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FINDINGS ON THE EARTHQUAKE RISK PREPAREDNESS OF THE CITY OF LA PAZ, BOLIVIA

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Abstract

Located on the Bolivian altiplano and built on the slopes of the canyon network eroded by the Choqueyapu river and its main tributaries, the city of La Paz is no stranger to natural disasters, having suffered catastrophic floods, hailstorms and landslides in recent memory, such as the hailstorm in 2002 that caused at least 69 deaths and 100 disappearances or the 2011 Pampahasi-Cayapa mega-landslide, which destroyed more than 800 homes. However, despite its location in the South American subduction context and evidence of paleoseismicity in local fault networks, historical and instrumental seismic activity has been relatively low and therefore not a priority in local settlement and construction practices. As part of an ongoing effort by local authorities to increase risk preparedness, a preliminary diagnosis of the earthquake risk preparedness of the city was commissioned by the Municipality of La Paz, with funding from the European Commission DIPECHO programme. This study, whose main findings are presented in this paper, is based on a review and analysis of seismic hazard literature as well as a series of interviews with local actors in the fields of catastrophe management, geological research, seismographic surveillance, land-use planning and structural design. An assessment of the seismogenic potential of local faults and a simple deterministic seismic hazard analysis are first carried out to give an idea of possible hazard. This information is then completed with an analysis of existing vulnerabilities from a legislative and urban planning point of view, as well as commentary on current risk management efforts. Finally, the earthquake hazard is analyzed in the context of a high landslide hazard, analyzing the interactions between risk management strategies for both types of hazards particularly with respect to earthquake-induced landslides.

Keywords: La Paz, Bolivia; earthquake risk preparedness; triggered landslides; deterministic seismic hazard analysis

1. Introduction

This article presents some selected results of a diagnosis of seismic risk and induced landslide risk management and preparedness in the city of La Paz carried out by BRGM (*Bureau de Recherches Géologiques et Minières*) in 2014. The full report reference is found under [1].

The city of La Paz, the administrative capital of Bolivia, is a large metropolis built on the eponymous valley in the Altiplano. At an altitude of over 3600 m, it is the highest administrative capital in the world, and a city of extremes, with a particularly high natural hazards profile due to highly mobile local geology, very abrupt topography, and harsh weather, including a very intense rain season. These factors combine to create a densely populated city that is highly prone to slope instabilities, floods and hailstorms. An analysis of the geological and natural risk situation of La Paz was carried out in the 1970s by BRGM researchers [2] which remains to this day the most thorough study on the subject, but has been updated by works such as the landslide hazard, vulnerability and risk maps carried out by the local municipal risk management team [3].

And yet, despite being a South-American metropolis located relatively close to the Pacific coast, a region known for its large destructive earthquakes, the region of La Paz lacks records of historical earthquakes, with the area remaining fairly aseismic in recent memory. This has resulted in a situation where seismic risk has been neglected compared to the large investments in managing landslide and flood risks. In fact, one of the first questions which we had to give an answer to in our consultancy was whether there was significant earthquake hazard in La Paz.

2. Context and methodology

This project took place as part of the project “Building Urban Resilience to Natural Hazards in the Metropolitan Areas of La Paz and El Alto”, financed by the General Directorate of Humanitarian Aid and Civil Protection of the European Commission together with The Oxford Committee for Famine Relief (OXFAM GB) within the framework of the VIII DIPECHO (Disaster Preparedness ECHO Programme) Action Plan, and subscribed by OXFAM GB in Bolivia and FUNDEPCO (Fundacion para el Desarrollo Participativo Comunitario).

