A METHODOLOGY FOR SEISMIC MICROZONATION USING GIS AND SHAKE - A CASE STUDY FROM ARMENIA, COLOMBIA.

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ABSTRACT: Seismic micro hazard zonation is the first step towards a seismic risk analysis and mitigation strategy. Essential here is to obtain a proper understanding of the local subsurface conditions. In this study it is demonstrated that it is possible to make better use of any (limited) geotechnical, geomorphological and geological information by creating a simplified semi-3D ground model in a GIS. Through linking of the ground model with a seismic response modelling program such as SHAKE, it is possible to obtain a delineation of the spatial variation in seismic responses. This can be used as a basis for seismic micro-zonation mapping. The method has a clear advantage above the "traditional" way of microzonation because it incorporates any a-priori geological and geotechnical knowledge. The method was developed and tested for an earthquake damage assessment and hazard analysis project in the city of Armenia, Colombia.

RÉSUMÉ: La micro-zonation des dangers sismiques est la première étape vers une analyse de risque sismique et une stratégie de mesures d'atténuation. Il est essentiel, dans ce contexte, d'obtenir une compréhension correcte des conditions locales du sous-sol. Dans cette étude, on a démontré qu'il est possible de faire un meilleur usage de toute information, même partielle, d'ordre géotechnique, géomorphologique et géologique en créant un modèle de terrain simplifié semi-3D dans un SIG. Au moyen d'un lien entre le modèle de terrain et un programme de modélisation de réponse sismique comme le programme SHAKE, il est possible d'obtenir un tracé des variations spatiales des réponses sismiques. Ce tracé peut être utilisé comme base pour la cartographie de la micro-zonation sismique. La méthode a un avantage marqué par rapport à la technique 'traditionnelle' de micro-zonation parce qu'elle intègre toute information a-priori autant d'ordre géologique que géotechnique. La méthode a été développée et vérifiée dans le cadre d'un projet d'évaluation des dommages causés par un tremblement de terre et d'analyse des dangers dans la ville d'Arménie en Colombie.

INTRODUCTION

Earthquake hazard zonation for urban areas, mostly referred to as seismic microzonation, is the first and most important step towards a seismic risk analysis and mitigation strategy in densely populated regions. In seismic micro hazard zonation, one would like to quantify the spatial variation of the subsurface response on a typical earthquake that can be expected in the area. In order to quantify the expected ground motion, we have to determine the manner in which the seismic signal is propagating through the subsurface. Propagation is particularly affected by the local geology and the geotechnical ground conditions. Large amplification of

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the seismic signals generally occurs in areas where layers of low seismic velocity overlie material with high seismic velocity, i.e. where soft sediments cover bedrock or more stiff soils.

Therefore, essential here is to obtain a good understanding of the local subsurface conditions. This poses already a problem in most areas, particularly in developing countries. Availability of borehole data, geophysical surveys and laboratory tests are often very limited. Subsequently, seismic microzonation is often carried out by dividing the project area in rather large sub-areas where the geological model and ground conditions are considered to be homogeneous. For each sub-area, the seismic response is calculated and assumed to be representative for this entire area. A problem with this method is that at the boundaries, the seismic response will show large discrepancies, which does not reflect the actual situation.

In this study it is demonstrated that it is possible to make better use of any limited geotechnical, geomorphological and geological information by creating a simplified semi-3D model in a GIS. Through linking of this 3D information in the GIS with a seismic response modelling program - such as the widely used software SHAKE - a more accurate spatial variation of the seismic response can be modelled, which will provide an improved basis for seismic (micro) hazard zonation.

GROUND RESPONSE ANALYSIS

The methods of one-dimensional ground response analysis are useful for level or gently sloping sites with parallel material boundaries. Such conditions are not uncommon and one-dimensional analyses are widely used in geotechnical earthquake practice (Kramer, 1995). The earliest software written that uses this principle is called: SHAKE. The computer program SHAKE was written in 1970-71 by Dr. Per Schnabel and Prof. John Lysmer (Schnabel et al., 1972). This has been by far the most widely used program for computing seismic response of horizontally layered soil deposits. Other software that are derived from this basic code or based on the same principle are: Shake91, Shakedit, ShakEdit32 or ProSHAKE. The principle of one-dimensional ground response analysis is based on the assumption that all boundaries are horizontal and soil and bedrock are assumed to extend infinitely in the horizontal direction (half-sphere). The second assumption is that inclined incoming seismic rays are reflected to a near-vertical direction, because of decrease in velocities of surface deposits. Therefore the response of the soil deposit is caused by shear waves propagating *vertically* from the underlying bedrock.

