Modeling the Specific Seismic Risk Considering the Weight of Determining Variables

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Abstract

The seismic risk determination for any country is a vital tool in the process of physical planning, construction and reduction of disasters caused by earthquakes. In recent years, there have been several studies on the subject, however, different methodologies could be improved from the design of a set of basic criteria, which using the advantages of Geographic Information Systems (GIS), could help to establish greater clarity in the seismic risk determining. To meet this goal, in this study, the authors propose a new allocation methodology based on levels of importance of variables that influence the specific seismic risk assessment and propose a new formula for mathematical determination through modeling with GIS.

Keywords

Earthquakes, Methodology, Model, Risk, Variables

Subject Areas: **Computer Engineering, Environmental Sciences, Geology, Geomorphology, Hydrology, Natural Geography**

1. Introduction

An earthquake or seism is a geological phenomenon product to a sudden release of energy in a point of the earth's crust, and this motion causes shock waves, also known as *seismic waves*, propagating from the point of origin and traveling through the Earth. Earthquakes are manifested in the formation and decay of rocks and soils, in the variation of their physical and stratified conditions, in the formation and variation of the relief of the land surface, in the construction of the crust and the internal structure of the Earth. To study them is extremely important for engineering processes, due to its influence on the stability of the ground, respectively, in existing works, planned, under construction, etc., (Cities, buildings, bridges, dams, roads, tunnels, airports , mines, qua-

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rries, etc.). The possible occurrence of earthquakes is a threat whose impact can lead to serious injury or geological risks.

Geological risks are events or circumstances that occur in the geological environment and can cause damage or harm to communities or infrastructure that are occupying a territory vulnerable areas [1]. According to Galbán *et al.* (2012) [2], seismic risks are a type of geological risk because the event which takes place in the geological vulnerable enhancer of damage is the earthquake. The determination of the seismic risk leads to follow three key steps: 1) the hazard assessment, 2) vulnerability and, 3) the evolution of risk. Changes in one or more of these parameters influence the risk in itself. To consider these elements is necessary to use or design a methodology to provide as much detail as possible to determine the behavior of risk in a given geographic area.

In the analysis of the seismic risk assessment at the international level were detected several methodologies in this regard, although the methodology mostly employed are the HAZUS promoted by The United States Geological Survey (USGS) and Federal Emergency Agency (FEMA), and the one used by Japanese Geological Survey [3].

Most of these methodologies modeled seismic risk from the occurrence or not of the different processes or factors that lead to hazards, vulnerability and seismic risk, however, with regard to the consideration of the effect or weight of the variables in their determination are not uniform, especially when it comes to damage to specific elements located on the ground (buildings and infrastructure, people, etc.), which is why it is necessary to address this gap and establish a new formulation for determining the seismic risk. To accomplish this task it is necessary to establish a new formula for mathematical determination of specific seismic risk through modeling with GIS. The novelty in this process comes in the allocation of a methodology based on levels of importance of variables that influence the specific seismic risk assessment which takes into account the behavior of elements involved in the manifestation of the phenomenon, as well as others related to the physical vulnerability discussed in the geographic spaces.

By other hand, the methodologies used so far internationally to determine the models do use the multiplication of hazard and vulnerability variables to find the risk. This point of view do not consider that factors multiplied only complicate the situation of the risk evaluation, giving them the possibility to be expressed in how many times or for which factor should be multiplied to obtain a final result, when in real life it is only a sum of pondered facts, which is why it is needed to solve these matters from a different perspective.

2. Definition of the Specific Seismic Risk Model

The Geographic Information Systems (GIS) are a valuable tool to tackle works that require multivariate modeling due to the large volume of information they can process, its ability to generate types, and therefore the possibility of overlapping maps coming to get a map that covers the features of all of them. These elements make them ideal tools for modeling the specific seismic risk.

