ICUR2016
LISBON 30 JUNE/JUNHO-2 JULY/JULHO

International Conference on Urban Risks
Conferência Internacional de Riscos Urbanos

# Seismic Vulnerability Analysis in 3D City Models (3DCM)

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**Abstract**: Lisbon is a city with high seismic risk, having been hit in the past by strong earthquakes. That's the reason why several seismic vulnerability studies have been made devoted to the buildings of the capital, aiming the creation of different scenarios that depend on the magnitude and source location of the earthquake. The results of these studies have been presented as maps resulting from crossing information contained in 2D layers and presented in a GIS environment.

3D City Models (3DCM) intend to associate a database of a city to a rigorous geospatial representation and close to the visible reality in an urban environment, combining geometry and semantics. As such, they may include tools that convey attribute analysis at different levels, allowing the generation of new knowledge on a phenomenon or its effects, not only at the statistical level but also in terms of visual impact on the object.

In this project it is intended to extend into the third dimension a seismic vulnerability study of the buildings of Lisbon held in 2D and explore the gains of spatial analysis in 3D representations. The various parameters that contribute to assess seismic vulnerability of buildings may be analyzed individually or simultaneously. The application of this tool will be demonstrated in a pilot area of Lisbon.

**Keywords**: Buildings vulnerability, 3D-GIS, seismic risk, 3D models

## 1. Introduction

The vulnerability of an urban area sets the inherent weakness of a city to certain aspects susceptible to cause damage due to social and biophysical characteristics or even due to urban morphology (Rashed and Weeks, 2003). The vulnerability analysis is required to determine the urban risk, which in turn indicates the degree of potential loss at each site due to a specific hazard and arises as the product of the probability with which the hazardous phenomenon happens with certain magnitude by the degree of vulnerability (risk = hazard x vulnerability). Thus, the vulnerability, unlike the risk is independent of the degree to which the dangerous event itself occurs, depending, instead, on the context in which it occurs, and the physical and social conditions in each local (Rashed and Weeks, 2003).

Focusing on the phenomenon of seismicity, urban vulnerability is associated with many factors, particularly physical and social, that have dynamic character in space and time. In most cases, both the physical factors (soil geology, topography, ground cover, type of construction, etc.) and social (average household income, average age of inhabitants, etc.) are likely to be represented in 2D maps enabling spatial analysis in GIS (Geographic Information Systems) as presented in Teves-Costa and Barreira (2012) for the city of Lisbon.

In addition, it is known that in situations of risk, situational awareness is one of the most important factors in decision making (Zlatanova, 2008), before an event, for simulations and taking preventive measures, or immediately after, in emergency management, or even later on the verification and recording of damages and planning of mitigation solutions.

The use of 3D City Models (3DCM) as support for risk management follows the conclusion advocated by some authors, that the 3D graphical views represent a communication tool even more effective than 2D maps already commonly used in studies of vulnerability, hazard and risk. 3D views significantly reduce the cognitive effort necessary to interpret data and analysis results, thereby improving the efficiency of the decision-making process (Kemec et al., 2009). In addition, showing citizens the urban environment from a perspective close to everyday reality awakens them to risk awareness, which may have positive consequences (alert for taking preventive measures) or negative consequences (alarmism, depreciation of certain property, localized increase of insurance premiums).

One of the urban elements that mostly influences the degree of seismic vulnerability of a city is the building stock (typology, design, age and conservation state of the buildings), although urban infrastructure, both above and underground, are as much or more vulnerable, considering the 'cascading effects' associated with them that will ultimately affect structures that originally were not directly destroyed by the earthquake. A common feature of these elements, buildings and infrastructure, is their three-dimensional geometric development.

For a 3DCM to suit certain goals, a set of constraints must be defined a *priori*, such as the concrete objective of the model and the public that will explore it, the geospatial extension of the model, the elements to be included in the model and the level of detail/accuracy of the representation of these elements (LOD - level of detail). Dependent on these conditions, it follows the acquisition phase of the geometric data and attributes to be associated with the elements, which must be in accordance to the objective. After the critical stage of geometric and semantics modelling of elements and attributes, using geometric primitives and data models either established or adapted to the objective in question, it comes the model exploitation phase, which may involve not only passive viewing and navigation in the model, but also the user's interaction, which has to be made possible, such as the ability to perform spatial analysis to gain new knowledge from the modelled data.

