Landslide hazard mapping for Lebanon

Cartographie des risques de glissements de terrain pour le Liban

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ABSTRACT: Landslides are a major hazard in Lebanon due to the country's rugged topography and its setting in a region of high seismicity and high rainfall intensity. The situation is further exasperated by rapid expansion in urban areas and lack of building code enforcement and land use regulations. In this work, we present a framework developed to assess earthquake-induced and rainfall-induced landslide hazards for the purpose of generating a comprehensive national map. Our goal is to raise the awareness of the need to address landslide hazards in the country and the associated consequences on human and capital losses. The proposed methods are based on the geological maps, a high-resolution digital elevation model (DEM), earthquake peak ground acceleration (PGA) maps, rainfall data, and a preliminary landslide inventory database. The results are calibrated over a representative region of Lebanon using the Geographic Information Systems (GIS). This study identifies the critical elements that aggravate the landslide hazard and/or present a major consequence of such an event. In addition to the obvious benefits for Lebanon, the methods developed and adopted in this work will be applicable globally and offer benefits for the mapping of landslide hazards in the community worldwide.

RÉSUMÉ : Les glissements de terrain constituent un danger majeur au Liban en raison de la topographie accidentée du pays situé dans une région à forte sismicité et à forte intensité de précipitations. La situation est encore exaspérée par l'expansion rapide dans les zones urbaines et l'absence d'application des codes du bâtiment et de réglementation de l'utilisation des terres. Dans ce travail, nous présentons un cadre développé pour évaluer les risques de glissements de terrain induits par les tremblements de terre et par les précipitations afin de produire une carte nationale complète. Notre objectif est de sensibiliser à la nécessité de faire face aux dangers des glissements de terrain dans le pays et aux conséquences qui en découlent pour les pertes humaines et les pertes en capital. Les méthodes proposées sont fondées sur les cartes géologiques, un modèle altimétrique numérique à haute résolution (MAN), des cartes d'accélération maximale du sol, des données sur les précipitations et une base de données préliminaires sur les glissements de terrain. Les résultats sont calibrés sur une région représentative du Liban à l'aide des systèmes d'information géographique (SIG). Cette étude identifie les éléments critiques qui aggravent le risque de glissement de terrain et/ou présentent une conséquence majeure d'un tel événement. En plus des avantages évidents pour le Liban, les méthodes développées et adoptées dans ce travail seront applicables au niveau mondial et offrent des avantages pour la cartographie des risques de glissements de terrain dans la communauté à travers le monde.

KEYWORDS: landslide, earthquake, rainfall, GIS, hazard

1 INTRODUCTION

Earthquake-induced landslides occur in great numbers across large regions following significant (M > 5) earthquakes (e.g. Keefer 1984; Rodríguez et al. 1999). For example, the 1989 **M**6.9 Loma Prieta, California earthquake caused an estimated 1,280 landslides within a highly impacted zone of 2,000km^2, over a total region affected by landsliding close to 15,000km^2 (Keefer, 2000). Extreme precipitation events can also cause multiple landslides across an affected region, but the number of initiated landslides is typically less during major rainstorms.

Lebanon is a country that is located in a relatively high seismic zone with a rugged topography making it vulnerable to landslide hazards due to earthquakes and rainfall. Although Lebanon has not experienced any major earthquake since 1956, the recent discovery of an active thrusting fault close to its coastline has significantly raised its risk of being hit by a high magnitude earthquake (Elias et al. 2007). Studies on the seismic hazards in Lebanon have focused on seismic zoning and its impact on the structural engineering design (Huijer et al. 2011). At the same time, many researchers have assessed slope stability hazards in certain areas of Lebanon based on static conditions such as change in elevation of groundwater table, rainfall rate, slope angle, bedrock exposure, bedrock jointing and dipping, and distance to faults. No effort has been done to assess the impact of a seismic or rainfall event on the risks of triggering landslide hazards across the whole country.

