AUTOMATIC SYSTEM FOR POST-EARTHQUAKE EVALUATION OF CITY DAMAGE IN BOGOTÁ

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ABSTRACT

This work presents the development of a system for the automatic evaluation of damage after an earthquake in the city of Bogotá. The Laboratory of Automatic Seismic Instrumentation (LISA in Spanish: Laboratorio de Instrumentación Sísmica Automática) was established with the aim of bolstering the management of seismic risk in Bogotá, particularly regarding emergency response, given that it provides key information for the proper allocation of physical and human resources in an earthquake crisis. The system performs a continuous and on-line monitoring of Bogotá's Accelerograph Network where ground motion is recorded at rock level when an earthquake occurs. The recorded signal is sent via telemetry to the central data repository of the District's Institute for Risk Management and Climate Change (IDIGER, in Spanish), where LISA initially executes a series of validation processes to determine if it corresponds to a real seismic event or not. Once the signal is validated, the one-dimensional dynamic response of the city soils is modeled using a geotechnical model comprised of synthetic stratigraphy generated over a calculation grid that covers the entire city. Complete accelerograms are obtained at surface level for each grid point, from which maps showing the distribution of strong motion intensities can be obtained for the whole city (in terms of PGA and spectral accelerations among others). Immediately afterwards the system determines the expected damage for each asset in the city given the ground motion felt at the site, as well as the probability of collapse and the probable number of deceased and injured people. The results are reported to e-mail accounts and phone numbers of city authorities and registered users within minutes of the event, where the report contain general damage values and maps with neighborhood and block resolution.

Keywords: Post-earthquake damage assessment; Automatic systems; Emergency response; CAPRA.

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1 Introduction

Ten years have passed since the development of the first version of CAPRA (Cardona et al. 2012; Marulanda et al. 2013). Since then, several improvements have been made to the software, new models were added, and specific models were developed for cities, regions and governments. The new CAPRA platform looks very differently than its original version. One of the main improvements was the development of systems for the automatic assessment of post-earthquake damage in cities (LISA in Spanish, Laboratorio de Instrumentación Sísmica Automática: Laboratory of Automatic Seismic Instrumentation). Currently there are four LISA systems developed for the cities of Manizales (SISMAN-LISA) and Bogotá (SISMARB-LISA) in Colombia, and Port-of-Spain and San Fernando (Quake Response) in Trinidad and Tobago. These specific versions of CAPRA take into consideration local and very specific issues of the seismic conditions of the cities to provide suitable inputs for comprehensive earthquake risk management (Cardona 2001, 2004, 2011; Carreño 2006; Marulanda et al. 2009).

The LISA system for Bogotá was developed as part of a specific project of adaptation of the CAPRA platform for the District's Institute for Risk Management and Climate Change (IDIGER) in 2016. The result was the launch of the SISMARB software platform (SISMARB is an acronym in Spanish that stands for Hazard and Risk Modeling System of Bogotá), which includes the LISA module.

LISA is a tool designed to improve disaster risk management in Bogotá, particularly with respect to preparedness and emergency response, as it provides important inputs for the appropriate assignment of physical and human resources during an earthquake crisis. The LISA system currently installed in the city, constantly monitors the accelerograph network from which receives the acceleration time-history recorded after the occurrence of an earthquake, and automatically calculates the intensities of strong motion at the ground surface, and the expected building damage throughout the city. These results are published to an FTP site and sent via email and SMS to the city authorities and users registered in the system. The LISA system incorporates procedures and methodologies compatible with the current state of knowledge, so that the city of Bogotá nowadays has a reliable and efficient tool for dealing with seismic emergencies. The system has capabilities of database storage of events, automatic analysis of seismological variables, remote administration and protocols for automatic publication of reports via the internet, as can be seen in Figure 1.