In this work it is intended to generate a 3DCM for the study of the seismic vulnerability of the buildings in Lisbon analysing its advantages, exemplifying in a pilot area. The project's conditioning parameters are set in the following section. The methodology is presented in Section 3, while Section 4 summarizes the results obtained and the respective analysis. Section 5 gathers some final conclusions.

## 2. Project definition

In the following, the constraints of the project and the aspects considered in their definition are presented.
Objective of the 3DCM:  The model is intended to enable a seismic vulnerability study of the buildings of a city.
Target audience:  Experts, elected officials, planners, civil protection agents, those involved in emergency response.
Extension of 3DCM:  Area of the Municipality of Lisbon. Although the prototype is applied to a pilot zone, the study is not confined to that zone, extending throughout the city.
Elements to include: Elements at risk to consider in the study and framing elements:
- Ground;
- Buildings with spatial and vulnerability attributes;
- Streets with spatial attributes. Underground roads (in tunnels) will not be considered.
Level of Detail: To choose the level of detail it is necessary to consider several aspects. It was decided to adopt the scale of CityGML detail levels (CityGML, 2016) that has been widely implemented in the field of 3D modelling. CityGML is an open standard of the OGC (Open Geospatial Consortium) for 3DCM' s encoding, in which five levels of detail are defined for the elements, from LOD0 to LOD4 in ascending order of spatial detail and geometric precision of the data. In the scope of disaster management, Kemec et al. (2009) present a hierarchical decision rule to set the appropriate LOD depending on the type of hazard, illustrating with a seismic risk study of a city in Turkey. Such a rule, which will be adopted in the present study, is based on eight decision-making criteria to which values will be assigned according to the characteristics of the concrete area and hazard to consider. The criteria are grouped in an AHP (Analytic Hierarchy Process) decision tree, as

follow: two of spatial nature of the area to study (extension of urban area, population density), two of spatial nature of the hazardous event (spatial dispersion; affected area), three of temporal nature of the hazard (speed of onset, duration, frequency) and finally a single criterion that is related to the penetration of the inner space of the building caused by the event (for example, floods and avalanches invade the interior of buildings with external material; earthquakes, by itself, do not). While the scale values to be assigned to the first seven criteria go from 1 to 5, the eighth criterion is of binary nature, having only values of 0 (non-penetrating) or 1 (penetrating). The meaning of the values of the scale of 1 to 5 is different for each of the criteria and is explained in Tables 1, 2 and 4. Note that the classification of Tables 1 and 2 comes from Kemec et al. (2009) and refers to the geographical reality of Turkey concerning the two parameters, here assumed valid also for Portugal, but eventually needing calibration. In Tables 3 and 4, the values assigned to each criterion in the decision tree for the present case - Lisbon and seismic hazard - can be seen. Table 3 refers to criteria dependent on the study area while Table 4 refers to criteria describing the hazard under study.

**Table 1:** Scale for criterion Urban Area Extension (from Kemec et al., 2009)

| Classes for Urban Area Extension (em ha) | Attribute value |
|---|---|
| 726 < area <= 4516 | 1 |
| 4516 < area <= 5089 | 2 |
| 5089 < area <= 8880 | 3 |
| 8880 < area <= 33940 | 4 |
| 33940 < area <= 199632 | 5 |

**Table 2:** Scale of criterion Population Density (from Kemec et al., 2009)

| Classes of population density (per/ha) | Attribute value |
|---|---|
| 0.65 < dens <= 4.47 | 5 |
| 4.47 < dens <= 5.30 | 4 |
| 5.30 < dens <= 9.12 | 3 |
| 9.12 < dens <= 26.74 | 2 |
| 26.74 < dens <= 108.05 | 1 |

**Table 3:** Values assigned to decision criteria dependent from study area

| Criterion | Symbol | Value for Lisbon | Attribute value |
|---|---|---|---|
| Urban Area Extension | $a_{ue}$ | 10000 ha | 4 |
| Population Density | p | 54.77 per/ha | 1 |