As part of the consultancy a series of interviews with the main local actors in natural risks preparedness in La Paz were carried out over the course of two visits, supplemented with a literature review and several field visits to the sites of recent and old landslides in La Paz. Members of the following bodies were interviewed during this time:

- the Special Directorate of Integrated Risk Management (DEGIR), now renamed the Municipal Secretariat of Integrated Risk Management (SMGIR) of the Autonomous Government of the Municipality of La Paz (GAMLP);
- the Directorate of Territorial and Cadastral Administration of the GAMLP;
- the Directorate of Municipal Research and Information of the GAMLP;
- the Faculty of Geological Sciences of the Universidad Mayor de San Andrés (UMSA);
- the Bolivian Institute of Standardization and Quality (IBNORCA);
- the San Calixto seismic observatory;
- the Geological and Mining Survey (SERGEOMIN);
- the National Meteorology and Hydrology Service (SENAHMI);
- the Bolivian Engineers’ Society (SIB).

In paragraph 3 we also present a basic deterministic seismic hazard assessment, using standard approaches to estimate maximum possible earthquakes for the identified near- and far-field sources and a range of PGA values possible in La Paz.

3. Regional seismic hazard

3.1 Seismotectonic context of La Paz

Nearly a third of Bolivia belongs to the Andes mountain range, whose origin is closely linked to the subduction of the Nazca plate under the South American plate, being located directly above the very tectonically active subduction zone. The Bolivian segment is located on the central part of the Andes range, at a location where the orogenic axis presents a notable curvature towards the north-west. It constitutes the widest portion of the Andes, at over 600km width, and is divided into a number of linear mountain ranges, separated by basins, the largest of which is the Bolivian Altiplano where the city of La Paz is located, a massive plateau located between the Cordillera Occidental and Cordillera Oriental at an altitude between 3600 m and 4100 m. The basin, currently endorheic, is riddled by normal faults with large offsets, particularly in the East, where the Altiplano is bordered by the abrupt faulting relief of the Cordillera Oriental and recent studies point towards the possibility of a mega-earthquake on the Mandeyapecua fault [4].

The Nazca plate subducts under the South American at an angle of about 15º in Bolivia, as can be seen by the increasing depth of the hypocenters in Figure 1: between 70 and 150 km under the Cordillera Occidental and then between 150 and 250 km under the Altiplano. After the Cordillera Oriental, the subduction plate descends rapidly, reaching more than 600 km of depth in the Eastern sub-Andine region.