Regional scale forecasting models (i.e., 1:250,000–1:25,000, Corominas et al., 2014) are valuable because they have the potential to capture "system-level" performance and spatial propagation of hazard across a region. Such capabilities are particularly important when considering the effects of landslides on geographically distributed critical infrastructure systems, which are highly susceptible to damage caused by slope failures (e.g. Wartman et al., 2003). Past approaches to regional-scale landslide hazard assessment (e.g. Jibson et al., 2000; Saygili and Rathje, 2008;) have been traditionally based on infinite-slope analyses or regression to a single formula from available landslide inventories. Field investigations have revealed a diverse style of landslides dues to earthquakes and rainfall including shallow disrupted soil or rock slides, rotational slumps, and lateral spreads. Infinite-slope analysis has been shown to effectively capture shallow disrupted soil slides only (Dreyfus et al. 2013). A regional scale assessment would not be complete unless it considers all types of coseismic and rainfall-induced landsliding.

In this paper, we present a multimodal approach for landslide hazard mapping in Lebanon where a landslide inventory is incomplete making it impractical to apply regression-based assessment procedures. The details of the model for coseismic landslide hazard assessment can be found in Grant et al. (2016). We explain in the following paragraphs the procedure that we followed to generate the landslide hazard maps for earthquake-induced and rainfall-induced sliding potential.

2 LANDSLIDE HAZARD IN LEBANON

Lebanon is a small (10,452km^2), mountainous, country located along the eastern Mediterranean (Figure 1). Numerous deeply incised east-west trending river valleys shape the western slopes of the Mount Lebanon Range. East of the Mount Lebanon Range, the landscape slopes steeply down over sparsely vegetated slopes to the Yammouneh fault, the major left-lateral restraining bend of the Levant Fault System (LFS). From the LFS, the terrain slopes gently to the Bekaa Valley, a major agricultural region. Continuing east, the relatively barren limestone mountains of the Anti-Lebanon Range rise to ~2,500m over rolling hillslopes that form Lebanon's border with Syria.

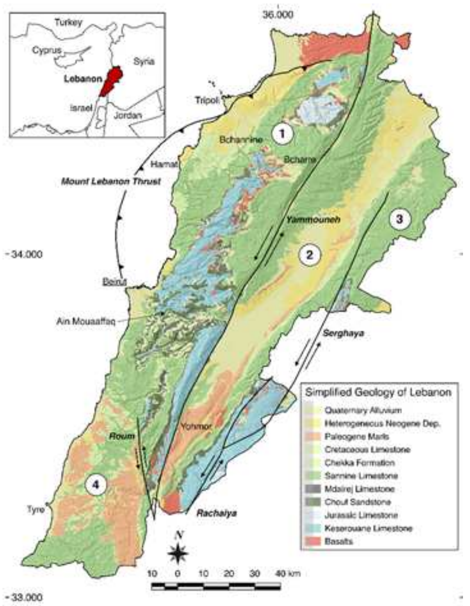

Figure 1. Major geologic units and faults (bold) of Lebanon and locations referenced in this work.

Geologic units in Lebanon are principally limestone and sandstone, dating back to the Early Jurassic. Four of these units, Kesrouane limestone, Sannine limestone, Chouf sandstone, and the Mdairej limestone, dominate the landscape. The Chouf sandstone unit is widespread and highly fractured. Sea-level rise during the Late Cretaceous led to the further deposition of limestones (Sannine and Mdairej), which were later uplifted to form the modern Mount Lebanon and Anti-Lebanon ranges. Today, the Sannine limestones form the highest slopes of the Mount Lebanon range and are largely structurally intact. The older Mdjairej limestones form a nearly continuous band of cliffs at mid to high elevations and are a major source of rockfalls.

