Ground subsidence influence on the seismic response of soil deposits in Aguascalientes City, Mexico

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SUMMARY:
The groundwater extraction for agricultural, industrial and domestic uses has induced important differential ground settlements within the graven of Aguascalientes. Accordingly, ground seismic response evaluations should take into account actual ground surface characteristics as well as the spatial variation of soil deposits properties, caused by non-homogeneous groundwater extraction and consolidation effects during the last two decades.
In order to study this time-varying problem, a two dimensional finite difference model has been implemented, which represents a west-south section across the city (approximately 10 km of length) intersecting the main fault systems and the areas with major water extraction. The model includes the piezometric falling process simulation and the consequent variation of the material properties, and the determination of the resultant free field acceleration spectrums.
Finally, the results included in this paper show the influence of the piezometric falling process, geological fault system, basal rock irregularities and the time depending variation of soil properties in the seismic response of free field and certain type of colonial and modern buildings.

Keywords: Ground subsidence, seismic response, piezometric falling process

1. INTRODUCTION

In the central region of Mexico (Aguascalientes, Morelia, Celaya, Puebla, Toluca, Querétaro, San Luis Potosí and México city), the drinkable water supplies are generating important problems concerned with the over extraction of groundwater deposits. These problems are relating to subsidence, soil cracking, variation of dynamic response of soil deposits and continuous changes respect to the potential risk and magnitude of possible damages caused by seismic action to historical and modern buildings.

This problem is getting worse, due to the continuous increase in the water supply requirements of the growing population and the economical developing of these regions. Furthermore, particular characteristics of some of these zones, concerned to geological materials and faults, topography, rock basement geometry and soil types, contribute to increasing the problem.

In the specific case of Aguascalientes, it is necessary to take into account the complex relation between the mechanisms that generates the variation of the seismic response of soil deposit. One of these aspects is related to cracking formation process, which is probably caused by the tectonic activity of low magnitude and regional subduction phenomena. The last phenomenon is influenced by the rock basement irregularities that produce differential sinking, and the phreatic level falling, which could be non-uniform due to the existence of important differences in the permeability and drain capacity at short distances. This situation causes an enhancement of the stress level, increasing the possibility of crack formation.

Other aspect related to seismic response variation of the soil deposit, is the groundwater extraction. This process generates changes in pore pressure that increases the effective stress, causing an effectively overload of the soil, which increases the consolidation process. Accordingly, the static and dynamic properties of the soil does change, and therefore the seismic response (Ovando et al., 2007).

This document presents the study of the variation on seismic response of the soil deposit due to the increase of effective stress caused by water extraction, cracking generation process at different zones of the city and the incidence of geological faults. For this purpose, a two dimensional finite difference model is formulated and an artificial earthquake was generated according to the seismicity of the zone. Finally, resultant acceleration spectrums are determined to analyze the evolution of the potential risk of diverse kind of buildings. The results show important variations in the seismic response, which are necessary to take into account in the hazard evaluation and determination of possible damages at structures and lifelines.

2. MATHEMATICAL MODEL FORMULATION

2.1 Model geometry

For the model formulation of piezometric level falling, geological faults, spatial variation in soil properties and seismic response, is used a geological section (A-A') of the valley of Aguascalientes city (Sifagg 2010). This section is located to the south of the city (Fig. 1). This section includes some geological faults (Fig. 2)