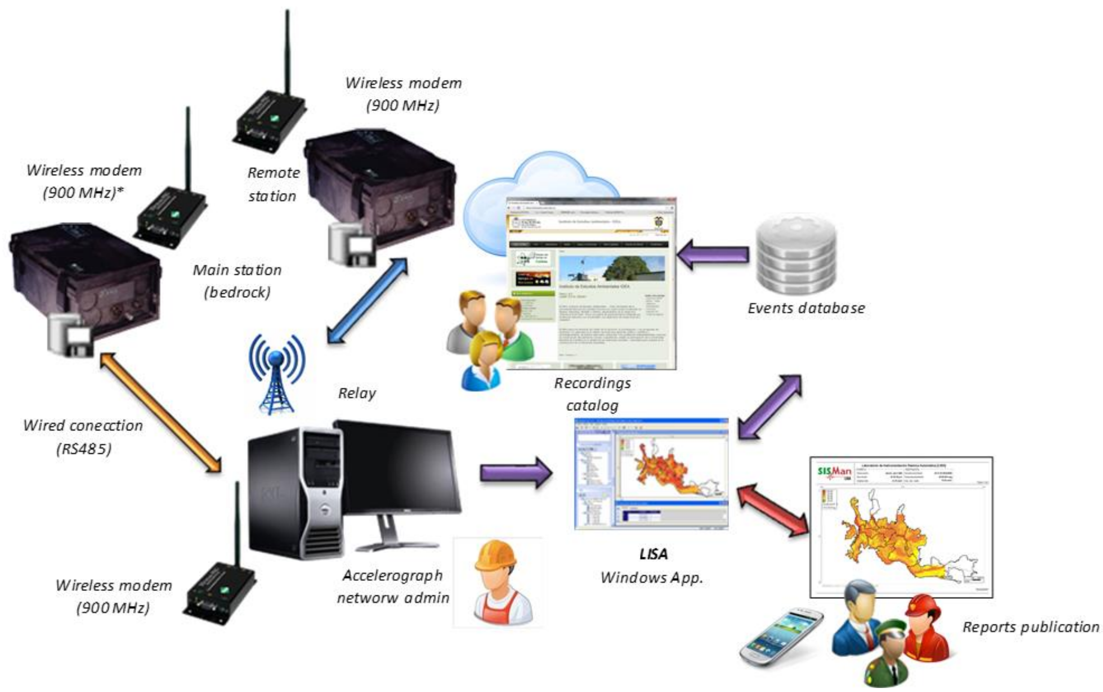


Figure 1. Structure and main components of LISA.

2 Verification of acceleration-time histories

Given the nature of automatic operation of LISA, it is important to have a mechanism for verifying the information recorded by the central station, in order to rule out possible situations that trigger the equipment and which do not correspond to actual earthquakes. To this end the system was designed for processing seismic signals which allows to determine, under certain general criteria, whether or not a registered signal is a signal corresponding to an earthquake.

To prevent the system to be triggered undesirably, protocols for automatic verification of seismic signals are set in order to establish for a fact that the signal comes from an earthquake. This verification could be done directly by consulting with other sensors on the network, however since the response time of LISA should be as soon as possible, this check is made only on the central station. Verification of the seismic signals is performed by studying the following characteristics: Response Spectrum, Fourier Spectrum and Husid Plot. Once verified that the signal is indeed an earthquake, it is sent to the calculation engine to continue with the process.

3 Site response model

The soil dynamic response model of Bogotá is a continuous model in which it is possible to calculate the dynamic response at any location within the city. This model is based on the methodology proposed by Bernal (2014) and can be seen in detail in Cardona (2016) and Bernal et al. (2017). This geotechnical model allows to synthetically determine the stratigraphy of any location and thus proceed to the one-dimensional evaluation of the dynamic response of the soft soil deposit.

3.1 Geotechnical information

Twenty-three exploratory drillings constitute the best basis of geotechnical information for the city in terms of evaluation of the dynamic response of the soil. Most are located on the deposits of pyroclastic fall. Each drill has the following information in depth:

- Soil classification in the USCS system.
- Description of the layer's material.
- Natural soil moisture, Atterberg limits (liquid limit and plastic limit) and index properties derived from these (plasticity and liquidity indexes).
- Specific weight.
- Shear wave velocity measured by down hole test.

3.2 Geometry of the geological formations

The depth to the bedrock was established by combining the information derived from the geotechnical explorations and the scientific knowledge related to the geological formations within the city A city-wide distribution of the depth of the soil deposit was generated (see Figure 2). Bogotá soft soils come from alluvial (Subachoque formation) and lagoon (Sabana formation) deposits. According to Helmens and Van der Hammen (1995), the Subachoque formation consists mainly of fine materials alternating with clayey sands and gravels. The Sabana formation, which is lacustrine deposits that outcrop throughout the entire savannah of Bogotá, is mainly composed of clays (Cardona and Yamin, 1997). The topography used in this study has a spatial resolution of 30 m and was obtained from ASTER GDEM NASA project.