A so-called Transfer Function is used as a technique for 1D ground response analysis. Here the time history of the bedrock (input) motion is in the frequency domain represented as a Fourier Series using Fourier transform. Each term in the Fourier series is subsequently multiplied by the Transfer Function. The surface (output) motion is then expressed in the time domain using the inverse Fourier transform.

The complex transfer function is however only valid for linear behaviour of soils. Therefore this approach has to be modified to account for the non-linearity. The linear approach assumes that shear strength (G) and damping (ξ) are constant. However, the non-linear behaviour of soils is well known and can be determined very well in a laboratory environment. Shear strength reduces with shear strain, while damping increases with shear strain. These relationships can be tested an plotted in curves, called *shear modulus reduction curves* and *damping curves*, respectively. The problem then reduces to determining the equivalent values consistent with the level of strain induced in each layer. This is achieved by using an iterative procedure on the basis of these curves (Idriss and Sun, 1992).

INPUT DATA FOR THE GROUND RESPONSE ANALYSIS

The most important input information for the ground response analysis is a *subsurface model* that represent the variation in thickness of the soil layers. This model should at least contain information on the depth of the bedrock to the top of the soil layers where the shear wave velocities or shear strengths approach a level that is comparable to rock. Even based on limited site investigation data, an experienced engineering geologist has in his or her mind already a more or less detailed 3D model of the expected subsurface conditions. This model can be translated into cross sections, sketch maps or thickness estimation maps. The idea behind this study is to translate this "virtual" 3D model, together with available "hard" data (boreholes, geophysical surveys, digital elevation model, geological maps, etc) into a digital 3D GIS model. Since real 3D GIS programs are very expensive and difficult to work with, and not readily available in developing countries, it was decided to use a 2D GIS package to create this 3D model. The GIS that was used is Ilwis, which is a PC-based GIS and Image processing package designed for the Windows environment (ITC, 2001). This package was selected because of its strong raster analysis and modelling functionalities.

In order to build a model of the subsurface in a 2D GIS, the levels or depths of the boundary layers have be represented. This is only possible when they are horizontally layered. These boundaries can be represented by triangulated surfaces (TIN's) or continuous grid or raster data layers that are created using the standard interpolation techniques that most GIS packages include. Instead of modelling the boundaries, it is also possible to represent the layers by thickness maps, again represented as continuous grids or rasters in the GIS. Subtracting the thickness maps from the Digital Elevation Model (DEM) will subsequently yield the boundary maps and vice versa. More complicated geology, such as lenses, wedging of layers, faulting or overtrusts and overturns are more difficult and mostly impossible to model in a 2D GIS. Information is however often so limited that it is not possible to detect or model these complicated structures anyway. Also, modelling of local geological conditions, at the scale of a small to medium sized city, will not require the amount of detail or entails such complicated variation in geology, that this would endorse the use of a genuine 3D GIS.

The *static soil properties* required in the 1D ground response analysis with SHAKE are: Maximum Shear wave velocity or Maximum Shear strength and Unit weight. Since the analysis accounts for the non-linear behaviour of the soils using an iterative procedure, *dynamic soil properties* play an important role. The shear modulus reduction curves and damping curves are obtained from laboratory test data (cyclical triaxial soil tests). Since the variation in geotechnical properties of the individual soil layers are mostly impossible to model, because of the shear lack of data, these properties should be assumed constant for each defined soil layer. If no reliable laboratory data exist, it is possible to use existing literature data on shear strength, shear wave velocity, damping curves and shear modulus reduction curves for similar soil types.

A proper design for building earthquake resistant structures should take into account a *design earthquake* that adequately represents the expected ground motion. Particularly the motion that would drive the structure to its critical response, resulting in the highest damage potential. This can be a historic earthquake that has been recorded in the area or an earthquake signal recorded further away, transformed to reflect the characteristics it would have when arriving at the site. Typically, one would use the nearest and most recent seismic record that has been recorded for an earthquake that caused the largest damage. The seismogram would have to be recorded by a seismometer situated in rock, because the simulation assumes an input signal from bedrock to surface level. The seismic signal is considered the same for the entire study area.