Using GIS seismic risk assessment is carried out through the acquisition or development of a set of maps or models of hazard, vulnerability and specific seismic risk, which are governed by the following mathematical formulation:

$$\mathbf{Rs} = \mathbf{R1}(\mathbf{0.30}) + \mathbf{R2}(\mathbf{0.20}) + \mathbf{R3}(\mathbf{0.50})$$

where:

1) **R1** or **Liquefaction Model** = underwater level (0.30) + Geological Susceptibility (0.30) + Seismic Acceleration (0.40).
2) **R2** or **Earthquakes Landslide Model** = Vegetation (0.05) + underwater level (0.05) + Geological Susceptibility (0.25) + Topographic slope (0.25) + Faults (0.10) + Seismic Acceleration (0.30).
3) **R3** or **Specific vulnerability model** = structural seismic vulnerability of buildings per community (0.30) + structural seismic vulnerability of the Roads (0.10) + Population at risk (0.30) + Seismic Acceleration (0.30).

In the formulation are introduced values which should be multiplied by the variables that influence the hazard identification, vulnerability and seismic risk; they obey to the weight of these variables in the occurrence or not of different primary and secondary events.

To represent the interaction of the different variables was used the sums of each to obtain the different basic models. The final specific risk model obtained from this algorithm is reclassified by importance ranges, assigning to each basic model final weight. Each classification is made based on expert judgment, in this case with the support of other documented experiences and qualitative analysis of the distribution of the values of the variables in space.

For a better understanding and correspondence between levels and generating information through maps and graphics or mathematical models, it is suggested to standardize the values from the proposition made by Galbán *et al.* (2012) [2], so that the hazards, vulnerability and risks are classified on a scale from zero to one (0 - 1) following levels represented in **Table 1**.

The proposal aims to integrate on a numerical scale that standardized assessments of hazard, vulnerability and risk, ensuring that all estimates are based probabilistically by its more affordable comparison; action that is performed by applying mathematical standardization and interpolation methods. The choice the method depends on the evaluators and can be done automatically with the help of GIS.

3. Evaluations of the Use of Variables

The underwater level is the underground water that exists on the planet and its depth varies depending on the geological and climatic circumstances. Its presence constitutes an extremely destructive agent when seismic waves are impacting soils and rocks, causing the phenomenon known as liquefaction. Its influence on the seismic risk is expressed in **Table 2**.

Seismic acceleration is the main characteristic of a seismic wave; its determination allows knowing its value at every point of the geography. The values used in the research for the consideration of seismic acceleration were taken form Galbán *et al.* (2012) [5], and are expressed in **Table 3**.

The vegetation development and its type is an important element in the succession of landslides in a given area. The vegetation and its root system is a factor that can decrease the speed of the slides, and even prevent them in slope areas. For the consideration of this item assumes the proposition made by Galbán *et al.* (2012) [5] and are expressed in **Table 4**.

3.1. Submodel Geological Susceptibility

Lithological variety according to their physical and mechanical properties, express certain geological levels of susceptibility to the occurrence of different geological processes and phenomena. This influences susceptibility

Table 1. Classification and standardization of values for hazards, vulnerability and risks [4].

	1st. Level	2nd. Level	3rd. Level	4th. Level
Hazards	None - Low (0 - 0.25)	Moderate (0.26 - 0.5)	High (0.51 - 0.75)	Very High (0.76 - 1)
Vulnerability	None - Low (0 - 0.25)	Moderate (0.26 - 0.5)	High (0.51 - 0.75)	Very High (0.76 - 1)
Risk	None - Low (0 - 0.25)	Moderate (0.26 - 0.5)	High (0.51 - 0.75)	Very High (0.76 - 1)

Table 2. Categorization of the influence by depths of groundwater level. Adapted from Japan Working Group, 1993.

DEPTH (m)	Hazard to Liquefaction
0 to 3	Very High
3 to 10	High
10 to 15	Moderate
More than 15	Low

Table 3. Values considered for seismic acceleration [5].

Indicator	Evaluation Grade			
	Low	Moderate	Stop	Very High
Seismic acceleration	Less than 0.10 g	Between 0.10 - 0.20 g	Between 0.2 to 0.30 g	Greater than 0.30 g

Table 4. Considerations for the influence of vegetation and hazard levels [5].