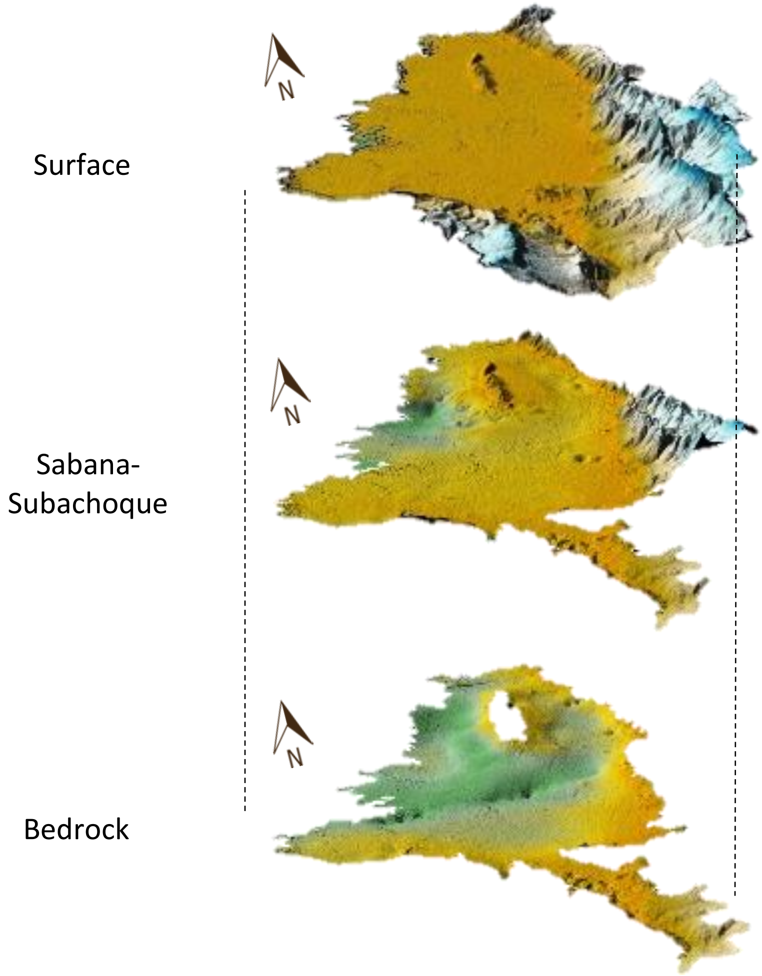


Figure 2. Scheme of the geometrical model in axonometric projections

3.3 Geotechnical model of seismic response

A modern methodology for evaluating site effects in cities was applied, which is based on the generation of synthetic stratigraphy at arbitrary locations. This stratigraphy is the basis for the evaluation of the dynamic response of soft soils. A stratigraphy is built based on the geometry of geological formations and soil types defined for each. Soil types account for the variation in depth of the statistical moments of all geotechnical properties. This means that the geotechnical properties are modelled as random variables. Geotechnical properties included in the model are:

- Moisture content
- Atterberg limits (liquid limit and plastic limit)
- Index properties (plasticity index and liquidity index)
- Specific weight
- Shear wave velocity

For each geotechnical property, a probability model is fitted by using a multicriteria approach based on the composite result of three statistical goodness-of-fit methods: Chi-squared, Kolmogorov-Smirnov and Anderson-Darling. In all cases, several probability distributions are tested, including: Normal, Lognormal, Gamma, Pearson III, Weibull, Gumbel, Logistic and Log-Logistic. This allows to randomly create a stratigraphy at any site, as seen schematically in Figure 3.