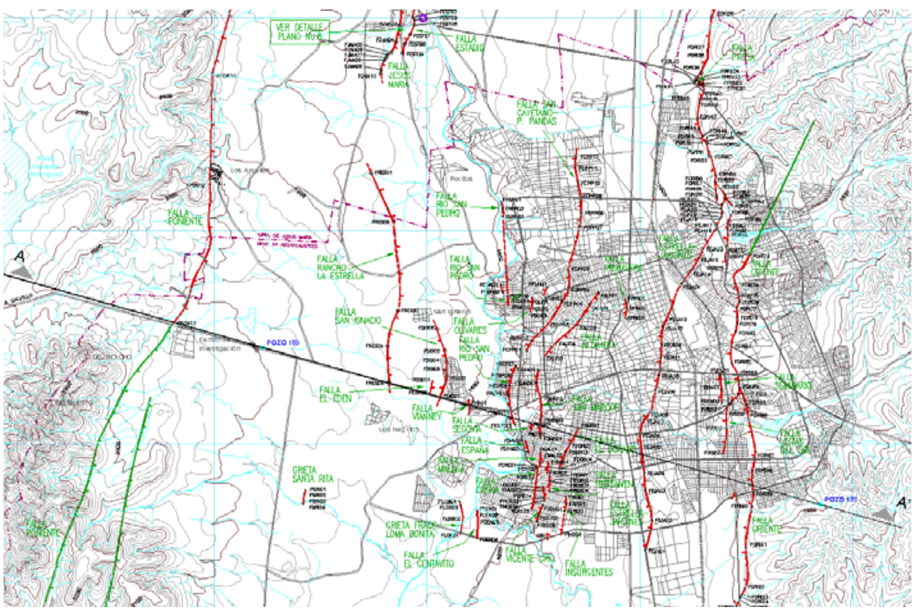


Figure 1. Location of the studied geological section (Sifagg 2010)

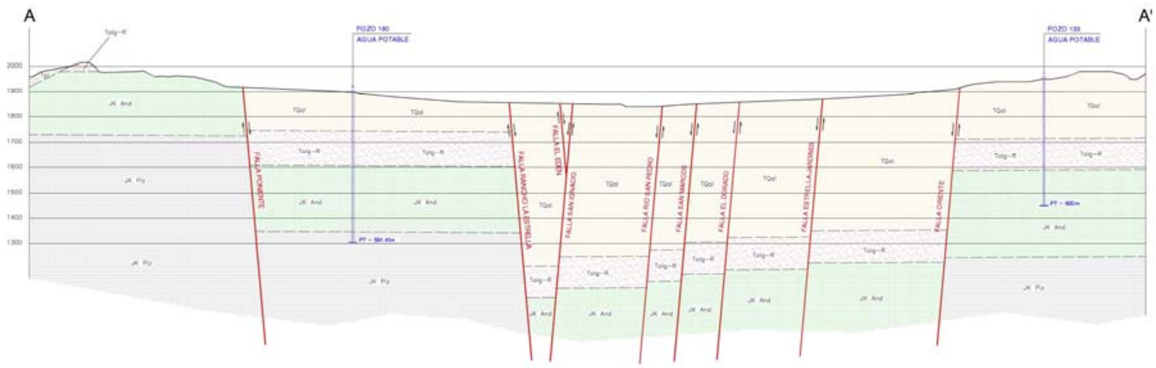


Figure 2. Geological section A-A’ (Sifagg 2010)

The numerical model is developed in FLAC3D (ICG, 2002). The relevant aspects involved in the modelling are related to the piezometric level falling, physical properties of geological materials, seismic environment, and geological faults and cracks family.

The proposed model has a length of 14,470 m, 500 m of wide, and 958.8 m of height. The model is conformed to 17,476 elements and 28,126 nodes (Fig. 3). Additionally, four interfaces were included with the purpose to characterize geological faults. The model represents the topography and strata distribution in longitudinal direction according with the geological section used. In normal direction, stratification and model geometry are maintained constant due to lack of information in this orientation.

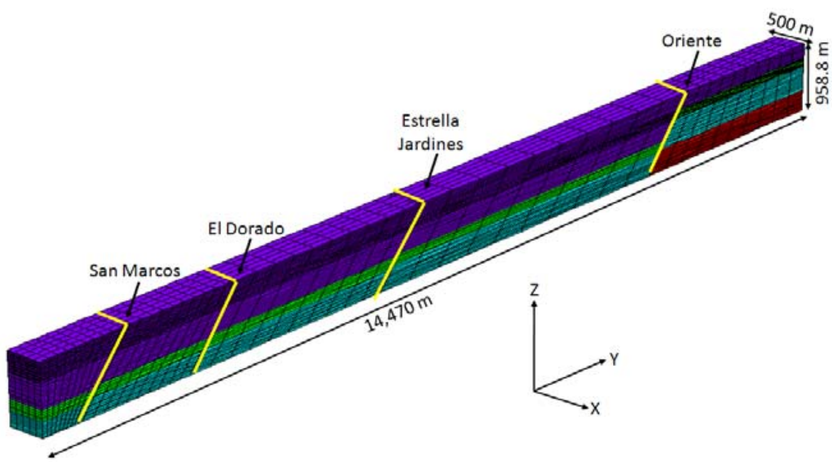


Figure 3. Finite difference model

2.2 Modelling the piezometric falling process

The piezometric falling process is simulated through reduction stages of 10 m. Assuming, that previous to the first stage the ground water level is near to the surface, and materials are completely saturated. In the phreatic level falling process advance, the weight of the affected materials changes from saturated weight to dry.