**Table 4:** Values assigned to decision criteria dependent from hazard in question (earthquake in Lisbon)

| Criterion | Symbol | Scale description | Attribute value |
|---|---|---|---|
| Frequency | f | Frequent (5) to Rare (1) | 2 |
| Duration | d | Long (5) to Short (1) | 1 |
| Speed of set on | $s_o$ | Slow (5) to Rapid (1) | 1 |
| Spatial Dispersion | $s_d$ | Large (5) to Small (1) | 3 |
| Affected Area | $a_e$ | Extense (5) to Limited (1) | 3 |
| Penetration inside | i | Penetrating (1), Non penetrating (0) | 0 |

The decision rule is based on the intensity value $I_v$ calculated by equation (1), which is first applied to the values of the listed attributes and then normalized, $I_{vnorm}$ (equation 2), resulting in the value $D$ (equation 3) which defines the LOD ($D$) to be applied in the 3DCM for the study. Being the attributes scale of each criterion, except for the density, defined incrementally according to the degree of predominance, higher $I_v$

values indicate a pervasive situation which requires little spatial detail, while lower values indicate one intense situation that requires modelling with high spatial detail (Kemec et al., 2009). The orientation of the scale for population density, with lower values for higher densities causes lower values of $I_v$, indicating a need for more detail in the most densely populated areas enabling, in this way, a more detailed analysis of risk.

$$I_v = [\left(\left(\frac{s_o+d+f}{3}\right) + \frac{\left(\frac{s_d+a_e}{2}\right)}{2}\right) \cdot \left(\frac{a_{ue}+p}{2}\right)] \tag{1}$$

$$I_{vnorm} = round\left(\frac{I_v - I_{vmax}}{I_{vmin} - I_{vmax}}\right) \cdot 4 \tag{2}$$

$$D = I_{vnorm} + i/2 \tag{3}$$

The values obtained in the present case are $I_v$ = 7.083, $I_{vnorm}$ = 1, resulting in $D$ = 1. That means, for the study of the seismic vulnerability of the buildings for the complete city of Lisbon, a 3DCM with LOD 1 would be appropriate. If the study area was much less, for example, limited to a parish of medium size, the attribute for the criterion $a_{ue}$ would be 1, keeping all other equal, and the resulting $D$ value would be equal to 3, meaning greater detail. In fact, in LOD1, buildings are represented only by geometric blocks (prisms) with the corresponding height but no details whereas in LOD 3 roofs are already modelled with the actual shape and the openings in facades (windows, balconies) are also shaped as well as all associated facilities such as outdoor stairways, lifts accessories on the roof, etc.. In this project, we chose to use LOD1, as recommended, for the full extent improving to LOD2 in the pilot area (Figure 1).



| Figure 1 – Buildings in the pilot area modelled in LOD2 using CityEngine (ESRI) | Figure 2 – Buildings modelled in LOD3 in the pilot area |

LOD 3, as recommended for small areas, was also tested (Figure 2) but the modelling was considered to be too time expensive for the kind of study and would exponentially increase the dimensions of the 3D scene hampering the dynamic exploration of the model on the web.

## 3. Methodology

### 3.1 Input data

The input data for the project come from the buildings database of the Municipality of Lisbon from where we obtained the 2D buildings' footprints, addresses and the number of floors above ground for each building. Data from the 2011 census, from the National Institute of Statistics, were used to characterize the buildings by construction material and construction year. Aerial photographs of Lisbon from several epochs (1947, 1978 and 2004) were used to refine, by photo-interpretation, the classification from the census regarding the time of construction, as this information in the census was delivered by statistical subsection and not by building. The landform came from GDEM V2 with a resolution of 30m, a global digital elevation model obtained from processing stereo satellite images from Aster and freely available in the internet. Soil geology classes and vulnerability indices come from Teves-Costa and Barreira (2012). Information about derelict buildings in the city of Lisbon was also added, originating from Santos et al. (2015). Additionally a landfills map was also attached to the data set containing landfills created between 1944 and 2006, information

obtained from Dias (2013). For the pilot area attributes such as 'roof type' as well as facade textures were also included which came from aerial image analysis and field work.