	Evaluation Grade			
	Low	**Moderate**	**High**	**Very High**
Influence of Vegetation	Over 70 percent. Well developed tree cover (forest)	Between 70 - 40 percent. Tree cover relatively developed	Between 40 - 20 percent. Tree cover interbedded with poorly developed herbaceous cover constants, crops and orchards	Less than 20 percent. Denuded areas with sparse grass and shrub cover (shrubs and secondary herbaceous communities) and crops and orchards

rocks ability not only to allow passage of the seismic waves, but also to increase the translation speed of them. Considering the above is proposed to employ the susceptibility for determining geologic model serving as indicated in **Table 5**.

3.2. Topographic Slope Sub Model

The topographic slope value is an element that affects the performance of the force of gravity on the phenomenon of sliding slope areas, because the greater the slope will have greater performance out of gravity in conjunction with other factors that also act in landslides. For the consideration of this item assumes the proposition made by Galbán *et al.* (2012) [5] and are expressed in **Table 6**.

3.3. Faults Sub Model

For hazard assessment and risk estimation is consider that the main effects related to active faults in the occurrence of a strong earthquake are given mainly in the fact that these are weak areas in the surface were increases of seismic intensity is experimented. Are also areas where differential movements can occur because faults constitute limits of different dynamic blocks and serve as a waveguide from the seismic focus or hypocenter. Based on these criteria is considered the following (**Table 7**).

3.4. Structural Seismic Vulnerability of Buildings per Community Sub Model

The structural seismic vulnerability of buildings is given by elements related to construction technical states of buildings in different areas, communities or cities that comprise the study area, taking into account the different constructive pathologies, speaking states (**Table 8**). Example: For states often adopt four levels or states of harm they might suffer these buildings and infrastructure [6]:

E1 = no damage;
E2 = slight damage, operating;
E3 = damage repairable, not operating;
E4 = severe damage or ruin, out of service.

Given these evaluations is then used the proposition of Galbán *et al.* (2012) [5].

3.5. Structural Seismic Vulnerability of the Roads Submodel

The structural seismic vulnerability of roads is given by elements related to construction technical states of roads in different areas that comprise the study area, taking into account the different pathologies that are presented from the bedrock to the asphalt or concrete surface. Given these assessment evaluations is then used on a scale of 1 to 10 for vulnerability levels as proposed in **Table 9**.

3.6. Population at Risk Sub Model

The population sub-model is obtained from the database for each region edited by government statistics offices. In it should be introduced, according to the population of different communities and local considerations, the evaluation criteria. One of the criteria set forth in **Table 10**.

4. Result of the Application of the General Formulation and Discussion of Models

To determine the resulting specific seismic hazard model, the basic models are calculated as stated below:

Table 5. Classification of lithological or geological susceptibility influence, according to the general conditions [5].

Rock types	*General lithology*	PFM behavior of rocks									
		GS	**Representative groups**	**RGS**	**Jointing or cracking**	**Permeability coefficient (cm/s)**	**Moisture**	**Void ratio**	**Deformability of soil (MPa)**	**Plasticity index**	**Compressive strength (Mpa)**
Any type of rock, sedimentary or crystalline (this material can be characterized by a propagation velocity of shear wave greater than 800 m/sec.)		Drop									
Rigid floors of thickness less than 60 m to the rock base, provided that the upper layers are composed of stable deposits of sand, gravel or hard clays (this material can be characterized by a propagation velocity of shear wave between 450 and 750 m/sec.).	Impermeable limestones, basalts, and esites, low degree of weathering, little fracturing rocks with high shear strength, low level of groundwater.	0 - 0.25	Basalt, diabase, gabbro	0.08							
Periods are between 0.3 and 0.5 sec.											
			Andesite, diorite, porphyry, granite	0.16	Less than 3%	Less than 10 - 8	Between 0% - 10%	Less than 0.15	Greater than 20,000	Less	Greater than 80
			Serpentinite, rhyodacite, rhyolite, marble, limestone compact	0.24						to 30	
Stable deposits of non-cohesive soils or hard clays when its depth to bedrock exceeds 60 m and the upper layers are composed of sand, gravel or hard clays (this material can be characterized by a propagation velocity of shear wave between 240 and 450 m/sec.)	High degree of weathering of rocks mentioned enzymes and massive clastic sedimentary rocks, low shear strength, shear fracture.	Moderate	Permeable limestones,	0.28							