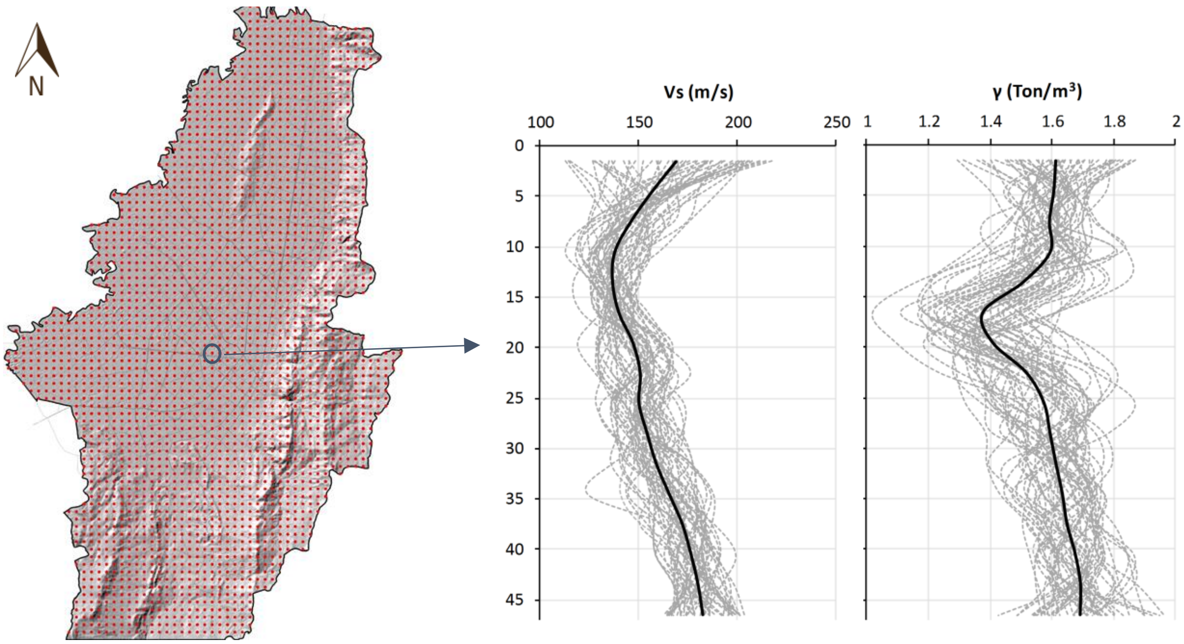


Figure 3. Synthetic stratigraphy generated at any location in the city

The degradation models of shear modulus and damping for the soil types defined in Bogotá were assigned as the Ishibashi and Zhang (1993) model for the Sabana formation, and the average value of given by Seed and Idriss (1970) for the Subachoque formation, as proposed by Bernal (2014).

For any synthetic stratigraphy, one-dimensional dynamic response is calculated using a nonlinear behavior model (linear equivalent). The dynamic response is calculated using the equivalent linear analysis method, first proposed by Idriss and Seed (1968). The linear response calculations were done using the propagator matrix method of Thompson- Haskell (Thompson 1950; Haskell 1953).

4 Shakemaps generation

The dynamic response across the city is mapped to reflect the intensity of the strong motion throughout the city. This type of maps are commonly known as shakemaps (i.e. maps of shaking) and are of great importance in the context of the development of SISMAN-LISA since they are the basis to establish the level of strong motion intensity in the location of each building. Damage to structures can be easily associated with a single parameter of strong motion, which is nothing more than a simplification of the real complexity of the field of accelerations incident in a building. To estimate damage in buildings, it is usually sufficient to know the following strong motion parameters:

- Peak Ground Acceleration (PGA)
- Spectral Accelerations (SA) for various structural vibration periods.

Despite this reality, the system will generate maps of other variables of interest in earthquake engineering, in order to generate as much information as possible for complete characterization of the seismic event. Additional parameters to be estimated are: peak ground velocity (PGV), peak ground displacement (PGD), ratio PGV / PGA, RMS (Root-Mean Square) acceleration, RMS velocity, RMS displacement and Arias intensity.

Using kriging for spatial interpolation, LISA will generate raster maps of the geographical distribution of each of the parameters defined above. These maps are the shakemaps that serve as input for calculating the expected damage. Figure 4 shows the shakemaps for Bogotá as subjected to the ground motion recorded in the Bocatoma station during the 1999 Quindio (Colombia) earthquake. Both the accelerograph and the resulting shakemaps of PGA and SA for five structural periods are included in the figure. It is important to note that LISA assumes that the motion at the bedrock, which is registered in the central station, is equal at the base of the soft soil deposit for any location in the city. The generation of the full dynamic response in the city of Bogotá takes about two minutes[3].

5 Damage assessment

From the shakemaps, LISA evaluates the expected damage in all buildings in the city of Bogotá, so that the authorities and institutions responsible for emergency response receive first-hand information regarding the places most affected within the city.

5.1 Exposure database

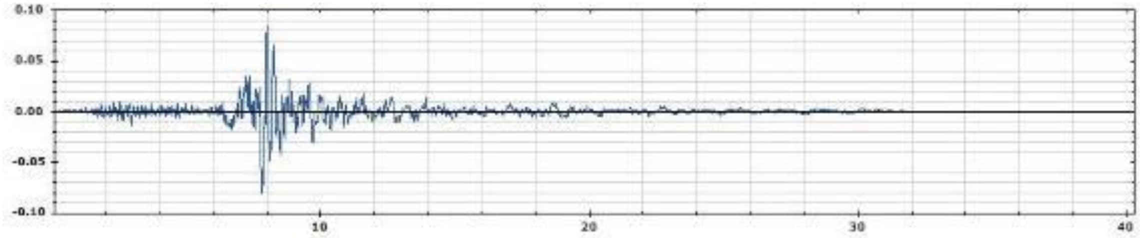
The database containing the location, appraisal and structural characteristics of the buildings in Bogotá was compiled by Cardona (2016) and is used in this paper as a basis for damage assessment. The database has 897,583 buildings. Figure 4 presents the distribution of the year of construction and number of stories of the city buildings.