3.2 Processing

All information was processed in a GIS environment where a spatial database (geodatabase) has been created in ArcMap (ESRI), relating the attributes to each considered unit of study: the building. The used reference system was ETRS89-PT-TM06. Vulnerability was calculated for two probable seismic scenarios as well as the probabilities for each building to suffer damage of several grades in each scenario. To achieve this, the same routines used in Teves-Costa and Barreira (2012) were applied to the present data resulting in a higher resolution vulnerability study at building scale. The geodatabase was then imported into CityEngine (ESRI) to continue with the three-dimensional modelling in LOD2 of the pilot zone. After importing the GDEM Aster to materialize the ground of the area, CGA (Computer Generated Architecture) rules were developed and applied to the buildings' footprints in order to achieve a geometrical 3D model. They were given the respective height, the roof according to each roof type, appropriate generic textures were applied to the roof and individual textures to the facades, which had also been previously photographically acquired in fieldwork and processed in the office. Also the streets were subjected to 3D modelling of the roadways and sidewalks with assignment of appropriate textures. The next step was creating one 3D information layer for each response to a given type of query performed on several seismic scenarios. In each response layer the buildings appear coloured according to the probability of damage occurrence of a certain grade. Also for this representation a CGA rule was developed for each layer. All layers were then exported together in WebScene format (ESRI extension '.3ws') and can be provided and explored by the users in a web environment by following a link shared with them. The WebScene of the pilot area will be hosted in the ArcGIS Online platform (ESRI) where it can be explored via a CityEngine WebViewer. The 3D model of the whole area of Lisbon cannot be domiciled in the ArcGIS Online platform, due to its dimension, so other solutions are ongoing for delivering and exploring large amounts of 3D data via web.

## 4. Results

The choice of the three-phase methodology presented - processing the input data in Geodatabase ESRI, 3D geometry modelling in CityEngine and representation in separate layers of answers to appropriate queries - allows providing relevant information in cases where the component responsible for exploring the results in the web has view capabilities but cannot perform queries by attributes or spatial analysis. In CityEngine environment one can not only view information in isolated or combined layers, but also prepare automatic result reports through CGA rules (Figure 3).
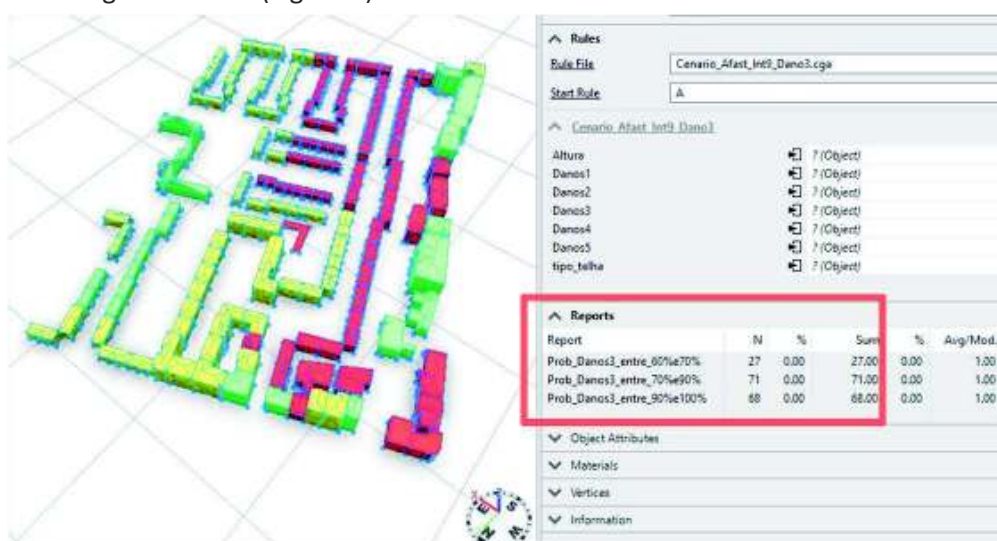


**Figure 3** – Scenario of damaged buildings after a far source earthquake producing intensity 9. The probability of occurrence of, at most, damage of degree 3 is classified in three classes (red: highest, green: lowest). Reported (in the red frame) is the counting of buildings with the classified probability (see Teves-Costa and Barreira, 2012)

