure was heavy rainfall plus leakage of wastewater at the site.

Road and rail networks are critical infrastructure, vital for ensuring the flow of essential goods and services necessary to maintain a

Figure 4. The impact of landslides onto the railway [1]

country's economic and national security [23]. Due to the earth movement, tracks can be damaged and the train can derail. Such an example is the derailment as consequence of a landslide near St. Moritz in Switzerland, in August 2014 [1]. The trigger for this event was heavy rain (Figure 4).

Landslides are natural hazards which can seriously affect road and rail networks, so in order to plan mitigation strategies, calculate losses and minimise casualties, it is necessary to know the risk posed by landslides. There are many potential triggers including precipitation, earthquakes and human activity, with heavy rainfall being the most common trigger.

3.5. Maritime

Due to the recent development of well-integrated surveying techniques of the sea-floor, significant improvements were achieved in mapping and describing the morphology of submarine mass movements [15]. Except for the occurrence of turbidity currents, the aquatic environment (marine and fresh water) experiences the same type of mass failure as found on land. Submarine mass movements however, can have run out distances in excess of 100 km so that their impact on any offshore activity needs to be integrated over a wide area. This great mobility of submarine mass movements is still not very well understood, in particular for cases like the far reaching debris flows mapped on the Mississippi Fan and the large submarine rock avalanches found around many volcanic islands. A major challenge ahead is the integration of mass movement mechanics in an appropriate evaluation of the hazard so that proper risk assessment methodologies can be developed and implemented for various human activities offshore, including the development of natural resources and establishment of reliable communication corridors.

Coastal landslides frequently occur during low tides through a mechanism similar to the rapid drawdown condition in earth dams or of failure at delta fronts. The Kitimat Arm failure, which occurred in British Columbia in 1975, is a classic example of such a mechanism, as is a more recent failure in Skagway, Alaska, that was responsible for killing a worker [15]. Low-tide-induced failures are part of a larger group of submarine landslides that are caused by water seepage effects. Seepage can occur beyond the immediate coastline through coastal aquifers and other pore fluid migration processes, including sediment subduction at plate boundaries. Under appropriate conditions, such seepage can lead to failure and potentially to the ultimate development of submarine canyons.

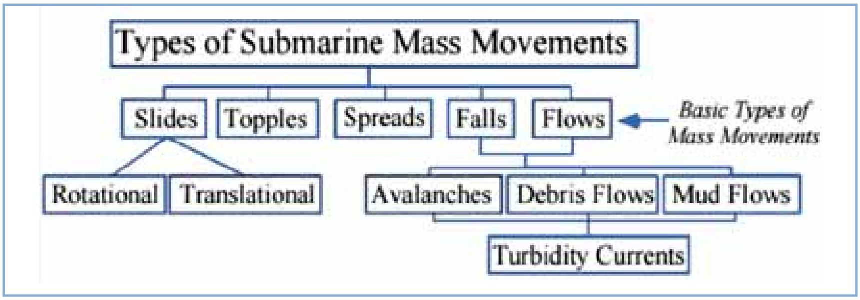

Figure 5. Classification of submarine mass movements adapted from sub-aerial classification proposed by the ISSMGE Technical Committee on Landslides [24]

Continental glaciation may play a significant role in inducing landslides. Factors that may be important include loading and flexing of the crust, greatly altered drainage and groundwater seepage, rapid sedimentation of low plasticity silts, and rapid emplacement of moraines and tills. A particularly dense set of large submarine failures off New England could be related in part to nearby continental glaciation. Following initial failure some landslides mobilize into flows whereas others remain as limited deformation slides and slumps. The mechanisms for mobilization into flows are not well understood but at least one factor is likely the initial density state of the sediment. If the sediment is less dense than an appropriate steady state condition (contractive sediment) the sediment appears to be more likely to flow than one that is denser than the steady state (dilative). The ability to flow may also be related to the amount of energy transferred to the failing sediment during the failure event.

The Storegga slide off the coast of Norway, which is one of the largest submarine landslides, was probably triggered by a process involving gas hydrates about 8000 years ago, involved a total volume of nearly 5000 km^3, and travelled from the western coast of Norway to the south of Iceland [25]. Of more immediate interest, warming of the sea floor through changes in major current flow patterns in the oceans or global warming could potentially cause similar effects.

3.6. Chemical Industry

Landslides have in the past damaged chemical and oil and gas infrastructures and cut off transportation networks. These events can disrupt or shut down operations, cause loss of containment and result in increased costs for maintenance, rebuilding and pollution remediation.