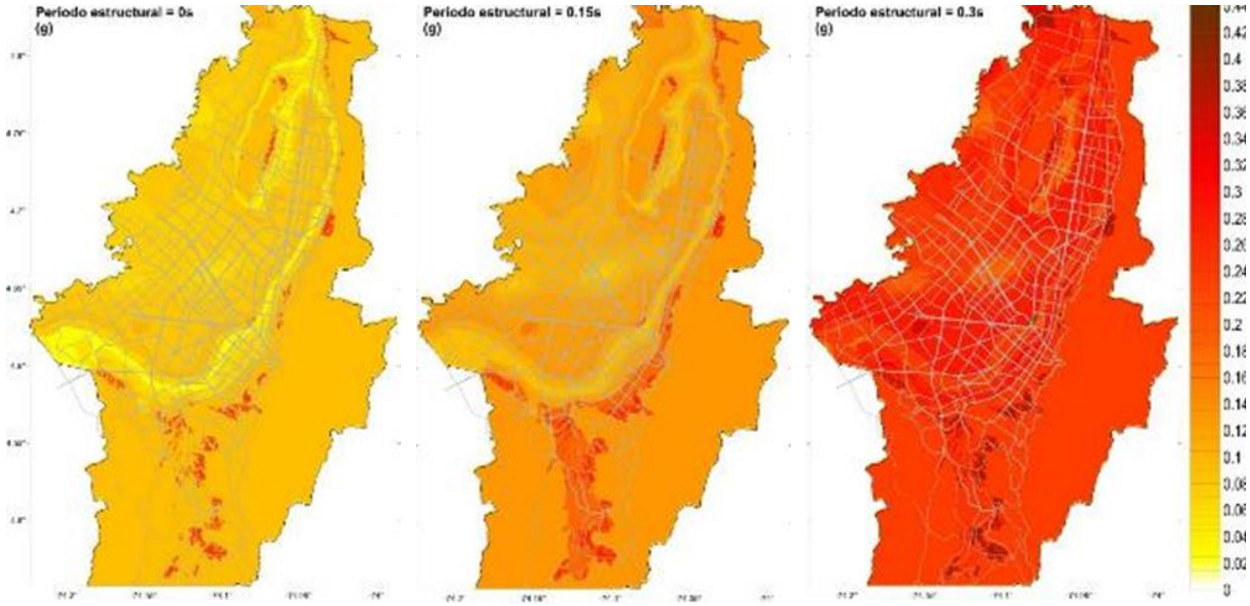
5.2 Vulnerability of buildings

The expected damage is calculated using seismic vulnerability functions. The vulnerability, which is an intrinsic characteristic of the exposed elements, characterizes the behavior of a building during the occurrence of an earthquake. Vulnerability curves relate probability moments

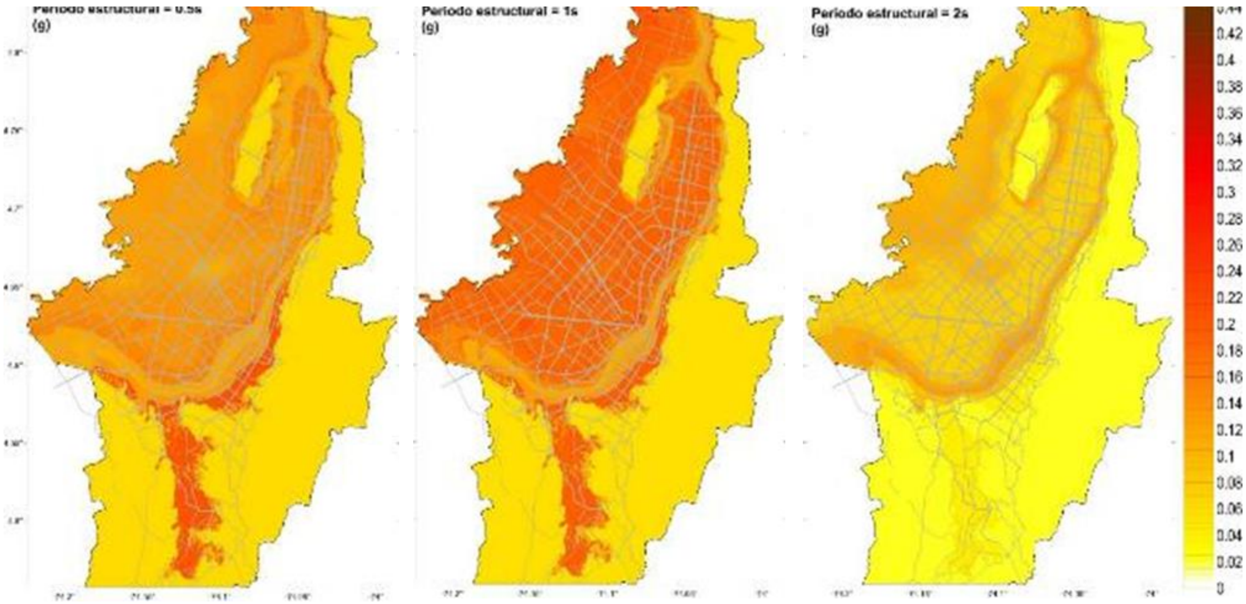
[3] This on a laptop with 6GB RAM, Intel Core i5-3210M @ 2.5GHz

(expected value and variance) of the loss in the exposed element as a function of the intensity of strong motion that occurs in the location of the building.





