ASSESSING LAHAR AND FLOOD HAZARDS IN THE CITY OF AREQUIPA, PERU: A CONTRIBUTION TO RISK MANAGEMENT

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INTRODUCTION

Risks due to earthquakes, volcanic eruptions and floods threaten large cities in the Andes. Arequipa, Peru's second largest, with one million people, is exposed to earthquakes, volcanic eruptions of El Misti volcano, lahars (volcanic debris flows) and flash floods. Following previous investigation initiated by Blaise-Pascal University, IRD and Peruvian partners and Civil Protection, our project termed 'Laharisk', funded by the French ANR RiskNat, has brought together geologists, economists, geographers and civil engineers. A multidisciplinary field campaign was conducted in summer 2010 in the city of Arequipa. The research objectives were threefold: (1) delineating hazard-prone areas with emphasis on lahars deposits, (2) assessing the physical vulnerability of buildings and bridges to lahar impacts, and (3) investigating the behavior of people at risk using surveys and experiments.

SETTING, LAHAR DEPOSITS AND CHARACTERISTICS

The city of Arequipa is located in a tectonic basin drained by the Rio Chili Valley in SW Peru. Besides earthquakes, the major persistent threat is the active El Misti volcano (5822 m asl.), located 17 km NE of the historical center of the city (2300 m asl.). Lahars and flash floods, the most recurrent flow categories in the city area (1.5 in every 10 years on average), are serious threats because these events can be triggered either during and after eruptions (e.g. AD 1440-1460 and c.2030 yr BP) or as a result of heavy rainfall (>30 mm/hour) for example in 1989, 1997, and 2011. Floods or debris flows can also be caused by the failure of natural dammed lakes and construction dams in the Rio Chili canyon, W and N of El Misti.

Field and laboratory observations point to the existence of three types of lahar deposits in the Arequipa area: fine hyperconcentrated-flow deposits (FHF), coarse hyperconcentrated-flow deposits (CHF), and debris-flow deposits (DF). We have measured the dry density and grain-size distribution and conducted methylene blue tests for clay determination on 41 soil samples. Both FHF and CHF lahar deposits are fine sand- and silt-rich deposits that lack clay particles. Two types of geotechnical tests were also carried out: (i) 39 in situ dynamic cone penetration soundings (PANDA-penetrometer) in ten sites on terraces across the Rio Chili Valley; (ii) Casagrande shear-box tests and oedometric tests on the fine-grained fraction (<400µ) of the three categories of deposits. Field investigations and laboratory tests led to the conclusion that lahar deposits show a low dry density (1.25 g/cm^3) and a high friction angle of 34.1-37.8°.

VULNERABILITY OF BUILDINGS AND URBAN INFRASTRUCTURE

We used three methods to assess the vulnerability of buildings and infrastructure. First, we identified critical parameters (pressure, velocity, density) of lahars as well as their recurrence and spatial distribution in order to estimate the load on structures. This first assessment is based on the study of the hydraulic characteristics of flows and the geotechnical characteristics of lahar deposits. Second, we

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characterized the conditions of buildings and urban infrastructure (roads, bridges, lifelines, communication systems, etc.) that may be damaged by lahars and floods in order to assess the resistance of engineered structures. Third, we assigned a vulnerability ranking to structures by combining lahar and flood impacts with land use, construction categories and conditions, and their mechanical resistance to debris flows and/or floods.

The goal of the Arequipa fieldwork was to collect data on geometry, location, building typology, construction materials and the mechanical resistance of bridges and buildings. We evaluated the present conditions of six bridges built over the Chili River within the city, plus two over the *Quebradas* (=ravines) Huarangual and San Lazaro tributaries. Nine groups of buildings were identified in the Rio Chili Valley and on the volcaniclastic fan of Quberada Huarangal NE of the city. Building groups were identified at the city-block scale and ranked according to: dominant building material, number of floors, roof type, opening type and quantity, age and maintenance of buildings, and overall building structural integrity. Tests on density, velocity, porosity, and Unconfined Compressive Strength of materials used in construction were carried out at the University in Arequipa and in Clermont. The data on Peruvian construction methods were collected in order to compare the actual methods with those required by law.

ELICITATION OF RISK ATTITUDES AND TIME PREFERENCES

To protect the population from potential damages due to lahars, this study aims to assess some of the key determinants of people's behaviour: (1) people's risk-perception with respect to their exposure to lahar risk (2) people's attitude to risk, and (3) people's subjective discount rate.

Based on questionnaires and experiments, we contrasted respondents' risk perception and risk attitudes by comparing exposed and non-exposed areas with respect to his/her location next to the nearest ravines, which cross Arequipa. Data from 209 participants in three densely populated *quebradas* were collected: 145 live in exposed areas, 40% have suffered damage due to lahars or floods in the past, 89% of the participants live with their families, 76% own their homes, 40% have a monthly income below 300 Soles (90 €); 30% are unemployed. Thirteen experimental sessions involved 16 to 20 respondents each, and each session included three parts: (1) Respondents answered questions that helped us to assess their knowledge and perception of lahar risk. (2) Respondents participated in incentivized experiments by which their risk and time-preferences were elicited on standard experimental protocols. They also participated in two experimental games (a trust game, an ultimatum bargaining or a step-level public good provision). Each game was intended to elicit a particular trait of their behavioral profile: competitiveness, cooperativeness or trust. (3) Respondents answered questions about income and social characteristics such as religiosity and stated trustfulness.

We were surprised to find that although respondents displayed a significant risk perception depending on whether they lived in exposed and non-exposed areas, those respondents who lived in exposed areas were not significantly more risk-averse than those living in non-exposed areas. Respondents whose income was more than twice the minimum wage exhibited lower impatience in non-exposed areas compared to those living in exposed areas. There is no correlation between respondents' *stated trust* (elicited in Part 3) and their *trusting behavior* (elicited in Part 2).

CONCLUSION AND OUTLOOK

A field survey and the analysis of lahar deposits and chronology of past events were carried out in order to delineate lahar and flood-prone areas. As a result, two maps embedded in a GIS portray a system of terraces in two selected pilot areas: the Rio Chili Valley across the city and the volcaniclastic fan of Huarangal. These terraces are defined according to five degrees in magnitude/frequency lahar and flood events. It is expected that the research project will contribute to raising the awareness of the population and helping the civil authorities implement prevention planning in the city of Arequipa in case of future eruptions, lahar~~s~~ and flood events. This process started in March 2011 when the City Hall of Arequipa began enforcing laws about construction standards in the city suburbs on the SW flanks of El Misti.

Keywords: hazard, lahar, geotechnics, vulnerability, infrastructure, risk attitude, risk management.