Monitoring historical urban infrastructure using multi-temporal InSAR techniques

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Abstract. Ranked tenth in the world regarding seismic risk, Bucharest is the most seismically exposed capital in Europe and has the highest risk among Romanian cities. Location on two faults, high population and preponderantly old buildings make Bucharest even more vulnerable to strong earthquakes that occur periodically in Romania. In order to prevent major live and material losses in the future, authorities are trying to generate a map of buildings classified according to the risk of collapsing at the next earthquakes. In an attempt to reduce the time necessary to identify buildings at high risk we propose using InSAR technology that detects fine movements of objects. In our study we are interested to find out if satellite measurements are able to distinguish between effects produced by damage and those brought about as a result of changes in for example non-structural components and the environmental conditions. Also it is important to consider whether the dynamic characteristics can be identified with the required accuracy using InSAR techniques. In this purpose we compare building behavior identified from satellite data with that resulted from terrestrial monitoring using high precision techniques. In the current paper, we present the methodology of rating buildings using health indices, and discuss possible outcomes.

Keywords: *infrastructure, InSAR, Permanent Scatterers, seismic risk*

1. INTRODUCTION

The forensic engineers that evaluate the health of buildings usually study the causes that lead to their failure in the first place. Most often, for finding the cause of collapsing, they analyze the failure mechanism of the building (Atkinson, 1998). The output of this type of studies can be used for improving the construction norms for future projects. The insight in the past offered by InSAR could represent a unique advantage in studying the causes that lead to infrastructure failure (Metternicht et al., 2005). Using this technology, we could observe the evolution of a deformation that is visible on the outer shell of constructions.

A forensic engineer can make a series of hypotheses regarding what caused the collapse, which can be eventually validated using InSAR. Studying building failure implies data collecting and analyzing for determining the cause of failure (Eisenhardt, 1989). The failure of a structure depends on the load and its ability to withstand the loads without the structural integrity to be affected (Ellingwood, 2006).

According to the Eurocode: Basis of structural design (2011), the loadings that can affect buildings are: permanent loadings, like the weight of structural elements, groundwater pressure or element tension that remain constant over time; and live loadings, such as people, cars, furniture, precipitations, wind loading, and temperature that vary most of the time; accidental loadings, like earthquakes, explosions or fires, that are characterized by large magnitudes and catastrophic consequences, but have a low chance of occurrence.

Being ranked as the tenth city in the world and first in Europe in terms of exposure to earthquakes, Bucharest is considered the city with the highest seismic risk in Romania (Armaș, 2006). Location on two faults, large population and large number of old buildings in the city increase the vulnerability to strong earthquakes that occur periodically in Vrancea.

There are many factors that influence the seismic risk in the capital (Carreño et al., 2007; Poljanšek et al., 2012), of which the most important are the geographical position – 100-170 km from the epicenter in Vrancea; the large number of buildings with more than P + 3 floors, constructed in concrete or masonry, built before 1940, with structures designed to withstand only the action of gravity, and degraded beforehand by earthquakes produced in 1940, 1977 1986 and 1990; lack of codes at national level during the construction of these buildings, providing knowledge and technical standards necessary for the realization of structures resistant to earthquakes; local conditions that lead to amplification of seismic movements with destructive effects on existing structures; own period of vibration of tall buildings built in the interwar period; vibration caused by strong earthquakes in the Vrancea, which produces the phenomenon of resonance is destructive for tall buildings (Vlad & Vlad, 2008).

In order to prevent loss of life and material in the future, authorities are trying to classify buildings according to the risk of collapse in the next earthquake.

Bucharest City Hall updated the list of earthquake risk buildings in the capital on October 30, 2015. According to the new data, 374 buildings present an extremely high seismic risk, of which 189 are classified as "public danger" and another 2,100 buildings fall into classes with lesser degrees of risk, requiring consolidation. 28 buildings have been consolidated so far.