Period = 0s (g) **Period = 0.15s (g)** **Period = 0.3s (g)**



Period = 0.5s (g) **Period = 1s (g)** **Period = 2s (g)**

Figure 4. Accelerograph and corresponding shakemaps in Bogotá

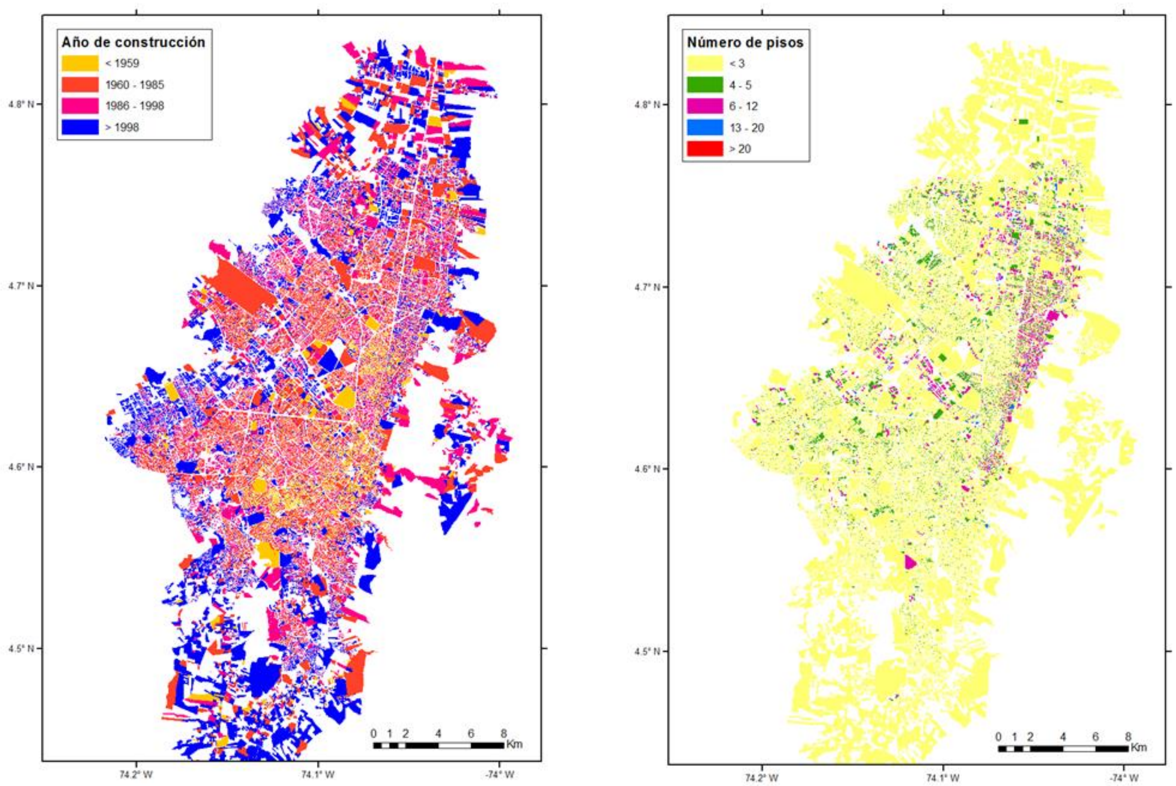


Figure 5. Maps of year of construction (left) and number of stories (right) of buildings in Bogotá.

6 Damage maps

LISA generates a series of thematic vector maps with information calculated in terms of damage, building by building. LISA provides information in two aggregation levels: by block and by neighborhood. In both cases, the following information is reported:

- Mean damage ratio
- Probability of collapse
- Number of collapses
- Economic loss
- Number of deceased
- Number of injured

Figure 6 shows an example of the maps generated by LISA. These maps are compiled in reports that are sent by e-mail to registered users, which are city officials responsible of the emergency and crisis attention in Bogotá. LISA generates three reports. The first report (first to be sent) contains information only in text format with general figures of the consequences (order of magnitude of number of buildings collapsed, people deceased and injured, and the expected economic loss). It is sent to email accounts and cellphones (as SMS) of city officials. The second report includes maps of number of collapsed buildings, people deceased and injured, by neighborhood. The third report is the last to be sent as it includes maps of consequences for sub-regions of Bogotá using block resolution.