QUANTIFICATION OF THE GROUND MOTION

In seismic microzonation we want to display the variation in seismic response of the subsurface and subsequently determine where the soil is being amplified to a level that may damage existing buildings or other structures at that location. Frequently *peak ground acceleration* is used to determine the maximum horizontal forces that can be expected. However, merely determining the spatial variation of peak ground acceleration is not adequate, because peak acceleration often correspond to high frequencies, which are out of range of the natural frequencies of most structures. Therefore, large values of peak ground acceleration alone can seldom initiate either resonance in the elastic range or be responsible for large scale damage in the inelastic range (Singh, 1995).

The largest amplification of the soil will occur at the lowest natural frequency or its *fundamental frequency* (see Equation 1). The period of vibration corresponding to the fundamental frequency is called the *characteristic site period* (see Equation 2). The characteristic site period, which only depends on the soil thickness and shear wave velocity of the soil, provides already a very useful indication of the period of vibration at which the most significant amplification can be expected. When the variation in soil thickness (or depth to base rock level) and an average shear wave velocity are known, the spatial variation in the characteristic site period can readily be modelled in a raster-based GIS approach.

The response of a building to shaking at its base depends, of course, on the design quality of the construction. However, what is a very important factor is the *height* of the building. All objects or structures have a natural tendency to vibrate. The rate at which it wants to vibrate is its *fundamental period* or *natural frequency*. High rise building (with a low natural frequency) react totally different than smaller building (with a much higher natural frequency). Examples of typical natural frequencies of different building sizes are given in *Table 1*.

$$\omega_0 = \frac{\pi V_s}{2H} \tag{1}$$

In which:
ω_0 = fundamental frequency
V_s = Shear wave velocity
H = Soil thickness

$$T_S = \frac{2\pi}{\omega_0} = \frac{4H}{V_S} \tag{2}$$

In which:
T_s = Characteristic site period

Buildings have a high probability to achieve (partial) resonance, when the natural frequency of the ground motion coincides with the natural frequency of the structure. Resonance will cause increase in swing of the structure and given sufficient duration, amplification of ground motion can result in damage or destruction. Specific ground conditions may result in resonance and large amplification of the seismic signal, but if the frequencies for which this occurs lie far outside the natural frequency range of our building, this may not have significant effects.

Table 1. Example of typical natural frequencies depending on building type (after: Kramer, 1995)

Type of object or structure	Natural frequency (Hz)
1 storey buildings	10
2 storey buildings	5
3-4 storey buildings	2
tall buildings	0.5-1.0
high rise building	0.17

Therefore, it is essential to determine the *spectral acceleration*, i.e. the amplification of the seismic signal for different frequencies or periods. For different site conditions, this can be done by carrying out *response spectra analysis*, which is currently the standard method for ground response analysis (Kramer, 1995). If building codes exist in a specific country or region in which the study is being carried out, the calculated response spectra can be compared with the response spectra that buildings in that area should comply to. The probability that damage will occur if a similar earthquake takes place is very high when the calculated spectral acceleration exceeds the forces that the buildings are supposed to withstand. By means of plotting the spatial variation of the calculated spectral acceleration in the GIS, it will be possible to outline these hazardous areas for buildings with those specific natural frequency characteristics.

DESCRIPTION OF THE METHODOLOGY - INTERFACE PROGRAM SHAKEMAP

In order to link the subsurface information from the GIS with the external seismic response analysis program, an interface – ShakeMap - was designed. This interface made it possible to calculate the seismic response for a large number of points in a relatively short time. ShakeMap was written in MS Visual Basic 6.0. and is links the subsurface data with ShakeEdit32, a 32-Bit Windows application based on SHAKE91

The program uses an ASCII format model of the subsoil, which gives information on the vertical ground profile of a number of predefined units, beneath a specific raster coordinate, for every coordinate in the given area. *Table 2* is an example of what a four-layer model looks like in the format used by ShakeMap (the 4th layer is the bedrock or base layer with infinitely assumed thickness). The first tow columns give the coordinates the other column gives the vertical *thickness* of a deeper unit (in feet, since the SHAKE software requires it). In this instance a GRID size of 15 m. was used in the GIS to represent the boundary layers.

Since it is assumed that the geotechnical properties are constant, the dynamic soil properties for each unit are entered into the standard input before running the program. In each program cycle ShakeMap extracts a record from the subsurface data table, the x and y coordinates are temporarily stored and each unit thickness is added to the standard input. The values for the dynamic soil properties are also assumed constant within a certain unit.