Thus, the list published on the official website shows 374 buildings framed in class I of seismic risk (corresponding high risk of collapse in case of an earthquake) - of which 189 are listed in the category "Public Danger" (Figure 1).
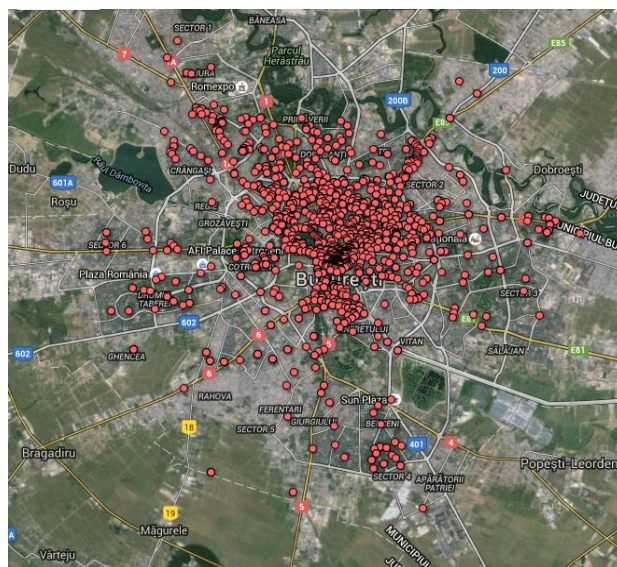

Figure 2. *Maps containing the location of buildings classified in the seismic risk class I within Bucharest (Source: www.riscseismic.ro)*

2. PROBLEM DESCRIPTION

Inventory process proves to be very difficult, mainly because the detection techniques used to identify structural defects in buildings is complex and lengthy (Glaser et al., 2007). The characterization of the likely behavior of a building in case of an earthquake must take into account a number of factors of different nature. Generally applicable rules cannot be given for the quantification of these factors, but by thorough interpretation of the results of all investigations made in the expertise, through comparisons with other similar situations, and by reasoning engineering, will be able to fit the building in question in one of the four classes of seismic risk.

From the point of view of seismic risk, meaning the likely effects of earthquakes, site characteristics, the existing buildings on that site, are the four classes of seismic risk established by authorities:

Class I matches for construction that presents a high risk of collapse in earthquakes with intensities corresponding to estimate seismic intervals (earthquake design);

II. Buildings corresponding to Class II have a reduced probability of collapsing, but major structural alterations that are expected incidence earthquake design;

III. Seismic risk III class contains corresponding constructions which are expected structural alterations that do not significantly affect the structural safety, but present damage of nonstructural elements that can be important;

IV. Seismic risk IV class corresponds to buildings with an expected seismic answer similar to new buildings designed based on regulations.

In deciding the seismic risk classes, the experts will take into account the seismic zone where the in construction is located and the composition criteria for construction, operation and behavior of seismic actions (Figure 2).
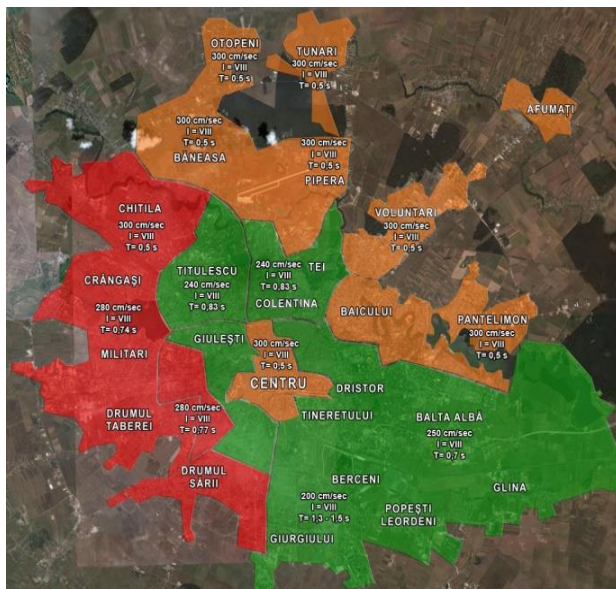

Figure 2. Seimsic areas in Bucharest classified according to soil acceleration in case of earthquakes; green corresponds to low acceleration, orange to medium and red to high (Source: www.riscseismic.ro)

Our study suggests the use of InSAR technology as a quicker alternative identification of high-risk buildings, identifying fine movements of objects. The accumulation of structural defects may cause a change in the dynamic characteristics of structures. In our study we want to know whether satellite measurements are sufficient to distinguish between structural defects and the results of structural components or changes in environmental conditions. Also we have to consider the precision in detecting the dynamic characteristics of the infrastructure. In the current article describes the current state of application infrastructure analysis

and investigation techniques using multi-temporal InsSAR.