The regional tectonics shaping Lebanon are dominated by three zones of movement. The offshore Mount Lebanon Thrust (MLT) is undergoing compressional displacements of 1.0-2.0mm/a (Elias et al., 2007). The Yammouneh fault, which bisects the length of Lebanon and bends eastward to compress and uplift the Mount Lebanon Range, is slipping at an estimated rate of 5.1±1.3mm/a. The coupled Rachaiya-Serghaya fault system, a left-lateral strain-partitioning complex through the Anti-Lebanon Range, shows 1.4±0.1mm/a of movement (Gomez et al., 2003). Huijer et al. (2011) aggregated the three major seismic sources in the region to producing the PGA values adopted for this work.

The basic causes of landslides are inherently linked to the composition and structure of the soil or rock, inclination of the slopes, groundwater table, rainfall intensity, seismic vibrations, and even construction activity. Many landslides occur annually in Lebanon due to these causes. In fact, most of the sudden landslide/collapse events in Lebanon (along roads and excavations done for the purpose of construction) occur after sudden and intensive long periods of rainfall. A high groundwater level is one of the frequent and main factors that influence the stability of a slope. The hazard is even higher when the infiltration of water into the ground due to rain or snow melt leads to increase in pore pressures and softening of the soil shear strength. The most recent example of such devastating failures happened in the northern town of Hasroun on March 12, 2015. The sloping terrain and heavy rainfall during that winter season led to the collapse of a water pond in the mountainous town resulting in a massive debris flow that quickly ran down the valley. Several homes were damaged, cars were displaced, the main Bsharri-Hasroun road was blocked, and two persons were injured.

Given the rugged topography of Lebanon, it is clear that ideal conditions for mass movement are available along the country's steep mountain sides. We conducted the landslide hazard mapping for Lebanon using estimates of the geological strength, a digital elevation model (DEM), rainfall records, and peak ground acceleration predictions. Rainfall rates were extracted from Plassard (1971) and complemented with the recent records from the national Meteorological Office. Peak ground acceleration values were obtained from the most recent probabilistic seismic hazard assessment study done by Huijer et al. (2011). We estimated soil and rock strength parameters (c and □) based on available geologic mapping (Dubertret 1945), unpublished engineering consulting reports, and in consultation with geotechnical professionals practicing in the area. A summary of the rock and soil parameters used in this work is presented in Grant et al. (2016). The DEM was developed at a resolution of 15m by digitizing contours from 1:20,000 scale topographic map of the country (DGA, 1963).

3 MODEL DEVELOPMENT

In a study of 40 historic earthquake-induced landslide datasets seven types of landslides were found to be "very abundant" or "abundant", including soil lateral spreads, soil slumps, and rock slides (Keefer, 1984). This work focuses on four key modes of failure: rock failures, disrupted soil slides, coherent soil failures (rotational slides or slumps), and lateral spreads. Less commonly occurring modes of failure, such as soil falls or slow earth flows are omitted, as they are unlikely to occur in most earthquakes. Debris-flows and rock wedge failures are considered in the rainfall-induced landslide hazard assessment. General limits on slopes susceptible to specific modes of failure have been observed. We used this simple approach to separate the landscape into zones susceptible to each mode of failure, as well as an intermediate zone of low likelihood of landsliding from 6 – 20°. The slope classification, shown in Table 1, was implemented rather than a statistical regression to a landslide dataset as no such temporal and specific landsliding data is available for Lebanon.

3.1 *Mode-specific earthquake-induced landslide hazard calculations*

Disrupted and coherent modes of failure (as listed in Table 1) were treated in a similar framework. DEM data was converted to slope angles and soil and rock strengths parameters were obtained from the geology maps in order to calculate yield accelerations. Yield accelerations were then used to predict Newmark displacements via Jibson (2007) probabilistic seismic hazard analysis (PSHA) shaking intensities. Lateral spreading was handled separately, due to a lack of geospatially continuous subsurface data. It was treated in a simple framework to predict regions most susceptible to significant co-seismic displacements. Figure 2 shows the geometries used for each mode of failure in order to calculate the factor of safety against sliding per pixel.

Table 1. Summary of modes of failure considered in this study. Modified from Grant et al. (2016).