Table 2. A sample input file for ShakeMap, containing the model information.

X	*Y*	*Thickness Layer 1*	*Thickness Layer 2)*	*Thickness Layer 3*
1153155	994260	0.33 (ft)	42.98 (ft)	42.98 (ft)
1153170	994260	0.33	42.98	42.98
1153185	994260	0.33	42.98	42.98
1153200	994260	2.62	41.67	41.67
1153215	994260	2.62	41.67	41.67
1153230	994260	5.25	40.35	40.35

ShakeMap activates SHAKEDIT32 and inserts the prepared input. Once SHAKEDIT32 has finished its calculations and prepared its output, ShakeMap starts reading the output and takes out the requested response values. The program as used in this project returns the maximum acceleration response at the location for three specific periods. In this test case spectral accelerations are obtained for: 0.1, 0.2 and 1.0 seconds. (10, 5 and 1 Hz, respectively). Any number of other response values can be extracted, depending on the typical natural frequency of the building for which the hazard zonation will be carried out.

At the end of each cycle the coordinates stored in memory and the response values read from the SHAKEDIT32 output are added into a new ASCII format table, containing the location. (X and Y). This table can be read by most GIS systems and X and Y values can be used to plot the spatial distribution of, in this case, spectral acceleration for specific periods or frequencies, which can be used in the seismic microzonation.Case study from armenia, colombia

Introduction

The 25 January 1999 Quindío earthquake in Colombia was a major disaster for the coffee-growing region in Colombia. The earthquake, with a magnitude of 6.1 on the Richter scale, killed more than 1,100 people and about 4,800 persons were injured. Approximately 45,000 houses were either destroyed or damaged (see Figure 1). Most of the damage occurred in the city of Armenia and surrounding villages. The RIED project (ITC, 2000) used aerial photographs to create a rapid inventory of the damage. The inventory was used for recognition and establishing of the major geotechnical influences of the subsurface geology on damage patterns. Microzonation maps were made based on these influences together with a surface response study. The zonation maps indicate the areas which, for a future (similar) earthquake, would be prone to damage.

Figure 1. An area in Armenia, that was severely damaged by the earthquake

The maps have been presented to the city planning authorities of Armenia so that reconstruction of the damaged areas can be made such that high-risk areas are avoided or that structures and houses are built according building standards for earthquake high-risk areas.

Geology and geotechnical sub-surface conditions

The region around Armenia is located in the western piedmont of the Central Cordillera, and consists mainly of metamorphic and sedimentary rocks from Palaeozoic to Cretaceous ages. Volcano-clastic deposits (the so-called Quindío Glacis) of Plio-quaternary age cover these rocks. The deposit consists of several lenses and layers of alternating and interfingering pyroclastic- and lahar flows. In the Armenia area two main (active) faults have been identified. A lineament analysis of the area of Armenia has been executed on 1:20,000 aerial photographs of 1981. The identified lineaments are defined by anomalies in the drainage pattern as well as slight topographical events in the surface of the "Glacis del Quindío". Near surface all sub-surface materials have been weathered to residual soils with varying thickness.

Generalised geotechnical model for Armenia

The geological context has been transferred into a simplified subsurface model. In this subsurface model distinction should be made between soil and rock units which have distinctly different geotechnical parameters with respect to the seismic response modelling. In INGEOMINAS (1999) all available geotechnical data are reported. The information in this report is based on borehole data, laboratory testing data and results of seismic and geo-electric surveys. On the basis of these results a generalised geotechnical model is assumed, consisting of the units described below (in stratigraphic order from top to bottom - the corresponding geological code is indicated between brackets). These deposits are volcanic in origin and can be found as continuous deposits over the entire Armenia area. Because of its erodibility the upper Ash deposits are removed by streams and rivers and the ash deposits are thinning out towards the drainage valleys. A short description of each unit is given below:

1. Ash - (QPc) A thick blanket of volcanic Ash and Lapilli that covers the entire area.
2. Residual soil - (QSr) Soil formed from, or resting on, consolidated rock of the same type as that from which it was formed and in the same location. (from Tv unit). Overlying Saprolite layer.
3. Saprolite - (Sp) A soft, clay-rich, thoroughly decomposed rock formed in place by chemical weathering of igneous or metamorphic rock from unit 4 (Tv). Forms in humid, tropical, or subtropical climates. It underlies Residual soil and contains rock fragments and gravels in a clayey matrix of completely decomposed material.
4. Pyroclastic flow deposits and lahar deposits - (Tv) This unit is composed mostly of very dense and welded pyroclastic flows and lahars (with high content of volcanic material) as well as debris and mud flows.