The objective of this study is to verify the feasibility of the technique InSAR in monitoring degradation and identifying the degradation causes. We will mainly focus on the historical buildings found in the first seismic class. For our study we will consider firstly the database of buildings classified as class I of seismic risk. The first important information that must be known when analyzing a structure is the general information about it. It is mandatory to know its location, number of floors, building type and use of the building (Eastman et al., 2011). Where they exist, would also be important to have knowledge about possible types of phenomena affecting the building behavior: deformation description, construction materials, loadings of structural parts and other technical causes.

The studies of Terwel et al., (2012) and Terwel (2014) disclose that in buildings whose structure is affected by deformations, this becomes visible on the surface. Signs that may indicate strains include cracks, corrosion or displacement of elements and other indicators of physical degradation. For the current study, this category is very important as identifying indicators of degradation of the buildings is one of the most important aspects of the analysis of structures in danger.

3. METHODOLOGY

Monitoring buildings seeks to identify indicators of degradation, or indications that there is a danger of degradation in the future. The purpose of this section is to analyze how InSAR could be used as a means of monitoring, to serve the purpose of identifying those at high risk of collapsing buildings in Bucharest. First, it should be considered the difference between monitoring and investigating the causes of the collapse of buildings. Investigation is to identify the mechanism that led to the building and cause failure triggers, after the appearance of degradation (Chong et. al., 2006). Monitoring on the other hand tries to capture the initial stage of degradation, in order to prevent collapse. The

methodology that is presented in the following section is inspired from the paper of Pratesi et al., (2015) and refers to identifying and classifying buildings according to movements that indicate future degradation.

The methodology described is based on the use of indexes for classifying information contained by every Permanent scatterer (PS point), which can assess the state of decay of urban infrastructure at local scales (Lan et al., 2012). Permanent scatterers are either natural or manmade objects that remain stable over time from a coherence point of view (Ferretti et al., 2000; Ferretti et al., 2001; Hooper et al., 2007). They appear as bright coherent points in interferogams, and can be used to identify point displacements. In our cases, PS points will be represented mainly by urban infrastructure. Points are grouped into "test areas" that correspond to buildings and their surrounding areas. The indices refer to the density of PS points in a test area (I_D), and to the critical degree of deformation of the individual structures of the adjacent areas (I_{CS}, I_{CZ}). Distributions of displacements on buildings facades can be classified as isolated (i) or diffuse (d), according to the speed distribution index (I_{DV}). The indices I_C and I_D will be divided into classes A to E to simplify results interpretation.

The steps that will be taken in order to classify the points and identify the level of hazard for each structure are:

- Calculation of Index I_D;
- Calculation of critical deformation indices for individual structures and adjacent areas (I_{CS} I_{CZ});
- Integration of additional information to calculate indices.

Defining test areas and PS points selection

PS valid points are marked by clearly two areas: perimeter studied object is drawn using orthophotomaps and adjacent area is considered as a buffer of this object. Adjacent area is included in the buffer whose stability is considered important for an object. Size of the buffer is chosen according to the spatial resolution of satellite images SAR (for TSX it is 1.7 m × 3.4 m). Size of the buffer is important because it must include

georeferenced points that are a few meters outside the boundaries of the object, but resulted from a double reflection on the corners formed by the walls of the building and land area. Also the considered buffer zone can eliminate errors that occur when designing PS bracket points used to identify buildings (Figure 3, 4).
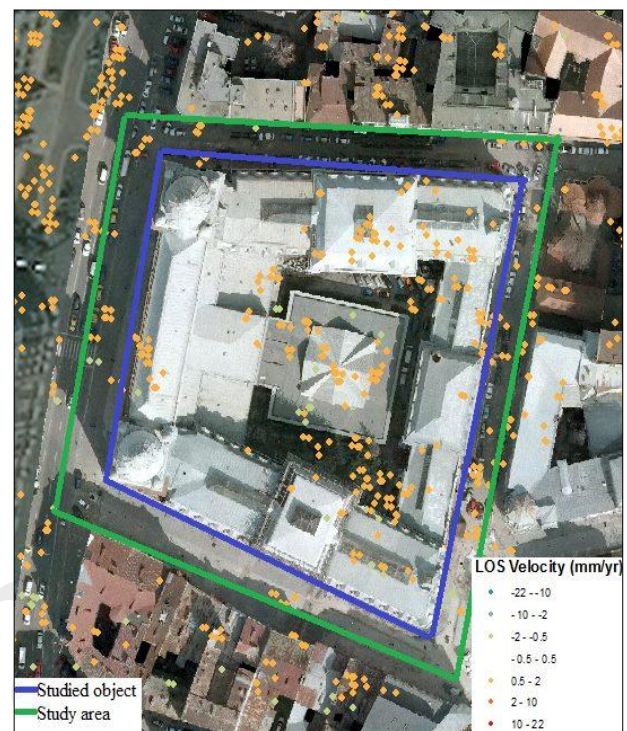