Landslide Category	Slope Range	Characteristics
A. Disrupted Rock Slides	35 - 90°	Landslide movement typically rapid. Movement by free fall, sliding, and/or rolling. Run-out often long, tens of meters to km.
B. Disrupted Soil Slides	20 - 50°	Landslide movement moderate to rapid. Movement by sliding. Displacements of meters to a hundred meters common.
C. Coherent Soil Slides	20 - 35°	Landslide movement typically slow to moderate. Movement by slumping or rotational sliding of a coherent mass. Displacement typically small (<2m), but large displacements have been reported in many instances.
D. Lateral Spreads	0 - 6°	Landslide movement typically rapid. Movement by the translational movement of a semi-liquid mass. Displacements typically small (<2m), but may be large in the case of flow failures.

Rock-slope failures were modeled as Culmann wedge-like masses (Duncan et al., 2014). This methodology captures both the brittle behavior typically associated with rock-slope failures and the planar nature of structural controls (i.e., discontinuities). The local topographic slope, and local relief, coupled with the internal friction angle of the rock, defined the wedge geometry. We assumed rock-slope failures act along the top quarter of local relief for any given hillslope.

Factors-of-safety against shallow disrupted sliding were calculated assuming dry infinite slope-like failure while including root cohesion to the most intensely vegetated portions of our study region. We assumed a failure plane depth of 2m based on Northridge studies where observations showed that typical landslide depths were between 1-2m, and shallow sliding failures rarely exceeded 2-3m for slopes of 30-60°.

To analyze coherent, slump-like, rotational slides in a pixel-based GIS platform, we developed a uniform idealized failure surface that combines larger hillslope conditions with individual pixel properties (i.e. c and □). We determined local hillslope relief (H) and assumed that the radius of a circular failure plane (R) acting through a dry homogeneous hillslope would be one and a half times the local relief (R = 1.5H, Fig. 2C). By constraining R and assuming a circular-segment shaped failure body, we compute the internal angle (δ) and failure plane length (L =2δR [m]). Adopting the solution for yield acceleration developed by Kim and Sitar (2004) for an ordinary method of slices analysis, and projecting our 2D circular failure across each pixel as a cylindrical surface of width y, yield accelerations were computed on a per-pixel basis for dry slopes using a single slice calculation, as shown in Grant et al. (2016).

3.2 *Mode-specific rainfall-induced landslide hazard calculations*

The two most common modes of failure that occur during intense storms or periods of extended rainfall in Lebanon are debris flows and rock wedge failures. The potential for debris flow failures was assessed using the Montgomery and Dietrich (1994) debris flow model which provides a quantitative method to assess the topographic influence on shallow landsliding. Soil saturation, assessed through a hydrological model, and potential for slope instability were combined with the DEM data to predict the critical steady-state rainfall quantity necessary to initiate slope failure throughout a catchment area. The model was relatively simple and easy to apply in an area where a spatial and temporal landslide inventory is unavailable.

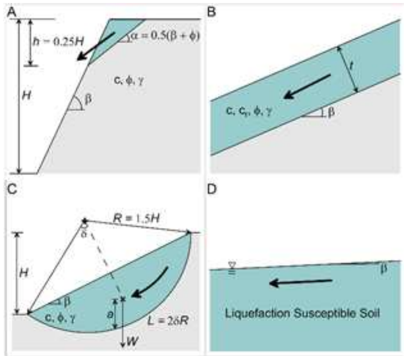

Figure 2. Geometry used for each mode of failure. A. Rock slope failures, B. disrupted soil slides, C. coherent soil failures, D. lateral spreads.

Factors-of-safety against rock-slope failures due to heavy rainfall were assessed as Culmann wedge-like masses similarly to the conditions applied for earthquake-induced rock-slope failures. Here, we considered the wedge failures act along the top quarter to middle height of the local relief for any given hillslope and the effect of rainfall was incorporated by filling the crack with water and adding the pore pressure into the calculation of the factor of safety. Here, we assumed that the crack was dry prior to the rainfall events and became fully saturated at the time of failure.