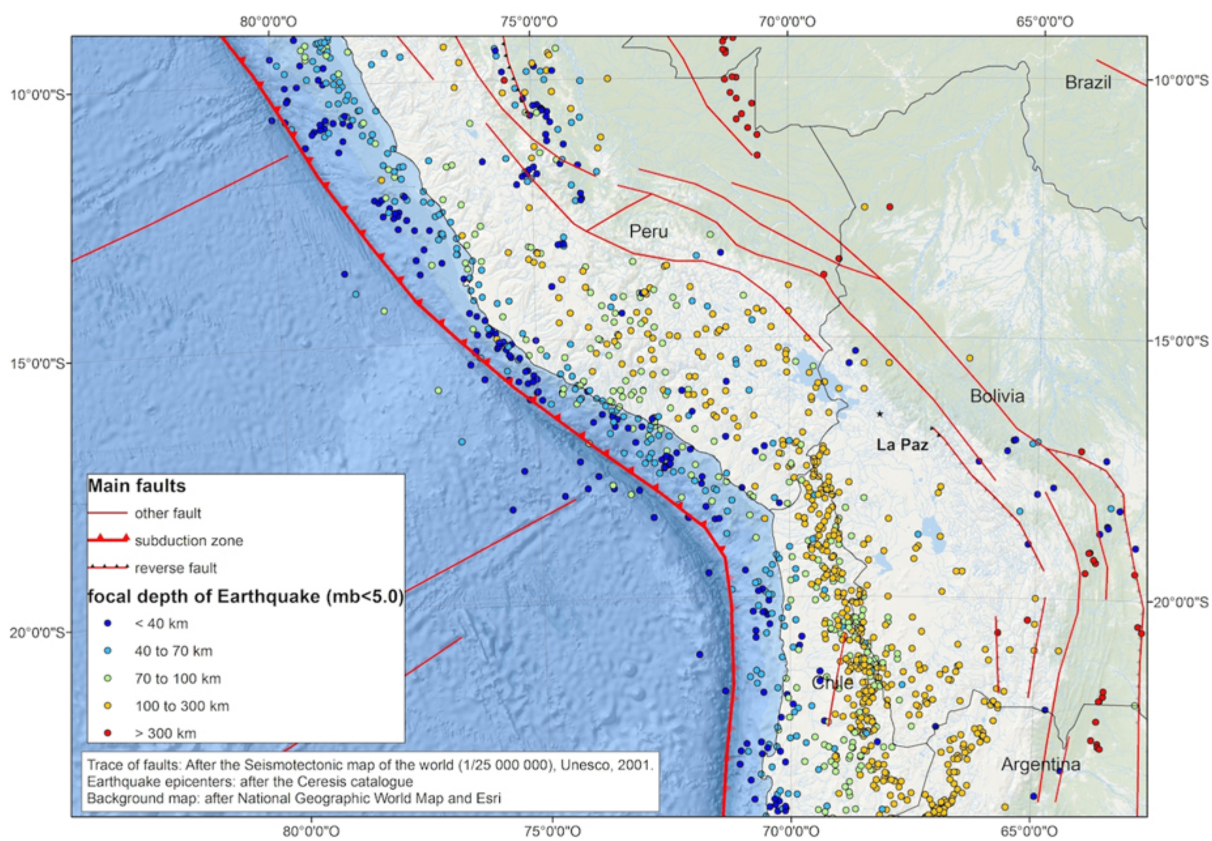

Fig. 1 – Seismotectonic context of Bolivia. References: Trace of faults [5]; earthquake epicenters [6]; background [7]

Apart from the earthquakes in the Benioff zone, seismicity has also been detected inside the leading South American plate. These earthquakes are less frequent and of lower maximum magnitude than those in the Benioff zone. The strongest quake measured in Bolivia in the Benioff zone is that Mw 8 earthquake of 1994, at 630 km under the Beni department. As to the South-American intraplate earthquakes, the GEM-ISC catalog [8] indicates a strong concentration of earthquakes in the Cochabamba and Santa Cruz de la Sierra regions, including the magnitude 6.5 earthquake of the 22nd of May 1998 at an estimated focal depth of 25 km. Despite the lower frequency and magnitude of intraplate earthquakes, the shallow depths can generate fault ruptures that can propagate to the surface.

As to near-field sources, tectonic studies show many active normal and strike-slip faults are visible on the Altiplano, and a number of them in close proximity to La Paz [9, 10, 11]. We will be focusing on the two most notable examples:

The best-known near-field fault is the so-called El Alto fault, located to the southwest of the city of La Paz on the Altiplano. This fault in described in [12] and has been the subject of trenches to study its paleoseismicity. The database on active faults in Bolivia (http://observatoriosancalixto.com/bdtectonica) maintained by the San Calixto Observatory indicates a normal drift of about 0.2 mm/year for a fault length of 1.5 km (this is probably a secondary segment of the fault) and a maximum possible magnitude of 5.1.

To the southwest of La Paz, the trace of the El Alto fault is a system of staggered kilometric faults with normal behaviour. These stepped segments are lined up from the northeast to the southeast, with the fault segments curving towards the east. Indeed, the El Alto fault trace does not correspond to a single fault plane, but to various smaller secondary faults that together constitute the El Alto fault system. The paleoseismicity trenches show that this system has had activity at various points during the Quaternary period. The current known length for the fault system is of 8 km. If we apply the empirical laws proposed by Wells & Coppersmith [13] we can estimate that earthquakes of magnitude around 5.7 for rupture lengths of 8km. With a mean displacement of 0.2 mm/year, we'd then obtain a return period of about 100 years for 5.7 magnitude quakes. These are very rough approximations, and more precision is required particularly to characterize the geometry of the seismogenic segments, but we can still estimate 5.7 magnitude quakes with a return period of a few centuries to 100 years.