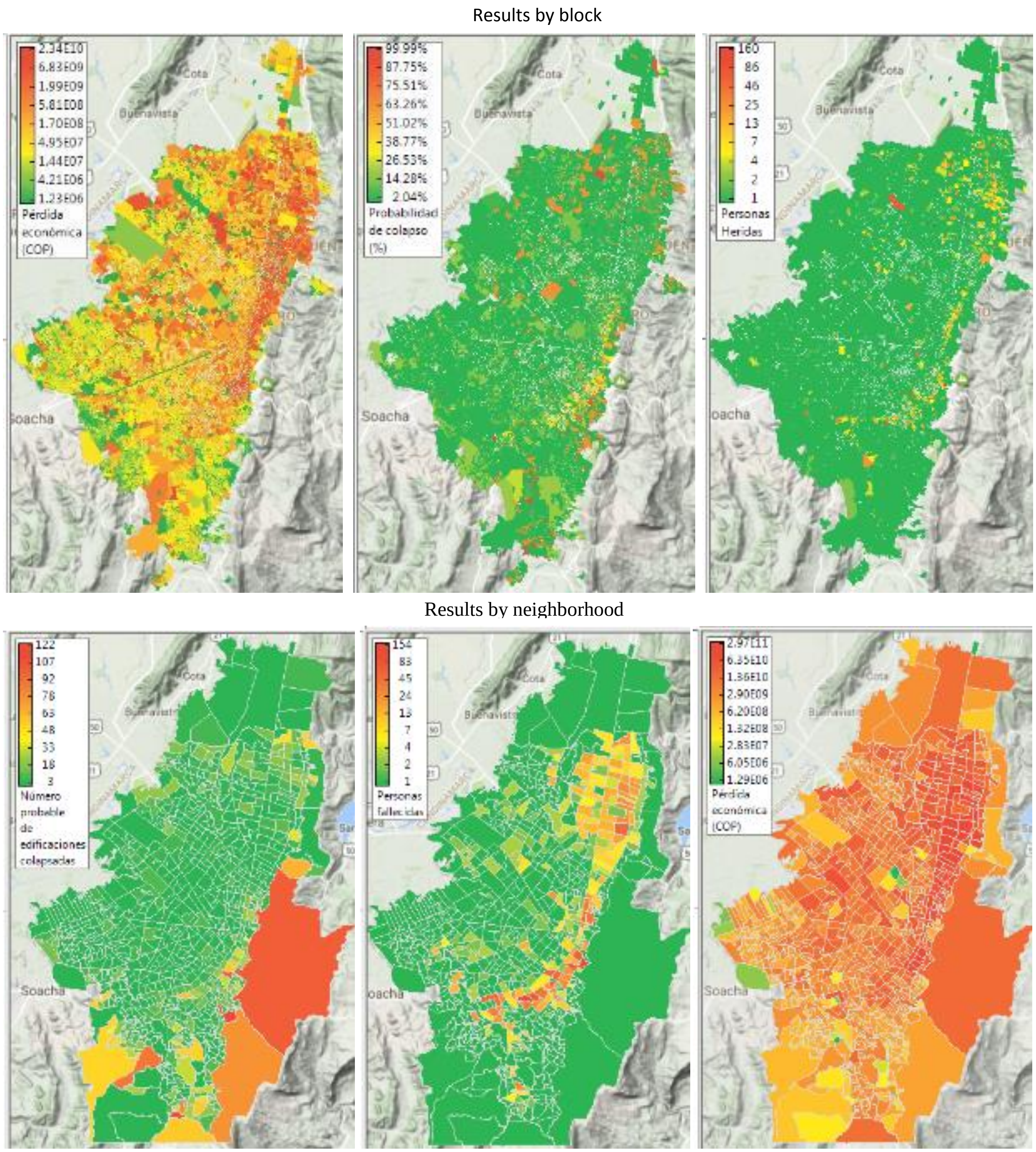


Figure 6. Example of maps reported by LISA. The color scales are: up-left: Economic loss (in $COP); up-center: Collapse probability; up-right: Injured; down-left: Number of collapses; down-center: Deceased; down-right: Economic loss (in COP).

7 Conclusions

LISA is a unique platform, allowing cities to generate information about the possible consequences of an earthquake, just after its occurrence. It provides state-of-the-art assessments of damage, based on advances models of the seismic response of soils and buildings.

The LISA system of Bogotá allows permanent communication with the RAB (Bogotá Network of Accelerators) to determine the occurrence of events in real time, evaluates the dynamic response of the soil throughout the city, and performs the calculation of damages, losses, deaths and injuries by location. After the occurrence of an event, LISA performs all these calculations automatically and generates reports with the results, which are sent, also automatically, to the officials designated to receive this information. All these processes occur in less than five minutes.