4 LANDSLIDE HAZARD AREAS IN LEBANON

4.1 *Earthquake-induced landslide hazards*

Huijer et al. (2011) conducted a probabilistic seismic hazard analysis (PSHA) to develop updated ground shaking intensity maps for Lebanon. The 10% chance of exceedance in 50 years (i.e., 475-year return period) PGA values are highest (~0.35g) along the coast near the MLT and also along the Yammouneh fault. For the 475-year return period PSHA ground motions, our analyses identify areas having a high disrupted soil slides and rock-slope failure hazards along the steeply incised river valleys of the Mount Lebanon Range (Fig. 3A) and close to the Litani River canyon near Yohmor (Fig. 3B). We did not find densely concentrated high co-seismic landslide hazard zones for these disrupted modes of failure in other parts of the country. Isolated cliff bands and talus slopes across the western portion of the country exhibit a low to moderate hazard that is limited to small, localized zones. We identified moderate coherent landslide hazard levels near the Abou Ali River in Bchannine (Fig. 3A) in the north-central Mount Lebanon Range. In other areas of the country, we found a low to negligible hazard for this mode of landsliding. In recent deposits along the coast and Litani River of the Bekaa Valley moderate to high lateral spreading hazard was predicted. The highest concentration of high lateral spread hazard was identified near Beirut, where anthropogenic fill and alluvial deposits lie close to the MLT fault that locally drives higher PSHA acceleration values.

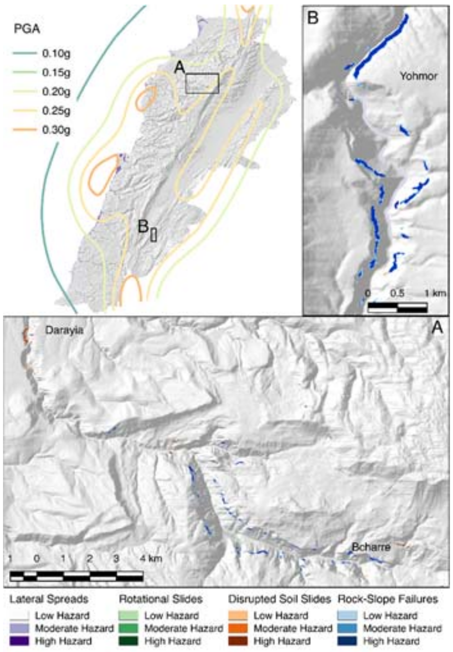

Figure 3. Multimodal landslide hazard output for 475-year (10% in 50 years) return period PSHA ground shaking intensities

4.2 *Rainfall-induced landslide hazards*

For the average annual rainfall values of Plassard (1971), our analyses again identify areas having high debris flow and wedge failure hazards along the steeply incised river valleys of the Mount Lebanon Range (Fig. 4A). Cliff bands and talus slopes across the western portion of the country exhibit high hazard of rock wedge failures (Fig. 4B). The highest concentration of high debris flow hazard was identified in the northern part of the country where rainfall amounts are significantly larger along the western side of the Mount Lebanon Range.

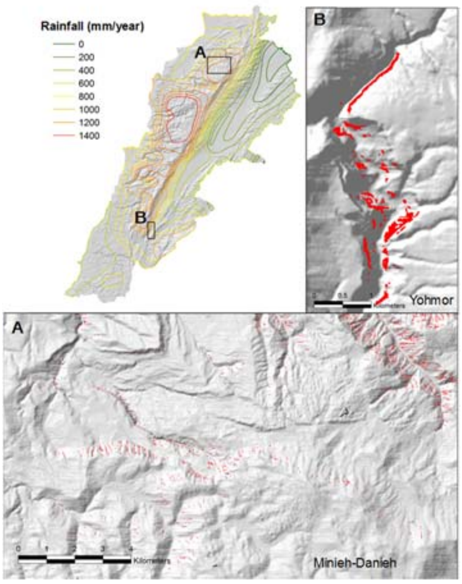

Figure 4. Multimodal landslide hazard output for average annual rainfall based on Plassard (1971)

5 ACKNOWLEDGEMENTS

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6 REFERENCES

Keefer D.K. 1984. Landslides caused by earthquakes. *Geol. Soc. Am. Bull.* 95, 406-421.