To the south of La Paz we also encounter the Amachuma fault, with a northeast-southeast orientation, of about 40 km length, normal behaviour, a displacement velocity of about 0.1 mm/year and a maximum magnitude of Mw 7.0 according to the Tectonic Database. Again applying the Wells & Coppersmith relations for a 40 km rupture, we would obtain a corresponding magnitude of Mw 6.8 (±0.5).

3.2 Deterministic hazard analysis

Based on an analysis of regional seismicity, seismic hazard is evaluated using peak ground acceleration (PGA) as an indicator for the different seismogenic sources identified as having the potential to affect the city of La Paz. The objective is only to evaluate whether earthquakes affecting La Paz could provoke building damages and trigger landslides. We have chosen this approach because the currently available Seismic and Seismo-Volcanic Hazard map of Bolivia [14] seems to inadequately account for far-field sources, omitting them from the final analysis. In order to propose conservative scenarios, the largest recorded Mw magnitude for each source is displaced to the closest epicentral distance within the source to La Paz. The median PGA and its first standard deviation σ are then calculated for each scenario using two attenuation models selected following the recommendations in the Technical Report PEER 2013/22 [15] to obtain an interval with a maximum and minimum PGA value per scenario. The following sources have been considered:

- Scenario 1: An interplate subduction earthquake (depth 20-50 km) off the Peru-Chile coast, such as the Mw=8.4 23/06/2001 earthquake in this region.
- Scenario 2: An intraplate subduction earthquake (depth 100-150 km) under the Peru-Bolivia frontier, such as the Mw=8.2 9/12/1950 Chile earthquake.
- Scenario 3: A deep subduction earthquake in Bolivia (depth 600 km) like the Mw=8.2 9/6/1994 quake.
- Scenario 4: A mega-earthquake on the Eastern side of the Cordillera Oriental, as shown by models of the Mandeyapecua fault. A magnitude of Mw=8.2 similar to scenarios 2 and 3 is chosen.
- Scenario 5: A shallow earthquake on one of the near-field faults around La Paz, with a magnitude of Mw=5.7 as per our estimates (see previous paragraph).

Table 1 presents the specific parameters chosen for each scenario. Figure 2 presents the location of the chosen scenario earthquakes. The following attenuation laws were used:

- For subduction zones (Scenarios 1, 2 and 3): Zhao *et al.* 2006 (Zetal06) [16] and Atkinson & Boore 2003 [17]
- For active shallow zones (Scenarios 4 and 5): Chiou & Young 2008 (CY08) [18] and Akkar & Bommer 2010 (AB10) [19] attenuation laws.