Figure 3. PS point selection for a church in Bucharest's centre. Delimitation of the studied object and the adjacent study area

The calculation of the density index, I_D of points in a test area

This index shows the coverage of the object and its surroundings PS points, or degree of information for a study area. The numerical value of this index reflects the density of points PS (PS/m2) in the test area.

The first time the density of the points is calculated for the studied PS object (D_O). If it is 0, lower or higher than a fixed value for the average density of points PS (D_m), then the value attributed in part is 0, 0.25 or 0.5. The PS density in the surrounding area of the studied object (D_a) is calculated using the same partial scale as in the case of partial values of D_O. I_D is obtained then by adding the values of D_O and D_a, so I_D takes values

between 0 and 1-Class E-Class, with a difference of 0.25 from one class to another. Thus, class E corresponds to areas that do not show any PS point, which means that the critical deformation index cannot be calculated. In this situation it is not recommended to extrapolate points in the vicinity of the study area, because the behavior of a building is individual, and can only be influenced by the surface that it is located on, but not entirely depending on it.

As mentioned by Bayarri et al., (2015), the same average density, D_m cannot be used for peri-urban areas, since the density and type of construction in these areas are different from those of urban areas. The average density D_m is obtained by calculating average values for D_a and D_O characterizing a study area. Dm also depends on the type of data used and can be adjusted for both medium (Envisat, ERS) and high resolution satellites (TerraSAR-X, CosmoSkymed).

Figure 4. *PS point selection for The House of the People (Parlament Building). Delimitation of the studied object and the adjacent study area*

Critical deformation index calculation, I_C

This index expresses numerically the condition imposed for the studies object and the surrounding area, based on the maximum velocity value (Vmax) expressed along the Line-of-Sight (LOS) of the satellite for the whole period of monitoring, for all points in the study area. Similarly as in the density

calculation, in the case of the I_C index, two indices are calculated first, I_{CO} and I_{CA}, that represent the critical deformation indexes for the studied object and the surrounding area. Starting from Vmax value found in the study areas of control, I_{CO} and I_{CA} are classified using 5 classes for critical deformation index, I_C, whose range is determined by the limits of the speed value interval within the range of values determined for the entire study area.

Speed range interval which differentiates stable objects from the unstable ones is determined based on radar technology parameters used to determine the displacement and the distribution of speed values throughout the entire PS database. Class A indicates stable objects. Its limits depend on the precision achieved with a single measurement and the frequency of the radar signal. In the case of X-band radar sensor, the recommended standard deviation is 0.5 mm (Class A having Vmax≤0.5 mm/year). As mentioned in the literature (Hanssen, 2005; Crosetto et al., 2010; Cigna et al., 2013), rates higher than the signal wavelength lead to loss of coherence in SAR images. Class E is determined by the distribution of velocities of all PS points values. Intervals in Table 1 are set to encompass most PS points resulting from processing the SAR images the entire area of Bucharest.