2.3 Determination of the geological faults properties

The geological fault properties are defined by a back analysis during the piezometric falling process. This is an iterative process in which parameters of the interfaces (normal and shear stiffness, strain strength and friction coefficient) are modified until the results of displacements and cracks opening, are similar to those reported in literature.

2.4 Seismic environment determination

The model is excited at the base in uniform manner, east – west, and north – south directions. The seismic signal corresponds to a synthetic earthquake generated according to the Mexican seismic regionalization (Figs. 4 and 5). The synthetic signal is generated in domain frequency using the random vibration theory proposed by Vanmarcke and Gasparini (1976).

With the purpose of reaching a proper computational time, the duration of synthetic signal is fixed in 54.4 seconds. This duration allow to conserve the most representative characteristics of the natural earthquake, like intensity and transitory character (Fig. 6).

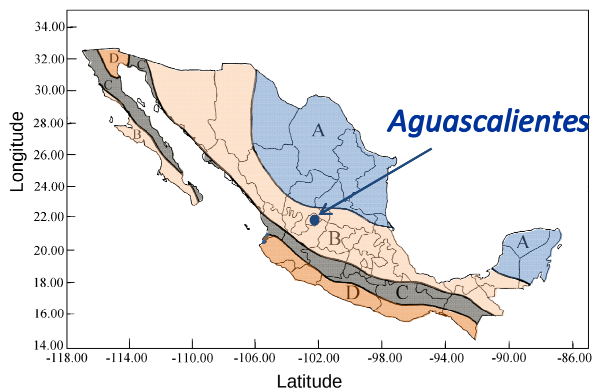


Figure 4. Seismic regionalization of Mexico (CFE, 1993)

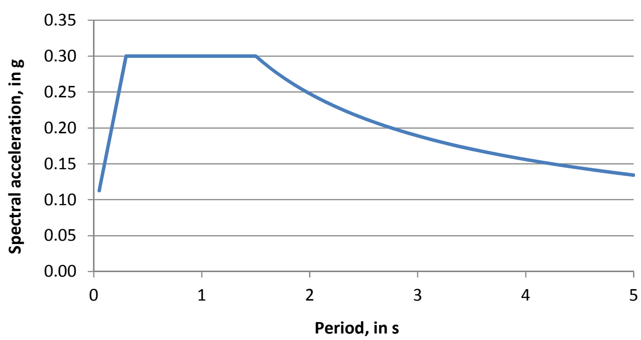


Figure 5. Spectrum regulatory zone B soil type II (CFE, 1993)

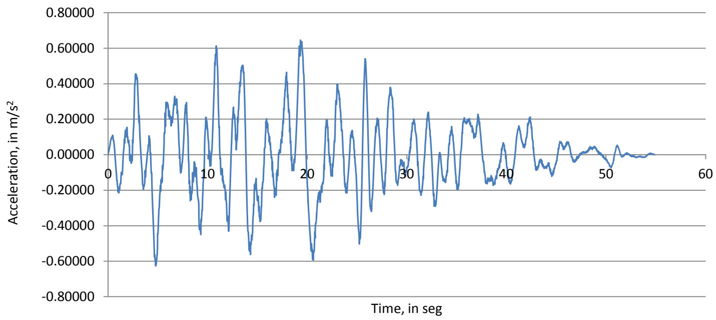


Figure 6. Synthetic earthquake

3. NUMERICAL FORMULATION

3.1 Case Studies

For analyses purposes, two main aspects are analyzed. The first corresponds to the determination of the variation in the stress state at the affected zone of soil deposit by the phreatic level decrease. The second phase of analysis is related to seismic response of the soil deposit at the beginning and end of the piezometric level falling process. This process was realized in 16 cycles, until it reaches a total phreatic fall of 165 m (Fig. 7). It is considered the minimum possible phreatic level, according to the geological characteristics of the zone.

For the seismic response analyses, 20 points in the numerical model were monitored with the purpose to calculate the soil deposit response in terms of acceleration spectrums (Fig. 7).