Continued

Periods are between 0.5 and 0.8 sec.											
		0.26 to 0.50									
			Schists, metamorphic clastic, igneous cracked	0.36	Between 3 and 10%	Between 10 - 8	Between 10% - 40%	0.15 to 0.25	Between 20,000 and 10,000	Between 30 and 50	Between 80 and 50
			Compact breccias and conglomerates, sandstones cohesive	0.48		And 10 - 5					
Soft clay deposits or sands averages and thicknesses of 10 m or more with or without the presence of intermediate layers of sand or other non-cohesive soils class (this material can be characterized by a propagation velocity of shear wave of less than 240 m/sec.)	Unconsolidated rock or soil, weatherproof í sm significant sedimentary rocks, intrusive and volcanic water table fluctuations.	Average	Volcano sedimentary rocks	0.54							
Periods are between 0.8 and 1.2 sec.		From 0.51 to 0.75									
			Clays compact	0.62	Between 10% and 30%	Between 10 - 2	Between 40% - 70%	Between 0.25 and 0.50	Between 10,000 and 5000	Between 50 and	Between 50 and 20
			With jointing massive argillaceous rocks, conglomerates with medium cohesion diaclasades	0.72		And 10 - 5				70	
		High									
Soft clay deposits with a thickness of 12 m (this material can be characterized by a propagation velocity of shear wave of less than 150 m/sec.)	Quaternary unconsolidated soils, fill clay soils and pyroclastic unconsolidated fluvio-lacustrine, shallow groundwater levels.		Loams, silts, sandstones	0.76							
		0.76 to 1	Sandy clay soils,	0.88	Over 30%	Greater than 10 - 2	Greater than 70%	Greater than 0.50	Less than 5.000	Greater than 70	Less than 20
			Swamp deposits, fluvio-lacustrine, alluvial	0.96							

GS: geological susceptibility, RGS: Range of geological susceptibility for groups of rocks.

4.1. Liquefaction Model

Liquefaction of soils is a physical phenomenon characterized by the complete loss of shear strength. This is bas-

Table 6. Considerations for the influence of the slope and hazard levels [5].

Evaluation of the topographic slope value			
Low	**Moderate**	**High**	**Very high**
Between 0 and 15 percent	Between 15 to 25 percent	Between 25 and 45 percent	More than 45 percent

Table 7. Considerations for the influence of faults and hazard levels [5].

Presence of active faults			
Low	**Moderate**	**Stop**	**Very high**
In remote locations of the selected area (more than 300 km^2)	In the vicinity of the selected location (between 50 and 300 km^2)	In close proximity to the selected location (between 5 and 50 km^2)	In the vicinity of the selected location (less than 5 km^2)

Table 8. Classification of construction technical states for buildings and infrastructure [5].

CTE	Index CTE	General description
Good	0 - 0.25	Prevalence of homes and buildings in good condition recent constructive. Good structural strength
Regular	0.26 to 0.50	Prevalence of buildings with different construction pathologies. Moderate structural strength
Bad	From 0.51 to 0.75	Prevalence of different materials damaged homes. Poor structural strength
Critical	0.76 to 1	Prevalence of huts, huts, temporary buildings with low cost materials, etc. No structurally resistant

Note: CTE construction technical states.

Table 9. Classification and constructivos of technical states road const [5].

ETC	Structural vulnerability of roads	General description
Good	0 - 0.25	Roads in good constructive. Good structural strength of the base and paving, generally stable soils.
Regular	0.26 to 0.50	Road construction with different pathologies. Paved surface subsidence in some cases or settlements light, presence of occasional bumps. Embankments improved
Bad	From 0.51 to 0.75	S diverse pathology roads, eroded in some sections, with frequent potholes and structural Poor resistance. Embankments not better ed
Critical	0.76 to 1	Roads with different pathologies constructive well marked. Paved surface in most cases with sinking or settlements, presence of holes, generally unstable soils or aggressive environments. No structurally resistant. Trails, roads, among others.

ically the result of increased pore pressure caused by cyclic strain: a granular material such as soil sands are shaken and these are subjected to a rapid compaction also when is saturated, the result of this compaction gives a rapid lifting of the pore pressure or, since the cutting resistance, which is directly and simply related to the effective force**.**

For determination of liquefaction model (R1) is considering making queries to the system from the primary base values established in the basic sub-models discussed above, obtaining the final model. Their basic interpretations are made from what was proposed in **Table 11**.