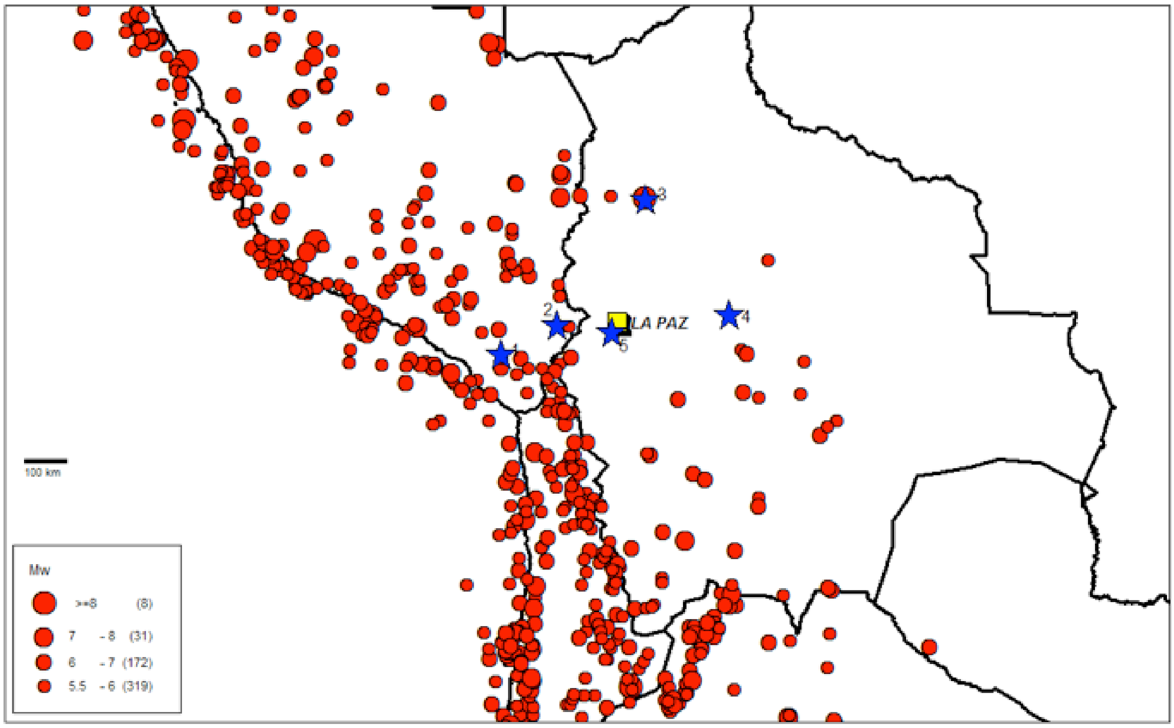

Fig. 2 – The red dots denote the instrumental quakes of Mw≥5.5 between 1900 and 2009 from the ISC-GEM Global Instrumental Earthquake Catalog [8]; the blue stars denote the five proposed scenarios. Image source: [1]

Table 1 – Depths, distances and Mw magnitudes of the five proposed scenarios

Scenario number and name	**Depth**	**Epicentral distance**	**Distance to fault rupture**	**Mw magnitude**
Scenario 1: Interplate subduction on the Peru-Chile coast	30 km	280 km	280 km	8.4
Scenario 2: Intraplate subduction on the Peru-Bolivia border	140 km	140 km	200 km	8.2
Scenario 3: Deep subduction in Bolivia	600 km	290 km	666 km	8.2
Scenario 4: Cordillera Oriental megaquake	20 km	250 km	250 km	8.2
Scenario 5: El Alto fault system shallow earthquake	10 km	10 km	14 km	5.7

As can be seen in Table 2, Scenario 2 provokes the strongest accelerations, with a PGA of 0.2g before taking site effects into account, which due to local geology could easily double the acceleration. This is a worstcase scenario without any consideration for return periods, but it gives a picture of what could happen in La Paz. Moving the same scenario to 200km distance from La Paz still produces PGA values between 0.1g and 0.2g before site effects. Furthermore, near-field Scenario 5 would have consequences only slightly less severe than Scenario 2.

The levels of PGA obtained for Scenarios 3 and 4 indicate that damage could be expected in areas of site amplification, whereas Scenario 3 would be widely felt but probably would not cause damage.

In any case, these preliminary calculations show that La Paz is indeed exposed to damaging earthquakes, with the near-field faults around La Paz and the 100-150 km subduction activity on the border of Bolivia deserving a more detailed study.

Table 2 – Calculated PGA values for the five proposed scenarios using two different models each

	Attenuation Model 1		**Attenuation Model 2**		**Resulting PGA interval**
	median PGA	*median PGA + σ*	*median PGA*	*median PGA + σ*	
Scenario 1	14 mg (AB03)	26 mg (AB03)	38 mg (Zetal06)	75 mg (Zetal06)	14-75 mg
Scenario 2	198 mg (AB03)	369 mg (AB03)	260 mg (Zetal06)	515 mg (Zetal06)	198-515 mg
Scenario 3	4 mg (AB03)	7 mg (AB03)	4 mg (Zetal06)	7 mg (Zetal06)	4-7 mg
Scenario 4	18 mg (CY08)	30 mg (CY08)	46 mg (AB10)	89 mg (AB10)	18-89 mg
Scenario 5	125 mg (CY08)	236 mg (CY08)	108 mg (AB10)	205 mg (AB10)	108-236 mg