I_C Class	Velocity range
A	$|V_{max}| \leq 0.5$ mm/yr
B	0.5 mm/yr $< |V_{max}| < 2.0$ mm/yr
C	2.0 mm/yr $< |V_{max}| < 3.5$ mm/yr
D	3.5 mm/yr $< |V_{max}| < 10.0$ mm/yr
E	10.0 mm/yr $< |V_{max}|$

Table 1 *Critical deformation index classes and corresponding PS velocity ranges (Bayarri et al., 2015)*

Distribution of velocity index calculation, I_{DV}

The number of unstable points and their spatial relationship with stable PS points from the study area do not influence the value of the I_C index. In order to numerically express the spatial distribution of the estimated displacements, it was introduced a new index, I_{DV}, that represents the estimated speed distribution and will be calculated for each study area using the following formula:

$$I_{DV} = (g / G) \times 100$$

Where "g" is the maximum value of (Vmax-Vmin) and (Vmed-Vmin) and G of (Vmax-Vmin) with Vmax, Vmin and Vmed being the mean, maximum and minimum average speed of the PS points in the control area.

I_{DV} shows the degree of symmetry of all the points in a test area, relative to Vmed, and can indicate if there are at least three points included within its boundaries.

4. EXPECTED RESULTS

The outcome of our study will consist in historical buildings classified according to their health rating in 5 classes. The classes are established by calculating a critical deformation index, I_C, which depends on the point density on a studied object and within the adjacent area, as well as on the distribution of velocity values for the points on the object and the study area. The classes range from A to E, with A meaning the studied object is stable, and E corresponding to critical movement of the object. The classification would be represented as a map where buildings are represented according to their health score (Figure 5).

Identifying buildings at risk can represent a challenge because their behavior in case of structural damage can depend on height, construction materials, age, soil type, and soil acceleration in case of earthquakes. Therefore our study must include as many building types as possible, located in different sites all over Bucharest. In order to eliminate movement due to seasonality a dataset of at least 20 SAR images that cover a time period longer than 1 year and terrestrial monitoring over the same period of time are needed.

Also it is important to consider whether the dynamic characteristics can be identified with the required accuracy using InSAR techniques. In this purpose we compare building behavior identified from satellite data with that resulted from terrestrial monitoring using high precision monitoring techniques. By using terrestrial

monitoring techniques we will analyze whether the processing results are reliable in the first place. The ground techniques will consist in high precision surveys and GNSS measurements.
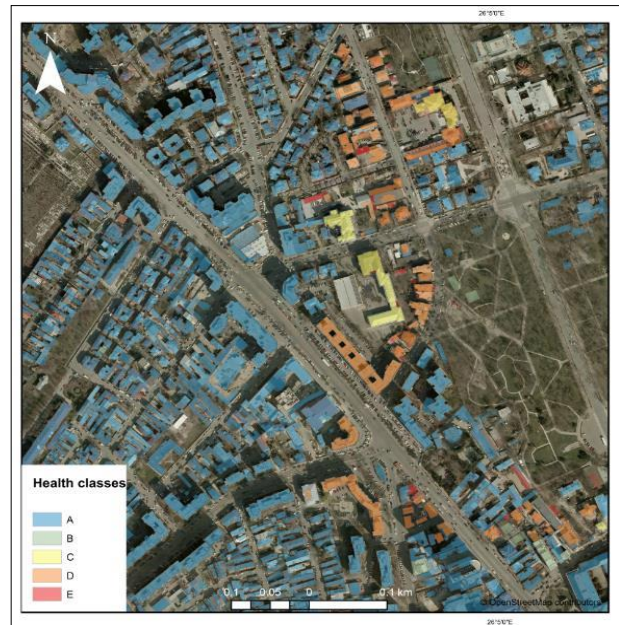

Figure 5. Example of map presenting buildings classified in 5 classes, from A to E, according to their health status estimated using health indexes

5. CONCLUSION

Our interest is mainly oriented to historical buildings corresponding to seismic risk class I. According to past theories, it is possible for the structural deformations to manifest on the outer shell of the building. Our hypothesis that the structure of old buildings with high failure risk displays a specific behavior over time that is visible on the outer shell can be tested by statistic analysis and ground validation. If the results are promising, the proposed approach may become a valuable tool in building monitoring and classification.

It is necessary to mention that we do not expect satellite technology to be able to entirely replace the classic methods of monitoring structures, but we hope that good results of the study will lead to an easier and faster identification of those buildings that are at high risk of collapsing and need further investigations using classic methods.

REFERENCES

Atkinson, A. (1998). Human error in the management of building projects. Construction Management & Economics, 16(3): 339-349.

Armaş, I. (2006). Earthquake risk perception in Bucharest, Romania. Risk Analysis, 26(5): 1223-1234.