4.2. Earthquakes Landslide Model

It is called slide to the mass of rock of low consolidation or compaction that has been moved or moves downhill slope shed or (artificial slope) under the effect of gravity, hydrodynamic pressure (saturation effect), seismic forces of various origins, etc. These agents may also act in landslides in combination. From the primary data of the final model is obtained by earthquakes landslides. Their results are interpreted as posed in **Table 12**.

4.3. Specific Vulnerability Model

To determine the specific vulnerability model (R3), it was considered make queries to the system from the primary core values, levels of specific damages are classified and interpreted as follows (**Table 13**).

4.4. Specific Seismic Risk Model

Finally the specific seismic risk model is obtained from the superposition of the previously obtained submodels. With the specific purpose of making an assessment as accurate as possible of the elements or variables that characterize the specific seismic risk, we suggest that the analysis for interpretation be made from what is stated in the **Table 14**.

5. Conclusions

A methodology for the determination of specific seismic risk through its modeling with the use of GIS, which has the novel feature weight consideration with the different variables in the process.

Sub models are some variables in concordance by level and values that can be obtained; the valuation of the

Table 10. Criteria for evaluation of the population at risk.

Exposure of the population	General description
Low	Rural communities usually isolated population, could be far from generators foci. Less than 10,000 inhabitants
Moderate	Semi rural communities with concentrated population, may be moderate distances to generators foci. Between 10,000 and 75,000 inhabitants.
High	Urban communities with concentrated population may be at near distances to generators foci. Between 75,000 and 250,000 inhabitants.
Very High	Urban communities with highly concentrated population and can be very close distances to generators foci. More than 250,000 inhabitants.

Table 11. Evaluation of risk levels for soil liquefaction.

Indicator	Evaluation Grade			
	Low	Moderate	High	Very High
Liquefaction	Ground solid state	Wet soil	Soil semi molten state (saturated)	Liquefied soil

Table 12. Evaluation of risk levels for soil liquefaction.

Indicator	Evaluation Grade			
	Low	Moderate	High	Very High
Soil liquefaction	Slow and limited land mass shifts	Moderate shifting of land masses. Few rock collapses.	Rapid and abundant land masses landslides, collapses, landslides, falling boulders	Shifting of large masses of land, lahars, breakdowns, etc.

Table 13. Levels of specific vulnerability proposed.

Indicator	Evaluation Grade			
	Under	Moderate	High	Very High
State of buildings and infrastructure pathologies.		Between 10 and 30 percent	Between 30 to 50 percent	More than 50 percent
population considerations	From 0 to 10 percent of buildings and infrastructure are already affected by different pathologies. The population is low, may be isolated and or have excellent knowledge or perception of risk	of buildings and infrastructure are already affected by different pathologies. The population is midle not concentrated and or have good knowledge or perception of risk	of buildings and infrastructure are already affected by different pathologies.	of buildings and infrastructure are already affected by different pathologies.
			The population is concentrated and or have not good knowledge or perception of risk	The population is highly concentrated and or have no knowledge or perception of risk

Table 14. General elements to consider in the interpretation of the specific seismic risk model.