4. Urban planning and risk management context

The “Atlas of vulnerability of the Metropolis of La Paz” [20] is currently the most up-to-date analysis of urban and systemic vulnerability for the city La Paz. It highlights in particular the very delicate situation regarding the transportation network: Beyond the daily congestion problems, whole boroughs can be rendered isolated fairly easily if the very few roads that link them to the rest of the city are cut off. This high vulnerability is in part due to the topographical challenges and the large number of rivers, which create chokepoints in the shape of bridges. One of the most memorable examples was in 2002 after the deadly hailstorm, when the whole Zona Sur was left isolated and without access to healthcare services, despite not having suffered significant damage. Cutting off roads and blocking access to certain boroughs has even become a form of protest in La Paz, often used as leverage during strikes.

However, possibly the biggest challenge to effective preventive urban planning in La Paz is the combination of a very high demographic pressure and a slow and contradictory legal framework for building permits and urban planning. Despite a slowdown in recent years compared to the period of large migrations in the 1980s due to the mining crises, the latest estimates from the National Statistics Institute (INE) registered a yearly population growth rate of 1.5% for the period of 2005-2010. For many years, the process of obtaining a legal construction permit was very slow compared to the very large population increase, inciting people to build illegally, and there have been various waves of regularization of buildings that were not within the norms motivated by political interest. The new law of urban land use, the LUSU (*Ley de uso de suelos urbanos*) of 2012 is a big step forward, explicitly putting the objective of risk reduction through urban planning first and foremost and introducing a series of measures to expedite building permits, as well as clearly setting limitations for building types according to the natural risks profile of each area of the city. However, as recently as 2011 contradictory legislation was still being passed, such as the municipal bylaw of 2011 for “zonation and zonal valuation of the urban area" which introduced a 15% tax break for housing tax in zones of very high risk. This tax break constituted a counterintuitive incentive to live in these areas.

Furthermore, the LUSU cannot counteract all the problems imposed by the rapid growth of La Paz: as the metropolitan area expands beyond the limits of the municipality of La Paz, where the LUSU applies, the city struggles to regulate the regions of its metropolitan area that are now located in other municipalities, particularly towards the south. Whole new areas of La Paz are being built in the municipalities of Achocalla, Mecapaca and Palca that fall outside the jurisdiction of the LUSU. In these areas town planning initiatives are vulnerable to "loteadores", opportunistic businesses that carry out earthworks and sell land parcels without following the city's stipulations. These earthworks have reportedly often been of dubious quality, increasing landslide risk.

In any case, problems specific to seismic risk, such as local site amplification, have so far not been considered for urban planning. The struggle to impose urban planning measures may explain why the municipality has so far concentrated more on operational risk management measures.

5. Construction codes and practices

Bolivia lacks a seismic code. After the failure of the proposal of a Bolivian Standard of Seismic Design in 2006 to move beyond the proposal stage, a new code is currently in development at the Bolivian Institute of Standards and Quality (IBNORCA), but its date of introduction is yet to be announced. In the meantime, the Bolivian Engineer's Society (SIB) of La Paz, which is in charge of validating construction projects, reports that they are requiring all buildings to at least demonstrate a degree of seismic resistance by applying an equivalent foreign code, such as the Chilean building code. It is however uncertain how successful this measure is, particularly if there is no certainty about the level of seismic aggression to apply for La Paz.