On the morning of April 18, 1991, a rockfall occurred on the west side of the Matter Valley near the village of Randa, in Switzerland [26]. The mass of approximately 20 x 106 m^3, mostly of gneiss, failed without clear warning signals, except for an increase in rockfall activity that began just before the event. It blocked the valley floor and the only road to Zermatt. The Vispa River was dammed by the rock mass, and the possible rupture of this dam threatened the dwellings and the chemical industry facilities downstream. The interest of this first Randa event is in the fact that the failure did not occur in the moment, but was obviously a continuing rockfall lasting some hours. The rock masses did not travel far, but formed a steep cone at the foot of the slope. They destroyed only some stables and holiday chalets without harming any people. The second failure, on May 5, enlarged the steep cone and increased the problems in the valley. The lower parts of the village of Randa were flooded by the lake dammed by the rockslide, before an artificial channel through the rock debris restored the runoff of the Vispa River. To avoid future problems caused by potential further rockfalls, a 3.6 km bypass tunnel was built. The Randa rockfall scar involves two geological formations: massive orthogneisses at the bottom and schistose paragneisses with amphibolites on the top. It is assumed that water entered into the upper parts of the series, which show deep stress-relief joints parallel to the surface due to stress-relaxation movements on the steep valley slope. The loss of former permafrost in the adjacent higher slopes might have caused the breakdown. The loss of permafrost enabled the infiltration of surface water, and consequently raised the joint water pressures and caused the erosion of cohesive joint fills.

3.7. Public sector

On January 10, 1962, a large debris avalanche was caused by the catastrophic failure of the west front of the hanging glacier on the north peak of Nevados Huascaran in the Cordillera Blanca of Peru at an elevation of 6300 m [12]. The original ice avalanche became a high-velocity debris avalanche as it gathered a great volume of blocks of granodiorite and descended 4000 m down the steep slopes of the highest peak in the Peruvian Andes, destroying everything in its path. The maximum velocity of the avalanche was ~100 km/h and the average velocity was 60 km/h. Nine small towns (including part of Ranrahirca) were destroyed and ~4000-5000 people were killed. Cultivated fields were devastated, thousands of farm animals were killed, and great destruction occurredin an area famous for its beauty and fertility.

Although there is abundant geologic evidence of prehistoric landslides on the eastern slopes of the Andes of Argentina, information on historic catastrophic landslides in Argentina has not been widely circulated [12]. Notable exceptions have been damaging debris flows that have occurred regularly in Jujuy and Salta Provinces in extreme northern Argentina. Probably the best known of these events is the debris flow of January 17, 1976, that swept down the Rio Escoipe in Salta Province and buried the prosperous town of San Fernando de Escoipe under 3 m of mud and rock. The town was almost totally destroyed; only a few houses situated on elevated slopes at the edge of the town were spared. The debris flow, which originated in submetamorphic rocks through which the Rio Escoipe flowed, was caused by record rainfall during the summer of 1975-1976. A nearby meteorological station registered 207 mm of rain during January, compared to an average January rainfall of 68.7 mm recorded for the period from 1973 to 1985.

On June 28, 2010, a catastrophic rock avalanche occurred after an extreme rainstorm at Guanling, Guizhou, China [27]. This rock avalanche has a long-runout distance of 1.5 km and a debris volume of 1.75×106 m^3. It instantly buried two villages and resulted in a death toll of 99. The rainfall from June 27 to 28, 2010, was the apparent triggering factor of this catastrophic avalanche. The measured rainfall more than 310 mm within 24 hours hit the local historical records over the last 60 years. The pore water pressure in the discontinuities of sandstone had a significant effect on the slope stability. The valley runoff supplied a saturated base for the long-runout debris, inducing an additional increase in the terminus distance and the velocity of the avalanche movement.

4. CONCLUSION

Landslides are a significant threat to the critical infrastructures, and this hazard has two type of phenomena: in the first case, the infrastructure is targeted by a sliding material, and in the second case is itself an integral part of the landslide. In both cases, the damage to the infrastructure may be a large and accompanied by significant losses of human life and recovery may be a long and very expensive.

In this paper, the authors have made a systematic review of 25 disastrous landslides caused by changing weather conditions and comparing their triggers (Table 1). It is interesting that trigger rainfall occurs in as many as 19 cases. In other cases occurs also extreme snow melt, storm-wave, natural gas hydrates, water seepage effect and melting of permafrost. So, weather conditions, such as heavy rainfall, due to the increase of groundwater level and soil saturation are common triggers of landslides occurrence.