GRADE	Riesgos Risks
Under	The damage that can occur in buildings after the impact of an event is mild and can be treated easily, resolved with simple maintenance most of the time. Hairline cracks are usually seen on the roofs and walls of buildings, mild manifestations of moisture in walls and slabs and in some cases falling bits of plaster, among other minor affectations.
	The land hardly suffers transformations, is able to assimilate and/or easily adapted to the impacts of geological events. These areas are ideal for high-density urban uses and location of critical infrastructure such as hospitals, schools, regular Industries or treatment of hazardous substances (preferably outside the city limits), etc.
No damage.	The majority of shares to offset the impacts should be concentrated on reducing human action that can accelerate it, and environmental education.
	The impact both soil structure as buildings can reach 25%.
	Losses caused by the impact of a geological event can reach 35% of gross domestic product of a country, region or community, or the value of investment in state of no damage.
Moderate	The damage that can occur in buildings after the impact of an event are high and can only be assimilated by performing both preventive and remedial interventions reconstruction and/or rehabilitation of damaged structures. Cracks ranging between 1 and 5 inches thick on the roofs and walls reaching affect the columns and beams of buildings, intense manifestations of moisture in walls and slabs, in many cases partial or total fall of the walls are usually observed constructions of low strength materials, considerable subsidence structures, among other damages.
	It is necessary to implement codes, strict geotechnical and earthquake-resistant standards.
Minor damage.	Losses caused by the impact of a geological event can reach 65% of gross domestic product of a country, region or community, or the value of the investment.
	The land can undergo significant transformations, it is able to absorb and/or adapt to the impacts of geological events by performing preventive and shaping actions, including containment works with concrete or steel, shaped land, pipelines are located, structural steel reinforcements and special concrete, precautionary signs, among others.
	use of these lands for urban uses only low density and high strength construction technician is recommended.
	Urban use is permitted after detailed studies by experienced specialists, to determine the degree of danger and set limits to the previous sector.
	The majority of shares to offset the impacts must be shared between environmental education, declining from human activities can accelerate and increase the structural strength performance requirements under normal following indications raised in earthquake resistant standards and codes, geotechnical against floods, among others.

Continued

High	The impact both soil structure like the buildings can reach 70% The damage that can occur in buildings after the impact of an event are high and can only be assimilated by performing both preventive and remedial interventions reconstruction and/or rehabilitation of damaged structures. Cracks ranging between 1 and 5 inches thick on the roofs and walls reaching affect the columns and beams of buildings, intense manifestations of moisture in walls and slabs, in many cases partial or total fall of the walls are usually observed constructions of low strength materials, considerable subsidence structures, among other damages. It is necessary to implement codes, strict geotechnical and earthquake-resistant standards.
Serious damage	Losses caused by the impact of a geological event can reach 65% of gross domestic product of a country, region or community, or the value of the investment. The land can undergo significant transformations, it is able to absorb and/or adapt to the impacts of geological events by performing preventive and shaping actions, including containment works with concrete or steel, shaped land, pipelines are located, structural steel reinforcements and special concrete, precautionary signs, among others. The use of these lands for urban uses only low density and high strength construction technician is recommended. Urban use is permitted after detailed studies by experienced specialists, to determine the degree of danger and set limits to the previous sector. The majority of shares to offset the impacts must be shared between environmental education, declining from human activities can accelerate and increase the structural strength performance requirements under normal following indications raised in earthquake resistant standards and codes, geotechnical against floods, among others.
Very high	The impact both soil structure like the buildings can reach 70%. Damage can occur in buildings after the impact of an event are severe. The cost of rehabilitation of the building is so high that it becomes impractical implementation. Generally seen widespread cracking in buildings, loss of stability of structures, intense scouring of foundations, in many cases failure or partial or total collapse of buildings and infrastructure (bridges, roads, etc.), considerable subsidence and landslides structures, destruction, among other damages.
Irreparable damage	The land can suffer large transformations presented, depending on the phenomenon that impacts: severe cracking, high porosity, subsidence and collapse, opening, rollovers, changes in topography, etc. That is, not assimilate impacts of geological events. In some cases it is advisable to perform preventive and shaping actions, including containment works with concrete or steel, terrain profiling, piping, structural steel reinforcements and special high-strength concrete, precautionary signs, among others are. Do not use this land for urban purposes is recommended. Only exceptions strategic or historical nature allowed for a community using criteria of high structural and nonstructural resistivity element that can only be achieved with high investment costs. Could be used as ecological reserves, open recreation, parks or for growing short-cycle plants, consistent with the frequency of the threat. --These lands are accepted only for urban use of low density and high constructive technical resistance. Its urban use shall be conditioned on the completion of detailed studies by experienced specialists, to determine the degree of danger and set limits to the previous sector. The majority of shares to offset the impacts of geological events must be shared between environmental education, declining from human activities that can accelerate the impact, the relocation of infrastructure and increased structural strength under strict requirements control the execution of works by applying principles of total quality management. Losses to buildings can be up to 100% of the investment value. Destroying a whole can cost several times the GDP of a country, region or community.

variables can be adjusted or improved with more detailed requirement.

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