Bayarri, M. J., Berger, J. O., Calder, E. S., Patra, A. K., Pitman, E. B., Spiller, E. T., & Wolpert, R. L. (2015). Probabilistic quantification of hazards: A methodology using small ensembles of physics-based simulations and statistical surrogates. International Journal for Uncertainty Quantification, 5(4).

Carreño, M. L., Cardona, O. D., Barbat, A. H. (2007). Urban seismic risk evaluation: a holistic approach. Natural Hazards, 40(1): 137-172.

Cigna, F., Bianchini, S., Casagli, N. (2013). How to assess landslide activity and intensity with Persistent Scatterer Interferometry (PSI): the PSI-based matrix approach, Landslides, 10(3): 267-283.

Crosetto, M., Monserrat, O., Iglesias, R., & Crippa, B. (2010). Persistent scatterer interferometry. Photogrammetric Engineering & Remote Sensing, 76(9): 1061-1069.

Chong, W. K., & Low, S. P. (2006). Latent building defects: causes and design strategies to prevent them. Journal of Performance of Constructed Facilities, 20(3): 213-221.

Eastman, C., Eastman, C. M., Teicholz, P., Sacks, R., Liston, K. (2011). BIM handbook: A guide to building information modeling for owners, managers, designers, engineers and contractors. John Wiley & Sons.

Eisenhardt, K. M. (1989). Building theories from case study research. Academy of management review, 14(4): 532-550.

Ellingwood, B. R. (2006). Mitigating risk from abnormal loads and progressive collapse. Journal of Performance of Constructed Facilities, 20(4): 315-323.

Ferretti, A., Prati, C., & Rocca, F. (2001). Permanent scatterers in SAR interferometry. IEEE Transactions on geoscience and remote sensing, 39(1):8-20.

Ferretti, A., Prati, C., & Rocca, F. (2000). Nonlinear subsidence rate estimation using permanent scatterers in differential SAR interferometry. IEEE Transactions on Geoscience and Remote Sensing, 38(5):2202-2212.

Glaser, S. D., Li, H., Wang, M. L., Ou, J., & Lynch, J. (2007). Sensor technology innovation for the advancement of structural health monitoring: a strategic program of US-China research for the next decade. Smart Structures and Systems, 3(2): 221-244.

Hanssen, R. F. (2005). Satellite radar interferometry for deformation monitoring: a priori assessment of feasibility and accuracy. International journal of applied earth observation and geoinformation, 6(3): 253-260.

Hooper, A., Segall, P., & Zebker, H. (2007). Persistent scatterer interferometric synthetic aperture radar for crustal deformation analysis, with application to Volcán Alcedo, Galápagos. Journal of Geophysical Research: Solid Earth, 112(B7).

Lan, H., Li, L., Liu, H., & Yang, Z. (2012). Complex urban infrastructure deformation monitoring using high resolution PSI. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 5(2): 643-651.

Listele imobilelor expertizate tehnic din punct de vedere al riscului seismic actualizate la 30.10.2015, http://www.pmb.ro/.

Metternicht, G., Hurni, L., Gogu, R. (2005). Remote sensing of landslides: An analysis of the potential contribution to geo-spatial systems for hazard assessment in mountainous environments. Remote sensing of Environment, 98(2): 284-303.

Poljanšek, K., Bono, F., & Gutiérrez, E. (2012). Seismic risk assessment of interdependent critical infrastructure systems: the case of European gas and electricity networks. Earthquake Engineering & Structural Dynamics, 41(1): 61-79.

Pratesi, F., Tapete, D., Terenzi, G., Del Ventisette, C., & Moretti, S. (2015). Rating health and stability of engineering structures via classification indexes of InSAR Persistent Scatterers, International Journal of Applied Earth Observation and Geoinformation, 40: 81-90.

Terwel, K., Hanssen, R., van Waning, H. (2015). Predicting structural disasters with Radar interferometry. IABSE Symposium Report. International Association for Bridge and Structural Engineering, 105(32): 1-8.

Terwel, K. C. (2014). Structural safety: Study into critical factors in the design and construction process, TU Delft, Delft University of Technology.

Vlad, I., Vlad, M. (2008). Behavior of dwellings during strong earthquakes in Romania. 14th World Conference on Earthquake Engineering.