A cursory visit to La Paz shows that there is a strong homogeneity in building types. A generalized lack of surface finishes shows that, outside of the Miraflores area where there is a variety of high-rise buildings, the residential quarters are mostly composed of low to midrise (2 to 4 stories) buildings designed as reinforced concrete frames with masonry infills. The infills are generally single shiner bonds (the bricks are laid on the narrow side, the broad side is exposed) and have very thick mortar beds. The same type of clay brick was used in nearly all of the observed buildings. The SIB reports that the average concrete cylindrical strength is H20, and that concrete with strength over H40 is rarely produced in La Paz, and there is an insufficient amount of steel reinforcement, as well as a lack of ductility detailing. Floor slabs are composed of thin concrete slabs supported by a network of beams in both directions, with the rectangular spaces between beams filled with blocks of polysterene. Visits to construction sites showed that beams in one direction are constructed first and then the other direction is added. A common architectural element is an overhang (about 50 to 70cm) of the frontal facade over the ground floor.

Regularly infilled concrete frames can have good behavior during earthquakes if they are properly constructed, even for self-built structures. However, two important factors that contribute to heightened building vulnerability were spotted during our visit to La Paz: The first is the addition of extra stories during the building's lifetime. This practice is fairly widespread in a city where space is so limited. It is particularly obvious in the poorer areas, where the ground floor is often made of baked clay bricks while higher stories made of better materials. Adding weight in this manner can severely impact the behavior of structures. The second factor is the use of slender piers or pilotis in order to build on the severely abrupt landscape. This practice is rarer, since in La Paz earthworks are often performed to level the terrain prior to construction but, in the areas where pilotis were spotted, they were present in most buildings in a borough, as seen in Fig. 3. These piers are very fragile and can significantly endanger a building's performance during an earthquake.

Fig. 3 – Use of slender pilotis in La Paz. Image source: [1]

6. Landslide risk

Triggered landslides pose a significant risk in case of earthquakes, a notable example being the Las Colinas landslide triggered by the 2001 El Salvador earthquake, causing more than 585 deaths. Landslides are triggered by earthquakes mostly through two mechanisms: either through liquefaction of moisture-saturated soil layers, which have a reduced shear resistance, or through the generation of destabilizing inertial forces, which are added on top of mobilizing forces. Ruptures can be either simultaneous to the earthquake or happen after a lapse of time. Sometimes the main shock merely destabilizes the slope, and it is an aftershock that provokes the landslide.

The city of La Paz is built on the basin of the river of the same name, at a point where several of its main tributaries some together. Together, these rivers have excavated a series of basins with more than 400m between the highest and lowest point, creating a very abrupt topography with high inclinations. Landslide risk in La Paz is well-documented, with the 1977 study by BRGM [2] already delineating areas of the city where landslide hazard is very high.

According to the Landslide Risk Map [3], the most up-to-date document on the subject, detailing 36 high risk areas in the city, more than a third of the current urban area is located on slopes with more than 50% inclination and the zones which are being added to the city will further increase that proportion. Only about a third of La Paz is located in areas with less than 10% slope. Local geology, as described in [21], is also very dynamic: the homonymous La Paz geological formation, a succession of glacial and fluvioglacial sediments in the Altiplano, evidenced by the succession of gravels and clays that characterize it, is highly mobile, and has a history of large mudslides and landslides.

These high slopes and mobile geology are compounded with a harsh mountain climate, characterized by a heavy rainfall season between September and April, ensuring soil saturation. Furthermore, the dense urbanization means the slopes must bear high loads. Most of the city also lacks a wastewater system, meaning infiltration of human wastewater into the soil can also facilitate ground movements. The groundwater situation in La Paz is overall very complex due and constitutes a major risk factor.

Catastrophic landslides such as the Cotahuma landslide in 1996, causing 40 deaths, have marked recent memory. However, the city of La Paz and especially the teams at DEGIR (now called SMGIR) in charge of landslide risk management can also claim important successes, such as the crisis management of the Retamani landslide in 2009 and the mega-landslide of Pampahasi-Callapa in 2011, neither of which caused any victims thanks to timely evacuation, despite the latter destroying more than 800 houses.