Table 3. Generalised geotechnical model and parameters for City of Armenia, Colombia.

Layer	*Description*	*Average thickness [m]*	*Unit Weight (KN/m^3)*	*V_s (Shear wave velocity) [m/s]*	*G_{max} (Max Shear Modulus) [MPa]*
Layer 1 – QPc	Ash and lapilli	16	15.1	158	39
Layer 2 – QSr	Residual soil	9	15.2	299	139
Layer 3 – Sp	Saprolite	9	16.3	416	291
Layer 4 – Tv	Pyroclastic flow and lahar deposits	∞	15.5	1300	2672

In order to calculate the seismic response throughout the Armenia area the following approach was used: A semi-3D or 2½D geotechnical model was created in the GIS (ILWIS) on the basis of the Digital Elevation Model and the INGEOMINAS information (from the 1999 report and maps). The model consists basically of interpolated surfaces representing the boundaries between the different geotechnical units. The boundaries are interpolated in the GIS from the elevation contour lines, isopach- and depth contour maps. An example of a cross section through the 2½D ground model is given in **Error! Reference source not found.**2.

The gridded surfaces are stored as raster layers in the GIS with a raster size of 15 m. This pixel size has been chosen rather arbitrarily. Since much of the input data was at 1:15:000 scale and because the maps had to be presented at this scale the 15 m (1 mm on the map) raster was chosen, so that the individual raster cells can not be detected on the final map scale. On the basis of the boundary surfaces the individual thickness of each layer or geotechnical unit at every location within the modelled area can be calculated, which is used as inputs for the numeric seismic response calculation. Consequently, for every 'block' of 15x15 m. size, throughout the modelled area, the seismic response is evaluated.

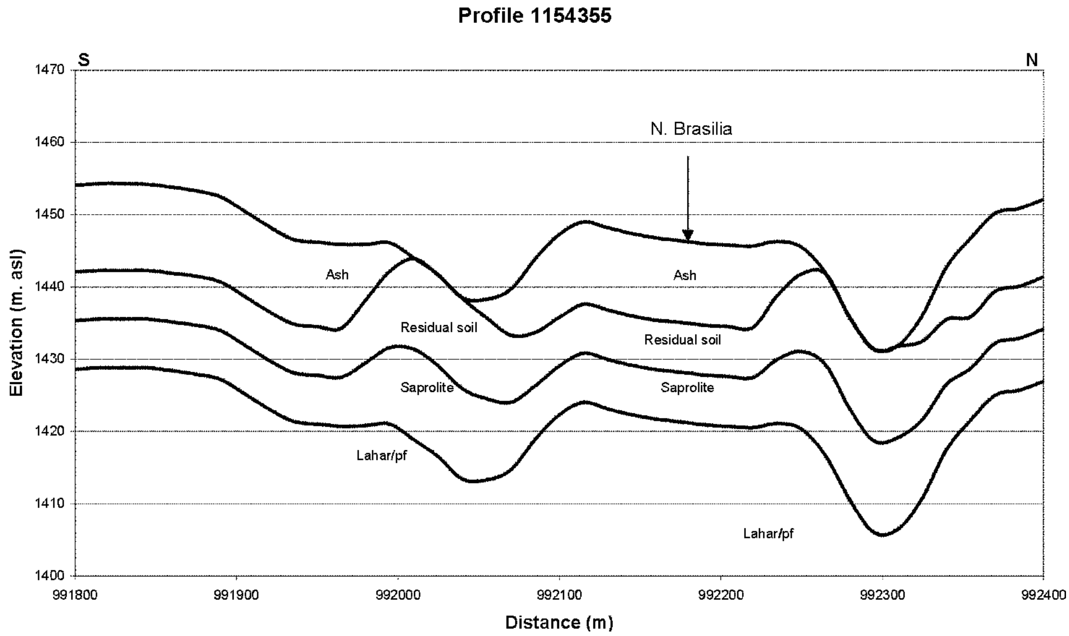

Figure 2. Cross section through the 2½ GIS model. The boundaries are modelled in the GIS as interpolated grid surfaces

A larger raster size than the 15 m. used in this study, will significantly decrease the amount of calculations, which is actually recommended. The results seem to be much smoother and looks more "appealing" with a high pixel resolution, but this can also be very deceiving. People tend to trust results more that "look" nice, while the underlying information may not be that accurate. For this reason it is also recommended to use a larger pixel size, which will actually be visible in the resulting map, to emphasize the fact that the results are based on a simplified raster based ground model.