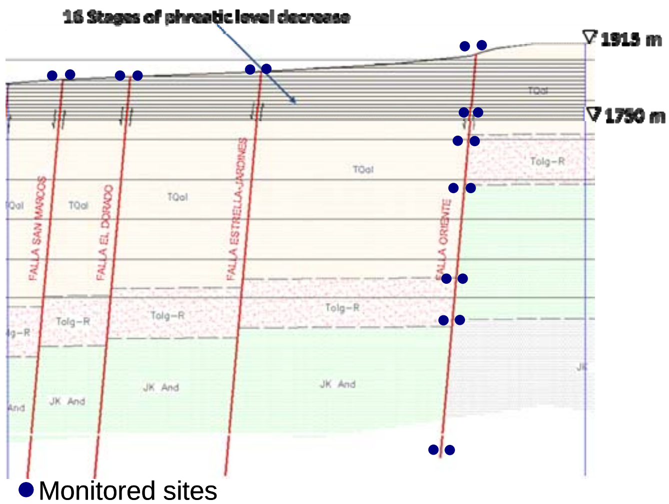


Figure 7. Stages of phreatic decrease level process and monitored sites for acceleration spectrums determination

4. ANALYSIS RESULTS

4.1 Phreatic decrease process

In the next Figures (8 to 10) are presented the normal stresses resulting at 5 m of depth caused by phreatic decreasing. In order to improve the understanding of the results, this figures present initial, final and intermediate stages of the developed analyses.

The results shown in Figures 8 to 10 indicate that in the proximity of El Dorado and Estrella-Jardines faults (see Fig. 8), during the phreatic decrease process, the stress forces are incrementing, being more important in the last five stages of the process. It is possible to associate the magnitude differences, in both sides of the fault, with the relative displacement process generated at geological faults. In the case of Oriente fault, the potent thickness of more compressible materials existent at west side of the fault is able to generate greater settlements and consequently, larger strain stresses. In addition, it is important to consider that in this zone occurred important topographical changes, which affect the resultant stress state.

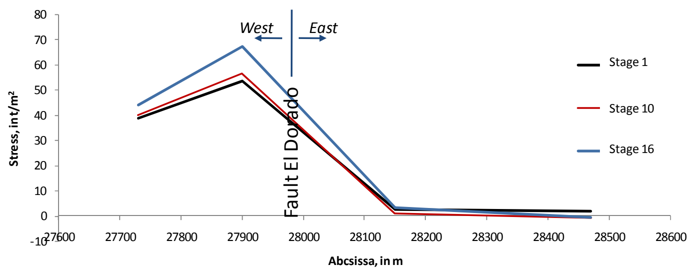


Figure 8. Resultant stresses in the zone of El Dorado fault

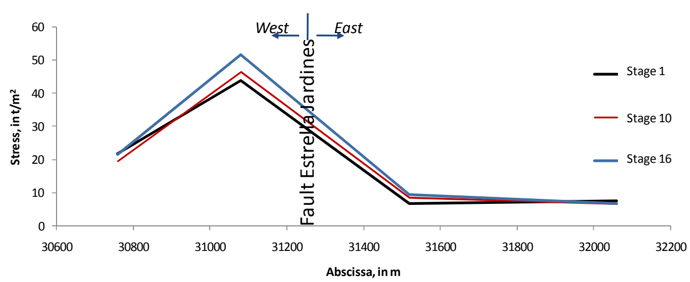


Figure 9. Resultant stresses in the zone of Estrella-Jardines fault

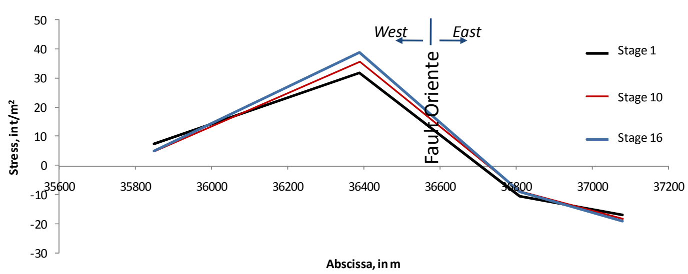
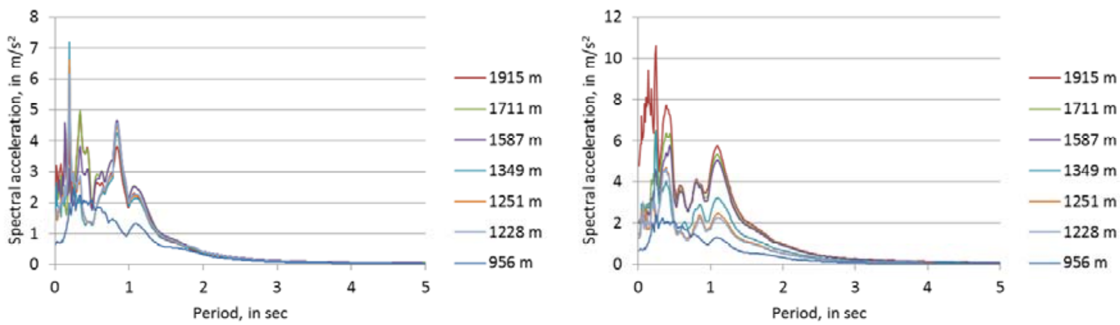