The constrain of this paper refers to a relatively small number of analised cases from which the trend is noticed, but the statistical sample is not enough large to generalize the conclusions. The possible way of the study's continuation is to analyze a larger number of landslide events in order to obtain a representative sample for statistical analysis and hypothesis testing. It's expected that the climate changes in the coming decades cause a significant increase in precipitation, which will directly affect the increase in the number of active landslides.

Acknowledgements

The paper is written based an on-going collaborative research project titled EU-CIRCLE (A pan-European framework for strengthening critical infrastructure resilience to climate change). EU-CIRCLE is a project that has received funding from the European Union´s Horizon 2020 research and innovation programme. This publication reflects the views only of the authors and the EU-CIRCLE consortium members and the Commission cannot be held responsible for any use, which may be made of the information contained therein. The authors would like to acknowledge the consortium members who provided their contribution to the state of the art of existing knowledge about landslides as climate related hazard, especially ADITESS Ltd, Cyprus; NCSR-Demokritos, Greece; Fraunhofer, Germany; D'Appolonia, Italy; European University, Cyprus and Center for Security Studies – KEMEA, Greece.

Table 1. Review of catastophic landslides caused by climate driven

Place	Month /Year	Triggers	Consequences	Impact (damages – cost – recovery – casualities)
Kulekhani, Nepal [11]	Jul 1993	Rainfall	Debris flow	Watershed reservoir received a tremendous amount of sediments. This is the only reservoir in Nepal and supports one third of the total electric power generation of Nepal.
Rio Paute, Ecuador [12]	Mar 1993	Heavy rainfall	Debris flow and mudflow flooded the valley downstream for a distance of 50 km	Hydroelectric plant, hundreds of private homes and several industrial complexes. People were evacuated and there were no casualties.
Rio Colorado, Chile [12]	Nov 1987	Significant water infiltration trough the fracture system due to extreme snow melt	Debris flow traveled 50 km down	Campsite, access roads, bridges and equipment that were supporting construction of the El Alfalfal (160 MW hydroelectric power plant). Landslide caused an earthquake with magnitude M=3. Damage is estimated on $65 million. Full recovery time was 5 years. Landslide caused 29 deaths.
Coca River, Ecuador [13]	May 2013	Rainfall	Drinking water polution	Oil pipeline ruptured - loss about 11500 barrels in environment. 80.000 inhabitants stay without drinking water supply.
Mississippi Delta, USA [15]	Aug **1969**	Storm-wave **(Hurricane Camille) Bubble-phase natural gas; Temperatures increase; Pressures decrease**	Bubble-phase gas charging can degrade sediment shear strength; **Submarine landslides**	Failure of or damage to several offshore drilling platforms
Khyex River, Canada [16]	Nov **2003**	Rain	Liquefaction earth flow	Severed a natural gas pipeline leaving the communities of Prince Rupert and Port Edward without a gas heat supply for a period of 10 days (about 13.000 people). Damage is estimated on $1.3 million.
Dongxiang, China[18]	Mar **1983**	No trigger is evident	Landslide debris	Three villages were completely destroyed and 237 people were killed.
Cascade Shores, USA [19]	May **Dec 2005**	Heavy rain; **Rainstorm**	Bluff adjacent	Significant damages of wastewater treatment plant for 80 homes.
Antofagasta, Chile [12]	Jun **1991**	Unusually heavy rain	Several debris flows	Destroyed 402 houses and damaged more then 2.000. In addition, Antofagasta´s water-supply system, roads and railway lines were damaged, affecting a total of 21.000 people. Damage is estimated on $27 million. The debris flows and associated flash floods killed 101 people and resulted in another 48 missing.
Fort William, Scotland [1]	Oct **2014**	Heavy rain	Debris flow	Buried Scottish motorway A82.
Milan, Italy [1]	Jun **2016**	Rain	Rockfall	Buried Via Aurelia.
Maracay, Venezuela [12]	Sep **1987**	Heavy rainfall **saturated the residual soils on steep slopes**	Very rapid debris avalanches and debris flows	Worst landslide catastrophe in the history of Venezuela: 20 000 people returning from a weekend at the beach were trapped on several sections of the highway; many were killed by debris flows. 1500 homes, 500 vehicles, three bridges and 25 km of roads; 210 people were killed, 400 were injured, and more than 30 000 people were temporarily stranded.