Distribution of spectral acceleration used as seismic micro zonation maps

The first analysis that can readily be carried out is the calculation of the spatial distribution of the *characteristic site period*, which is based on Equation 2. The average seismic velocity (V_s) for each location is calculated using the individual soil unit thickness and the corresponding seismic velocities. The total soil thickness at leach site (H) will subsequently yield the characteristic site period (See Figure 3). The average site period for the area lies around 0.347 sec (2.88 Hz) although large variations occur within a small area, which is primarily a result of the variation in soil thickness.

According to the methodology described before, maps are created for the city of Armenia that show for three different frequencies the spectral acceleration response: at 10, 5 and 1 Hz. Particularly the spatial distribution of acceleration response at 5 Hz (equivalent to natural frequency of 2 storey houses , pls. refer to *Table 1*) showed very high acceleration levels (see Figure 5). The calculated accelerations for even smaller houses (max 1 storey - 10Hz) are lower than for the 5Hz buildings, but the horizontal accelerations still exceed in many place 1.0 g (see Figure 4).

This analyis corresponds with the general observation that mainly the low-rise buildings were damaged during this earthquake. For these buildings protective measures should be taken in areas where the spectral acceleration exceeds the design spectrum (recommended by the national building code). This can be done by reinforcing the building, thus changing the resonance characteristics. The spectral acceleration distribution for 1 Hz showed no serious amplifications. The character of the signal from the Quindío earthquake and the local site conditions were such that the amplifications were largest in the high frequency range (> 2 Hz), which resulted in severe damage to low-rise buildings, while the high-rise buildings (> 4 storeys) were relatively undisturbed.

CONCLUSIONS

On the basis of the proposed method it is possible to obtain a detailed delineation of the spatial variation in seismic responses, which can be used as an improved basis for seismic micro-zonation mapping. This method has a clear advantage above the "traditional" way of microzonation because it incorporates any a-priori geological and geotechnical knowledge into the semi-3D model and can yield microzonation per building type. The classification into areas of different hazard level is done *after* the response analysis while the traditional method assumes a generalisation of the geological conditions *before* the analysis is carried out, disregarding essential geological information. However, the proposed method requires a very large number of seismic response calculations has to be carried out; one for every pixel in the GIS raster database. This problem is solved by automating the repetition of response calculation through the execution of a computer program that forms the interface between the gridded semi-3D ground model from the GIS and the seismic response calculation program SHAKE.

The methodology was applied to a case study from the city of Armenia in Colombia, which was affected by an earthquake in January 1999. The spatial variation of the spectral acceleration for different frequencies was determined. It could be concluded that the amplification of the seismic signal that was recorded for this particular earthquake was exceptionally high in the 5 Hz range, which generally corresponds to the natural frequencies of houses with about 2 stories. This was in correspondence with the general observations right after the earthquake, which revealed that the low-rise buildings experienced relatively more damage than the high-rise buildings.