Figure10. Resultant stresses in the zone of Oriente fault

4.2 Results of seismic analyses

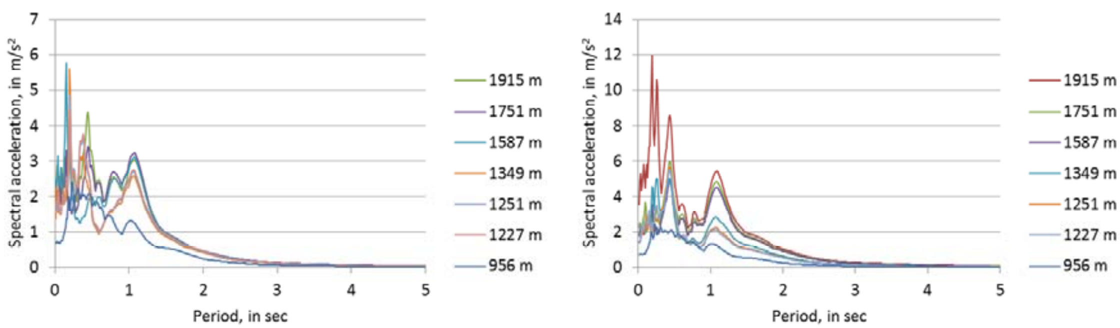
The study of the variation on seismic response influenced by the phreatic line decrease in Aguascalientes City, is divided in two parts. The first corresponds to the analyses of resultant accelerations evolution along the Oriente fault (Figs. 11 and 12). The second part is concerned to the variation study of changes at resultant free field along the geological section, including the denominated faults: Oriente, Jardines, Dorado and San Marcos (Figs. 13 to 15).

The Figures 11 and 12 show the acceleration spectrums before and after the phreatic level decreasing process. In these figures, it is possible to observe that at west side of the geological fault, the diminishing of the spectral acceleration amplitudes caused by the changes in the phreatic level are near of 10 %. However, the opposite situation occurs at the east side; in this, the resultant accelerations suffer an increase around 10%. The opposite behavior could be explained if it is considered the site effect caused by the near hills zone, the possible differences at the permeability of subsoil materials, the important basal rock irregularities caused by the Aguascalientes graven and probable displacements occurred at geological fault.