Place	Month /Year	Triggers	Consequences	Impact (damages – cost – recovery – casualities)
Chunchi, Ecuador [12]	Mar 1983	Rains (wettest year of the centuri)	Landslide of slope	Blocked the Pan-American Highway, buried vehicles on the highway and killed more than 150 people.
Rio de Janeiro and Vicinity, Brasil [12]	Jan **Feb 1966**	Heavy rains	Floods and landslide	Killed more than1000 people.
Serra das Araras, Brasil [12]	Jan **Feb 1967**	Heavy rains	Floods and landslide	Property and industrial damage was described as inestimable. Much damage was done to important hydroelectric installations in the area and to the highway. Killed more than 1700 people.
Hluboce, Czech Rep. [20]	Mar **Apr 2016**	Rapid snow melting and intense precipitation	Earthflow	Earthflow destroyed three buildings, the access road and caused total loss of about 350 000 EUR.
Pink Mountain, Canada [21]	Jun **Jul 2002**	Melt of snowpack; **Rainfall**	Rock slide-debris avalanche	Landslide destroyed 43 ha of non-commercial forest, covered an access road, and came to rest within a few kilometres of a ranch house.
St Moritz, Swiss [19]	Aug **2014**	Heavy rains	Debris flow	Derailment. Eleven people are reported to have been injured.
Kitimat Arm, Canada [12]	Apr **1975**	Water seepage effects	A tsunami with a maximum recorded wave height of 8.2 m	Damaged a First Nations village.
Almora District, India [22]	Sep **2010**	Rainfall (Monsoon downpour)	Landslides and debris flows; **The flood surge caused toe erosion that triggered further landslides**	Almora's infrastructure, especially its road network, was badly disrupted. People were killed when their homes became engulfed in landslide debris and hundreds of trucks were trapped on roads that were, variously, blocked by landslides, undercut by landslides or washed out by river erosion. The disaster had affected around 80 % of the district's people and the total damages exceeded US $ 125 million.
Caracas, Venezuela [12]	Sep **1993**	Heavy rainfall plus leakage of wastewater at the site	Rockfall	Landslide completely destroyed seven expensive homes and a 150 m section of street in a high-cost residential area. The slide blocked the main access to the suburban development, adversely affecting 20,000 families. Total damage was estimated at $2 million (U.S.), and engineering remedial measures cost another $6 million.
Randa, Switzerland [25]	Apr **May 1991**	Loss of permafrost enabled the infiltration of surface water	Rockfall	Blocked the valley floor and the only road to Zermatt (about 5000 inhabitants). Flooded by the lake dammed by the rockslide possible rupture of this dam threatened the dwellings and the chemical industry facilities downstream.
Cordillera Blanca, Peru [12]	Jan **1962**	Melt of frost and permafrost	Ice avalanche; **Debris avalanche; Failure of the hanging glacier**	Nine small towns were destroyed and 4000-5000 people were killed. Cultivated fields were devastated, housands of farm animals were killed and great destruction occurred in an area famous for its beauty and fertility.
San Fernando, Chile [12]	Jan **1976**	Rainfall	Debris flow	San Fernando was almost totally destroyed - under 3 m of mud and rock; only a few houses situated on elevated slopes at the edge of the town were spared.
Guanling, China [27]	Jun **2010**	Rainfall	Rock avalanche	Avalanche buried two villages and resulted in a death toll of 99.