Landslide risk management has since become a high priority for the municipality. Several strong points were identified:

- The high level of experience and training of the city's risk management staff.
- A high amount of well-organized data for landslide hazard studies: the municipal geotechnical laboratories keep a georeferenced record of all geotechnical experiments and a second, landslide-specific geotechnical database was compiled for the creation of the 2011 Landslide Risk Map. Furthermore, a database of historical landslides (based on photographic and orthophotographic records) is currently in development.
- Good knowledge of vulnerability and exposure levels: physical and socioeconomic vulnerability analyses were carried out for the preparation of the Landslide Risk Map. The municipality also maintains a database of the impacts of recent landslides on citizens and buildings, as well as a record of reparation actions and associated costs.
- Prevention initiatives such as the Zone Stabilization Plan (PEZ, Plan de Estabilización de Zonas), which seek to control and mitigate landslide hazards before damage takes place.

However, some areas of improvement were detected during our consultancy:

- No real-time monitoring of known landslide areas, and a lack of monitoring of areas where mitigation measures have taken place, making it difficult to ascertain their effectiveness.
- Emphasis on crisis management over risk management. This is not surprising, due to the high incidence of slope instabilities requiring big efforts in crisis management.
- Mixed success with mitigation measures, particularly retaining walls on slow landslides which have had to be repaired and strengthened several times.
- Insufficient interaction between concerned organisms: there is a particular lack of cooperation and knowledge-sharing between municipal bodies, such as the SMGIR, and national bodies, such as SENAHMI or SERGEOMIN, as well as lack of collaboration with the San Calixto seismic observatory.
- Absence of consideration of triggering factors, seismic or hydrological, in the current Landslide Risk Map.

This last point in particular deserves to be addressed, particularly in the light of the acceleration levels estimated in paragraph 3.2. However, despite the current absence of supporting calculations, the very high slope instability hazard that dominates much of the city leads us to believe that in case of an earthquake in La Paz, a destructive triggered landslide is a highly likely scenario, and could potentially prove more destructive than the direct impacts of the earthquake itself.

7. Conclusion

Risk preparedness activities in La Paz have so far prioritized crisis management and hazard mitigation through large public works such as the construction of containment walls to mitigate landslide risk and the canalization of river beds. Much less has been done in terms of risk prevention by reducing exposure and vulnerability.

As shown by our calculations, the regional seismotectonic context makes the existence of a significant seismic hazard undeniable but more research is required in order to adequately quantify the hazard levels. This regional context is compounded with a local hazard context whereby both strong site and topographic amplification effects are likely, as well as induced events such as soil liquefaction and triggered landslides. The latter is particularly worrying, due to the very high landslide hazard in the city even before taking earthquakes as a triggering factor into account. The city of La Paz has already taken big steps towards assessing and quantifying its landslide risk thanks to the Landslide Hazard Map, but this map does not sufficiently take meteorological and seismic trigger mechanisms into account. Deficient knowledge of the location and behavior of groundwater tables within the city, which are a major driver in landslide and induced landslide risk in a city without a sewage system, also needs improvement.

Many of the encountered problems in risk management are organizational and political: despite successful efforts to champion risk management initiatives by the SMGIR, there remains a lack of communication, cooperation and knowledge-sharing between many stakeholder organisms, including the local seismic observatory, meteorological agency, geological survey and national civil protection authorities. The strong demographic pressures and complex political power structure have also made it difficult to impose measures such as building standards and preventive urban planning that could help reduce risk.

Despite the lack of a national seismic code, under the initiative of the local engineers' association and thanks to the influence of neighboring countries such as Chile, engineered buildings in La Paz are often constructed following state-of-the-art seismic codes, but which level of hazard to apply remains an open question, leaving the achieved level of structural resistance uncertain. Furthermore, many types of local non-engineered structures follow simple designs and avoid many of the pitfalls that can make a structure more vulnerable to earthquakes, the main identified weakness being again the exposure to landslide risk due to faulty geotechnical and foundation work.

The city of La Paz has so far shown good initiative in managing its natural risks and can report big successes in its management of landslide risk. If the outlined problems are addressed, a large amount of progress could be made in the short and midterm.

8. Acknowledgements

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