In the web environment, information can indeed be explored by the user, without having to acquire ESRI software, and queries by attributes are possible. However, reports on the data are not available in the web viewer. Here too, new strategies are being developed to enable access to information not only by viewing coloured results but also with the ability to perform calculations and counts on them. Figures 4 to 7 show some examples of results of the interactive exploration of the 3D model for the seismic vulnerability of the pilot area. Each building can be queried individually (in blue in Figure 4) yielding all the corresponding attributes existing in the geodatabase. The whole area can be searched for the buildings of a certain vulnerability class, which appear highlighted (Figure 5). Direct comparisons can be made between the real and the classified buildings according to the probability of damage on a certain earthquake scenario (Figure 6) or between two different earthquake scenarios (Figure 7).



**Figure 4** – Query of attributes by building; selected building in blue and list of its attributes on the left



**Figure 5** – Buildings in the pilot area with class D vulnerability



**Figure 6** – Layer comparison: (top) far origin earthquake scenario, intensity 9, probability of damage degree 3; (down) realistic textured 3DCM



**Figure 7** – Layer comparison between two different earthquake scenarios of the same intensity for damage degree 3: (top) probability for a far source earthquake; (down) probability for a near source earthquake

## 5. Conclusion

Studies on the seismic vulnerability of city buildings can profit from the use of 3DCM especially when the city databases are detailed to the scale of a building.
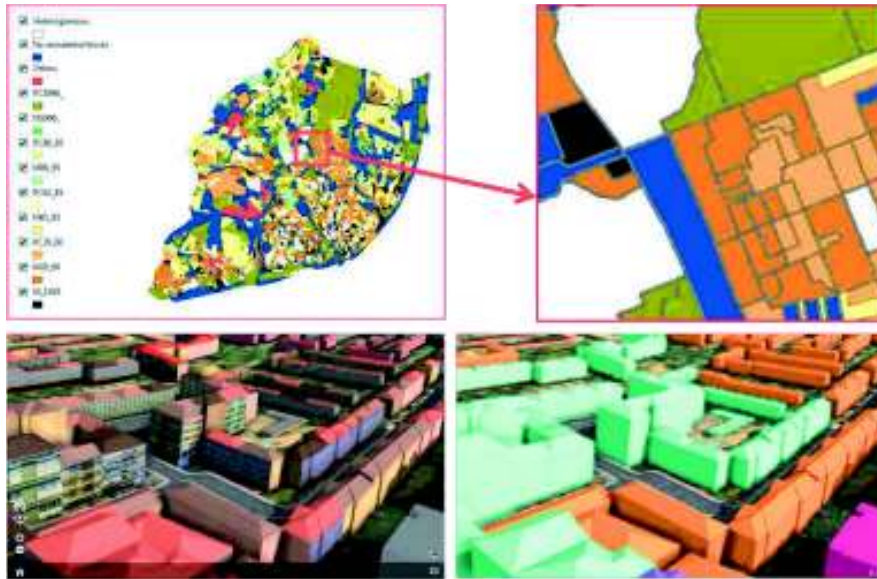
**Figure 8**- Similar basic information represented in 2D and 3D: (top) Building typology spatial distribution in Lisbon (left) and in the pilot zone (right) (Teves-Costa and Barreira, 2012); (down) Part of pilot zone (left) same area classified according to construction epoch (right)

Although LOD1 is recommended for large areas, LOD2 gives the buildings more recognition value that can be an advantage in emergency decision making. The 3D representation of the same basic data is richer and more comprehensive comparing to 2D (Figure 8). Associations of analysis results to geometric properties of the buildings are easier as well as comparisons between several scenarios. The reference to reality is more evident in 3D. In the context of a merely visual simulation of the effects of an earthquake, the results could be presented in an even more realistic way by procedurally modelling the buildings (Holzer, 2016), so that they show damages according to the calculated damage degree (Figure 9). Although suitable, it remains questionable if it should be applied to this kind of study, fearing that it might be too graphic for the public of interest.



**Figure 9 –** Procedurally modelled damaged building (Holzer, 2016)

## Acknowledgments

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