LISA should be seen not as a rigid platform, but as a flexible system which can be updated as more and better information is available. This is because all the layers of information and data that feed the system are replaceable by updated versions of them. This makes LISA a living instrument, capable of benefiting from advances in the science of earthquake engineering.

8 References

Bernal, G.A. (2014). Metodología para la modelación, cálculo y calibración de parámetros de la amenaza sísmica para la evaluación probabilista del riesgo. *Ph.D. Thesis*, Universitat Politecnica de Catalunya, Barcelona.

Bernal, G.A., Zuloaga, D., Cardona, O.D. (2017). Modelo probabilista de respuesta sísmica de los suelos de Bogotá. At *VII Nacional Conference on Earthquake Engineering*. Barranquilla, Colombia 2017.

Cardona O.D. (2001). Holistic evaluation of the seismic risk by using dynamic complex systems (Estimación holística del riesgo sísmico utilizando sistemas dinámicos complejos). *Ph.D. Thesis*, Universidad Politécnica de Cataluña, Barcelona (in Spanish).

Cardona O.D. (2004). The need for rethinking the concepts of vulnerability and risk from a holistic perspective: A necessary review and criticism for effective risk management. In *Mapping vulnerability: Disasters, development and people*, ed. G. Bankoff, G. Frerks, and D. Hilhorst, 37–51. London: Earthscan Publishers.

Cardona O.D. (2011). Disaster risk and vulnerability: Notions and measurement of human and environmental insecurity. In *Coping with global environmental change, disasters and security: Threats, challenges, vulnerabilities and risks*, ed. H.G. Brauch, U. Oswald Spring, C. Mesjasz, J. Grin, P. Kameri-Mbote, B. Chourou, P. Dunay, and J. Birkmann, 107–121. Berlin, Heidelberg, and New York: Springer-Verlag.

Cardona, O.D. (2016). Sistema de Modelación de Amenazas y Riesgos de Bogotá (Hazard and Risk Modelin System of Bogota). DOI: 10.13140/RG.2.2.31828.60800.

Cardona O.D., Yamin L.E. (1997) Seismic Microzonation and Estimation of Earthquake Loss Scenarios: Integrated Risk Mitigation Project of Bogota, Colombia. Earthquake Spectra: November 1997, Vol. 13, No. 4, pp. 795-814.

Cardona O.D., Ordaz M.G., Reinoso E., Yamín L.E., Barbat A.H. (2012). CAPRA - Comprehensive approach to probabilistic risk assessment: International initiative for risk management effectiveness. *In Proceedings of the 15th World Conference in Earthquake Engineering*, 24–28 September 2012, Lisbon, Portugal. Available at: http://www.nicee.org/wcee/ [Accessed July 4th, 2017]

Carreño M.L. (2006). Innovative techniques for seismic risk assessment and management in urban centers: Ex ante and ex post actions (Técnicas innovadoras para la evaluación del riego sísmico y su gestión en centros urbanos: Acciones ex ante y ex post). *Ph.D. Thesis*, Universidad Politécnica de Cataluña, Barcelona, Spain (in Spanish).

Haskell, N.A. (1953). The Dispersion of Surface Waves in Multilayered Media. *Bulletin of the Seismological Society of America*. Vol 43, pp. 17-34

Helmens K. & Van der Hammen T. (1995). Memoria explicativa de los mapas del Neógeno y Cuaternario de la Sabana de Bogotá-cuenca alta del río Bogotá. IGAG. *Análisis Geográficos*. Vol 24, pp. 91-142.

Idriss, M.I. y Seed, H.B. (1968). Seismic Response of Horizontal Soil Layers. *Journal of the Soil Mechanics and Foundations Division*, ASCE. Vol 94, No. SM4, pp. 1003-1031

Ishibashi, I. y Zhang, X. (1993). Unified Dynamic Shear Moduli and Damping Ratios of Sand and Clay. *Japanese Society of Soil Mechanics and Foundation Engineering*. Vol 33, No 1, pp. 182-191.

Marulanda M.C., Cardona O.D., Barbat A.H. (2009). Robustness of the holistic seismic risk evaluation in urban centers using the USRi. *Natural Hazards* 49(3): 501–516.

Marulanda M.C., Carreño M.L., Cardona O.D., Ordaz MG, Barbat A.H. (2013). Probabilistic earthquake risk assessment using CAPRA: Application to the city of Barcelona, Spain. *Natural Hazards* 69(1): 59–84.

Seed, H. B. & Idriss, M. I. 1970. Soil Moduli and Damping Factors for Dynamic Response Analysis. Report N° UCB/EERC-70/10, Earthquake Engineering Research Center, University of California, Berkeley.

Thompson, W.T. (1950). Transmission of Elastic Waves through a Stratified Solid. *Journal of Applied Physics*, 21, pp. 89-93