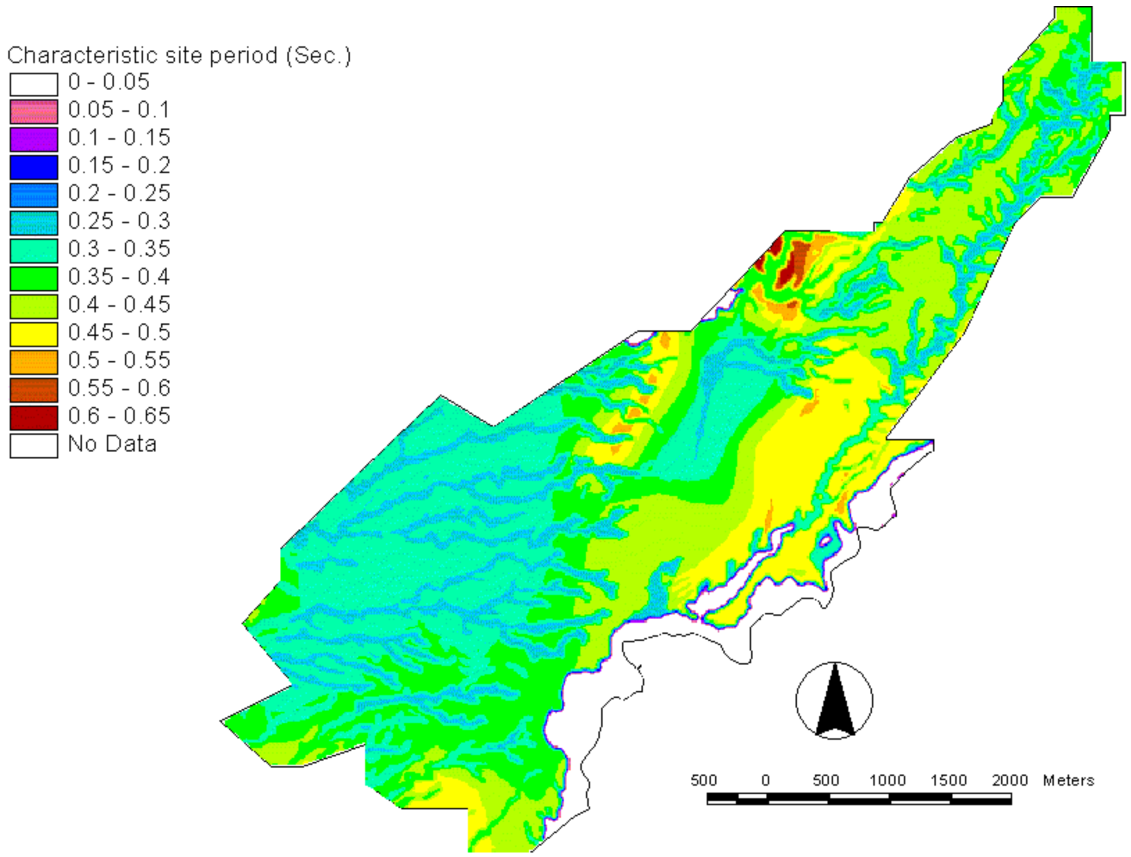

Figure 3. Characteristic Site period (in Seconds). Calculation based on Equation 2: $Ts = 4*H/Vs$. Vs is the average seismic velocity and H is the soil thickness. H and Vs are calculated using the generalised geotechnical model. Buildings with a natural frequency corresponding with the site's characteristic frequency have a higher probability of reaching a state of resonance, which can result in damage.