a)West side Oriente fault b)East side of Oriente fault

Figure11. Oriente fault before the phreatic decrease process

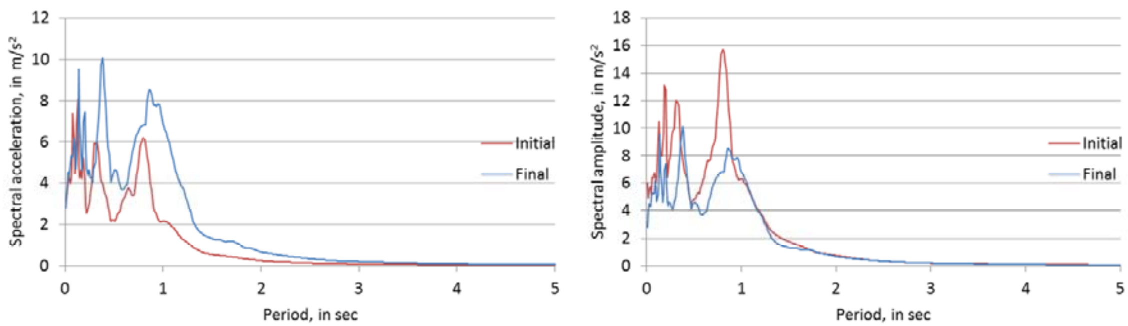


a)West side Oriente fault b)East side of Oriente fault

Figure12. Oriente fault after the phreatic decrease process

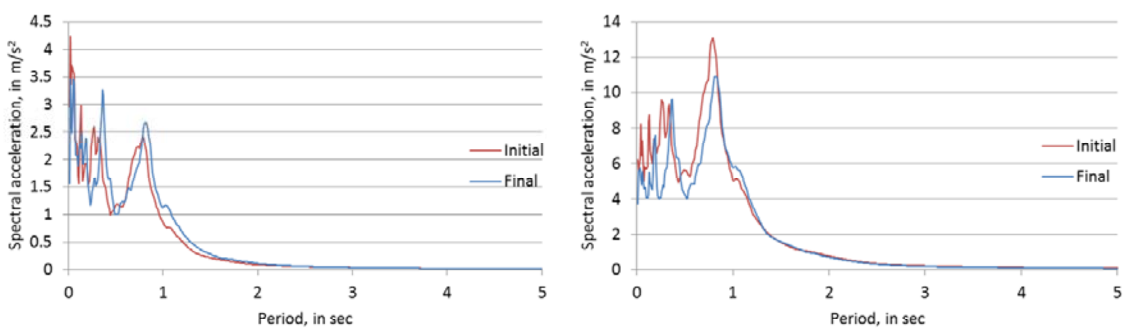
Figures 13 to 15 show the variation in spectral acceleration at the surface of soil deposit. The results present important differences in behavior tendencies. The zones located at west side of the faults present a growing trend towards the resultant accelerations during the consolidation process. On the other hand, the zones located at east side of the faults present decreases at the calculated accelerations. These results can be due to: 1) the fault acts that energy dissipater. The dip of fault could influence the soil deposit response intensity and 2) the variation with depth of determined layers at both sides of faults.

At the west site of the Jardines, El Dorado and San Marcos faults, spectral accelerations from short periods, are greater than those calculated at east side (see Figures 13 to 15). This aspect is important, because, short periods are related to small height buildings and structures with significant stiffness (i.e. historical monuments, very common in this city).



a)West side Jardines fault b)East side of Jardines fault

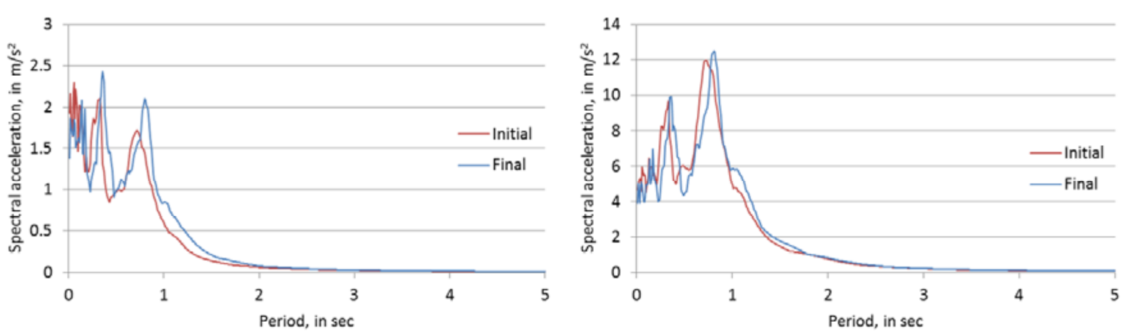
Figure13. Jardines fault after the phreatic decrease process



a)

West side Dorado fault b)East side of Dorado fault

Figure14. Dorado fault after the phreatic decrease process



a)

West side San Marcos fault b)East side of San Marcos fault

Figure15. San Marcos fault after the phreatic decrease process

5. CONCLUSIONS

The model presented helped to explain the influence of the phreatic level decrease phenomenon in specific locations of the city of Aguascalientes. It also allowed us to evaluate the potential damage of seismic events, especially hazardous for historic buildings. This conclusion may encourage the creation of hazard mitigation programs oriented to preserve this kind of constructions in the city.

The results evidence the importance of the interaction between geological faults, soil cracks, subsoil irregularities, site effects and phreatic level decrease in the progressive variation of the seismic response at different sites of the city.

It is important to consider the particularities generated by this interaction, which could produce significant variations at seismic response among sites relatively close.