Rodriguez C.E., Brommer J.J., Chandler R.J. 1999. Earthquake-induced landslides: 1980-1997. *Soil Dyn. Earthq. Eng.* 18 (5), 325-346.

Keefer D.K., 2000. *Statistical analysis of an earthquake-induced landslide distribution—the 1989 Loma Prieta, California event.* Eng. Geol. 58 (3), 231–249.

Elias A., Tapponnier P., Singh S.C., et al., 2007. Active thrusting offshore Mount Lebanon: source of the tsunamigenic AD 551 Beirut-Tripoli earthquake. *Geology* 35 (8), 755–758.

Huijer C., Harajli M., Sadek S., 2011. Upgrading the seismic hazard of Lebanon in light of the recent discovery of the offshore thrust fault system. *Lebanese Science Journal.* 12 (2), 67.

Corominas J., VanWesten C., Frattini P., et al., 2014. Recommendations for the quantitative analysis of landslide risk. *Bull. Eng. Geol. Environ.* 73 (2), 209–263.

Wartman J., Dunham L., Tiwari B., Pradel D., 2013. Landslides in eastern Honshu induced by the 2011 Tohoku earthquake. *Bull. Seismol. Soc. Am.* 103 (2B), 1503–1521.

Jibson R.W., Harp E.L., Michael J.A., 2000. A method for producing digital probabilistic seismic landslide hazard maps. *Eng. Geol.* 58, 271–289.

Saygili G., Rathje E.M., 2008. Empirical predictive models for earthquake-induced sliding displacements of slopes. *J. Geotech. Geoenviron.* 134 (6), 790–803.

Dreyfus D., Rathje E.M., Jibson R.W. 2013. The influence of different simplified sliding block models and input parameters on regional predictions of seismic landslides triggered by the Northridge earthquake. *Eng. Geol.* 163, 41–54.

Grant A., Wartman J., Abou-Jaoude G. 2016. Multimodal method for coseismic landslide hazard assessment. *Eng. Geol.* 212, 146-160.

Gomez F., Meghraoui M., Darkal A.N., et al., 2003. Holocene faulting and earthquake recurrence along the Serghaya branch of the Dead Sea Fault system in Syria and Lebanon. *Geophys. J. Int.* 153 (3), 658–674.

Plassard J. (1971). Pluviometric map of Lebanon at a scale of 1: 200,000. *Republic of Lebanon. Ministry of Public Affairs. General Direction of Civil Aviation.*

Dubertret L., 1945. *Cartes géologiques à l'échelle de 1/50 000 (Hamidieh, Halba, Batroun, Tripoli, Sir El Dannieh, Jbail, Qartaba, Baalbeck, Beirut, Zahle, Rayak, Saida, Jezzine, Rachaya).* République Libanaise, Ministère des Travaux publics, Beyrouth, Liban.

DGA, Direction of Geographic Affairs, 1963. Topographic Maps at a Scale 1:20,000. *Republic of Lebanon.*

Jibson R.W., 2007. *Regression models for estimating coseismic landslide displacement.* Eng. Geol. 91 (2), 209–218.

Duncan J.M., Wright S.G., Brandon T.L., 2014. *Soil Strength and Slope Stability.* John Wiley & Sons, Hoboken.

Kim J. and Sitar N., 2004. *Direct estimation of yield acceleration in slope stability analyses.* J. Geotech. Geoenviron. 130 (1), 111–115.

Montgomery D. R. and Dietrich, W. E. (1994). A physically based model for the topographic control on shallow landsliding. *Water resources research*, *30*(4), 1153-1171.