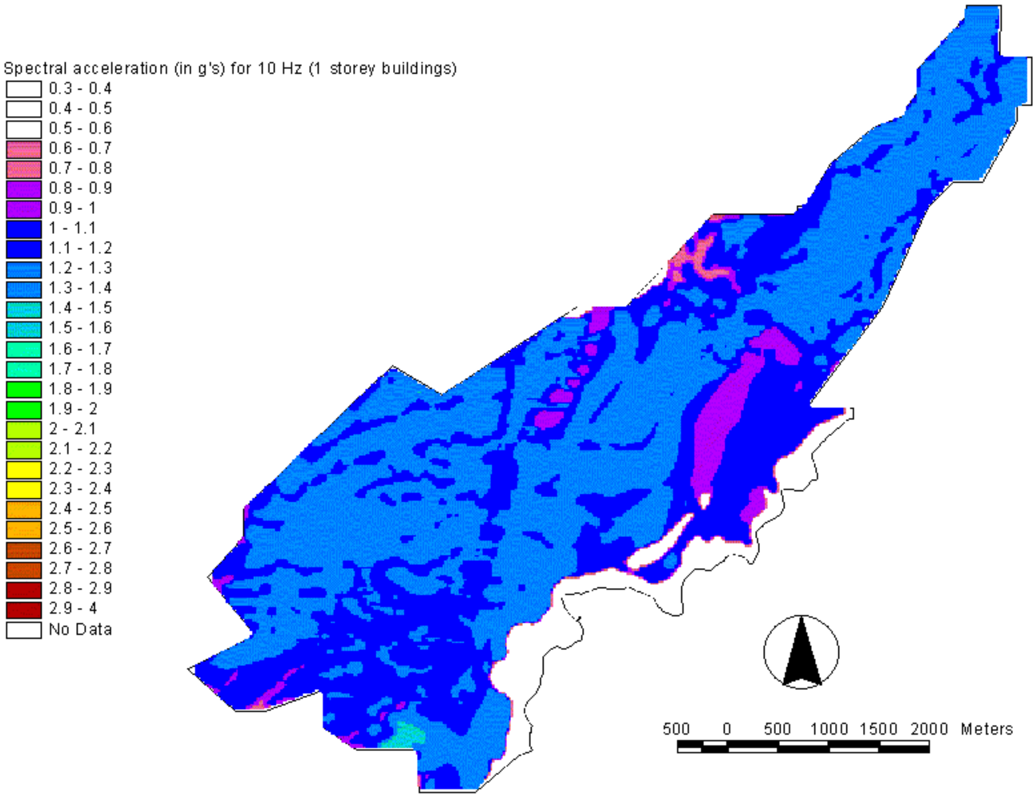

Figure 4. Spatial distribution of the spectral accelerations (in g's) for 10Hz.

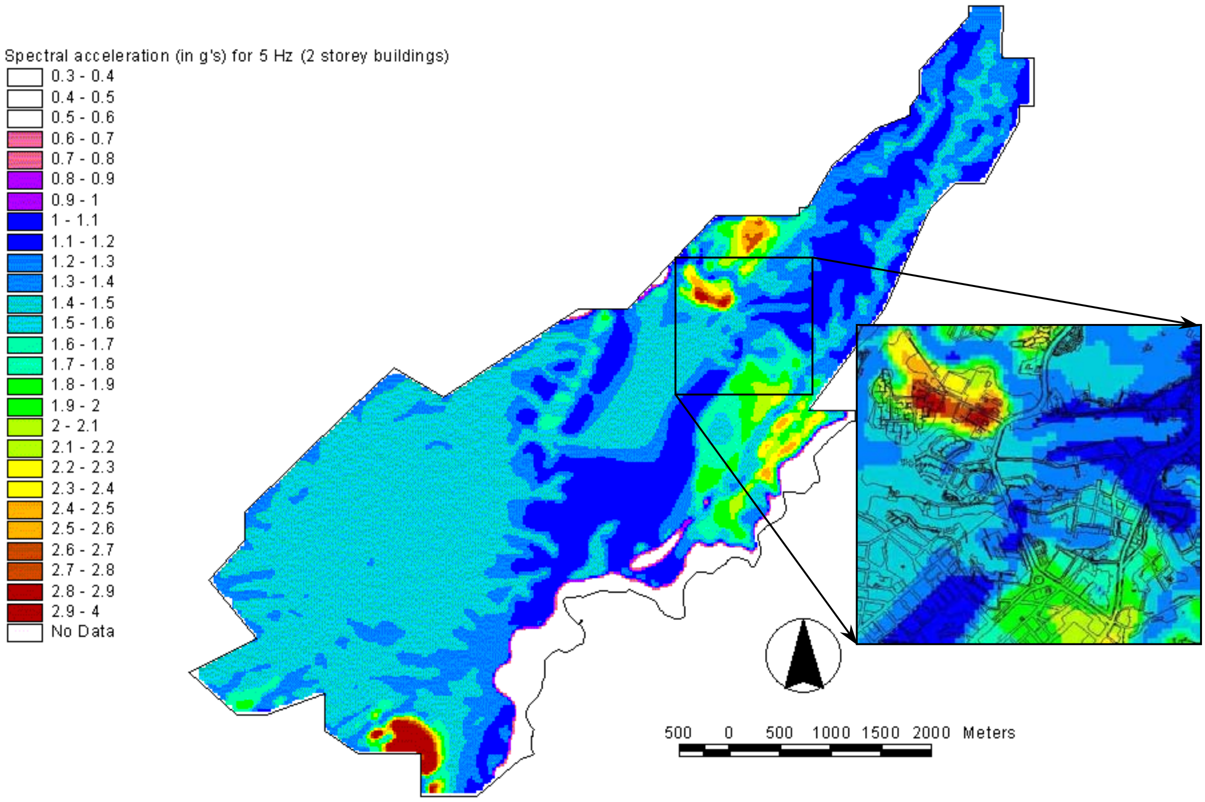

Figure 5. Spatial distribution of the spectral accelerations (in g's) for 5Hz. Observe the large difference in acceleration values with the 10 Hz map and clear "shift" of the highest intensity areas. Inset shows enlargement of indicated area, which illustrates the large variation in accelerations that can occur in a relative small area.

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