5. REFERENCES

1. EU-CIRCLE (2016). D1.2: State of the art review and taxonomy of existing knowledge. EU-CIRCLE Project (Grant Agreement n° 653824).
2. Geertsema, M. and Cruden, D. M. (2009). Rock movements in northeastern British Columbia. In Landslide Processes: From Geomorphologic Mapping to Dynamic Modelling, Strasbourg.
3. Cabinet Office (2011). Keeping the Country Running: Natural Hazards and Infrastructure. Whitehall London, 2011.
4. Božić, B., Lukić, I. and Petrović, N. (2015). Landslides as Threat to Critical infrastructure, Proceedings on 8th International Conference Crisis Management Days, Velika Gorica, ISBN 978-953-7716-66-0, 2015, p.285-298.
5. ITU (2014). Resilient pathways: the adaptation of the ICT sector to climate change.
6. Nadim, F., Kjekstad, O., Peduzzi, P., Herold, C. and Jaedicke, C. (2006). Global landslide and avalanche hotspots. Journal of the International Consortium on Landslides. 3 (2): 159-173.
7. Stoffel, M. and Huggel, C. (2012). Effects of climate change on mass movements in mountain environments. Progress in Physical Geography. 36(3): 421–439.
8. Hasan, S. and Foliente, G. (2015). Modeling infrastructure system interdependencies and socioeconomic impacts of failure in extreme events:emerging R&D challenges. Springer Science+Business Media, Dordrecht.
9. Taalab, K.P. and Cheng, T. (2015). Assessing the risk landslides pose to road and rail networks. 23rd GIS Research UK conference, 15th-17th April, Leeds.
10. Anderson, M., Brook, N., Holcombe, L., Newbold, D., Metson, S. and Wallace, M. (2008). High scale, computationally distributed landslide modelling. UK e-Science Programme, All Hands Meeting, York.
11. Dhakal, A.S., Amada, T. and Aniya, M. (2000). Landslide Hazard Mapping and its Evaluation Using GIS: An Investigation of Sampling Schemes for a Grid-Cell Based Quantitative Method. Photogrammetric Engineering & Remote Sensing. 66 (8): 981-989.
12. Schuster, R.L., Salcedo, D.A. and Valenzuela, L. (2002). Overview of catastrophic landslides of South America in the twentieth century. Reviews in Engineering Geology. Volume XV
13. American Geophysical Union (2013). AGU. Blogosphere [online], 12 June 2013, accessed 14 Feb 2016, URL: http://blogs.agu.org/landslideblog/2013/06/12/a-catastrophic-landslide-induced-oil-spill-in- ecuador-including-two-shocking-videos-of-the-pollution.
14. NBC (2015). Climate Risk Assessment for the Oil & Gas Sector. Project Report.
15. Locat, J.and Lee, H.J. (2000). Submarine Landslides: Advances and Challenges. Proceedings of the 8th International Symposium on Landslides, Cardiff.
16. Blais-Stevens, A., Schwab, J.W. and Geertsema, M. (2005). The Khyex River rapid earth flow, a catastrophic landslide near Prince Rupert, British Columbia, Canada. Geophysical Research Abstracts. Vol. 7, 07759.
17. Petrova, E. (2011). Critical infrastructure in Russia: geographical analysis of accidents triggered by natural hazards. Environmental Engineering and Management Journal. Vol. 10, pp. 53-58.
18. Zhang, Z.Y., Chen, S.M. and Tao, L.J. (2002). 1983 Sale Mountain landslide, Gansu Province, China. Reviews in Engineering Geology. Volume XV.
19. Nevada County Environmental Health Department (2005). Cascade Shores Wastewater Treatment Plant. Damaged by Landslide.
20. Klimes, J., Baron, I., Panek, T., Kosacik, T., Burda, J., Kresta, F. and Hradecky, J. (2009). Investigation of recent catastrophic landslides in the flysch belt of Outer Western Carpathians (Czech Republic): progress towards better hazard assessment. Nat. Hazards Earth Syst. Sci., 9, 119–128.
21. Geertsema, M., Clague, J.,Schwab, J. and Evans, S. (2006). An overview of recent large catastrophic landslides in northern British Columbia, Canada. Engineering Geology. 83: 120–143.
22. Haihg, M. and Rawat, J.S. (2011). Landslide causes: Human impacts on a Himalayan landslide swarm. Belgeo. 3-4: 201-220.

23 Taalab, K.P. and Cheng, T. (2015). Assessing the risk landslides pose to road and rail networks. In 23rd GIS Research UK conference.

24 J. Locat, J. (2001). Instabilities along ocean margins: a geomorphological and geotechnical perspective", Marine and Petroleum Geology. 18: 503-512.

25. Locat, J. and Lee, H.J. (2002). Submarine landslides: advances and challenges. Can. Geotech.J. 39: 193-212.

26. Poschinger, A. (2002). Large rockslides in the Alps: A commentary on the contribuiton of G. Abele (1937-1994) and a review of some recent developments. Reviews in Engineering Geology. Volume VX.

27. Yin, Y. (2011). Recent catastrophic landslides and mitigation in China. Journal of Rock Mechanics and Geotechnical Engineering. 3 (1): 10–18.

Sažetak

Klizišta predstavljaju značajnu opasnost za kritične infrastrukture i ta opasnost ima dva pojavna oblika: u prvom se slučaju infrastruktura nalazi na udaru klizećeg materijala, a u drugom je i sama sastavni dio klizišta. U oba slučaja šteta na infrastrukturi može biti velika i praćena značajnim gubicima ljudskih života, a oporavak dugotrajan i vrlo skup. Vremenski uvjeti, kao što su obilne padaline, usljed porasta razine podzemnih voda i vodozasićenosti tla česti su okidači nastanka klizišta. Očekuje se da će klimatske promjene tijekom predstojećih desetljeća izazvati i značajno povećanje količina oborina što će direktno utjecati i na povećanje broja aktivnih klizišta. U ovom radu daje se pregled utjecaja klimatskih promjena na opasnosti koje nastaju stvaranjem klizišta. Rad je rezultat znanstvenih istraživanja u projektu EU-CIRCLE, financiranom kroz Horizon 2020 program Europske unije.

Ključne riječi: Klimatske promjene, klizišta, kritične infrastrukture, EU-CIRCLE projekt.