Soil Cracks related to land subsidence. The main geotechnical hazard affecting to constructions in Aguascalientes City, México.

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ABSTRACT
We present a description of subsidence occurring in Aguascalientes Valley, covering the conceptual models of soil cracks generation, and the behaviour of the surface soil in the zone nearest to earth fissure path (width of influence). Furthermore, the observed pathologies in the damaged constructions by these earth discontinuities are evaluated. Additionally, we present a discussion about the geological and geophysical research implemented in the professional practice, in order to determine if an area is affected by an earth fissure, even when there is not visual damages on the constructions or deformation in the surface soil.

PRESENTACIONES TÉCNICAS
En este trabajo presentamos una descripción de la subsidencia del valle de Aguascalientes, abordando los modelos conceptuales del mecanismo de generación de los agrietamientos y el comportamiento del suelo en la zona de mayor deformación en los labios de las grietas (ancho de influencia), así como las patologías observadas en las construcciones afectadas por este tipo de discontinuidades del subsuelo. Se presenta además, una discusión sobre la investigación geológica y geofísica que se ha venido implementando en la práctica profesional para evaluar si un terreno es afectado por un agrietamiento, aún cuando este no se ha manifestado en la superficie.

1 INTRODUCTION

The city of Aguascalientes (AGSC) is located on the Aguascalientes Valley (AGSV) in the central part of México, at 420 km northwest from México City. The Aguascalientes Valley (AGSV) is within a tectonic fosse named Aguascalientes Graben (AGSG), which is 14-20 km width and 90 km length (figure 1). AGSG is a topographic depression formed by two N-S normal faults, and refilled by alluvial and fluvial sediments, due to this, the subsoil of AGSV is a sequence of Tertiary and Quaternary sediments with a consistency from moderately to well consolidated soils, whereas the underlying rocky basement is composed by volcanic rocks, mainly Tertiary rhyolites.

AGSV has a semiarid to arid climate, which is characterized by evaporation exceeding the precipitation, which is 526 mm/year average. Furthermore, the AGSV does not have superficial sources of fresh water. As a result the unique source of fresh water supply is the ground water.

In the AGSV, except in some very well identified sites, the soil has exceptional geotechnical properties (N60 > 20, ϕ>30°, LL<40, IP<20, E> 350 kg/cm2) due to this, the design of foundations and the cuts in excavations do not have technical complications. Nevertheless, in the decade of the 80's, several soil cracks started to develop and since then, they have multiplied and grown up. Currently they affect the urban infrastructure in general.

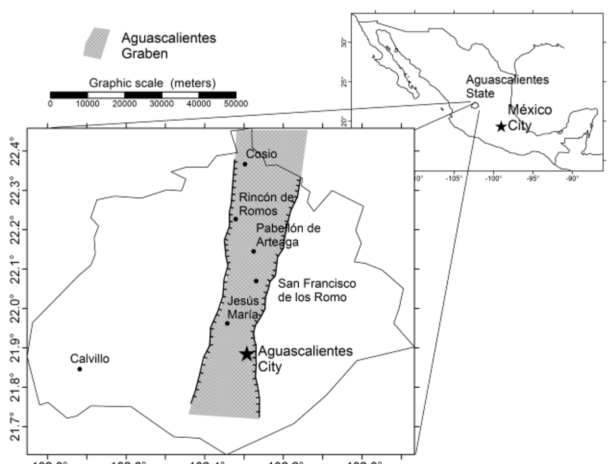

Figure 1. Location of Aguascalientes City

The cracks are widely spreaded over the entire valley of Aguascaliente, however its effects are more critical in the urban zones, mainly in the City of Aguascalientes (figure 2), At this place, the cracks have been inventoried and included in cartography that is annually updated by the office of public works of the municipality of Aguascalientes (SIDDIS ,2010).

The soil cracks at present are of several kilometres in length. Initially, they start as cracks with only some centimetres in width, but according to observations in the AGSV, their width can enlarge until near to 4 meters by the erosion, which is caused mainly by the rain. There are not measurements about their depth, but It was estimated that they can reach several tens of meters depth (Pacheco et al. 2006).

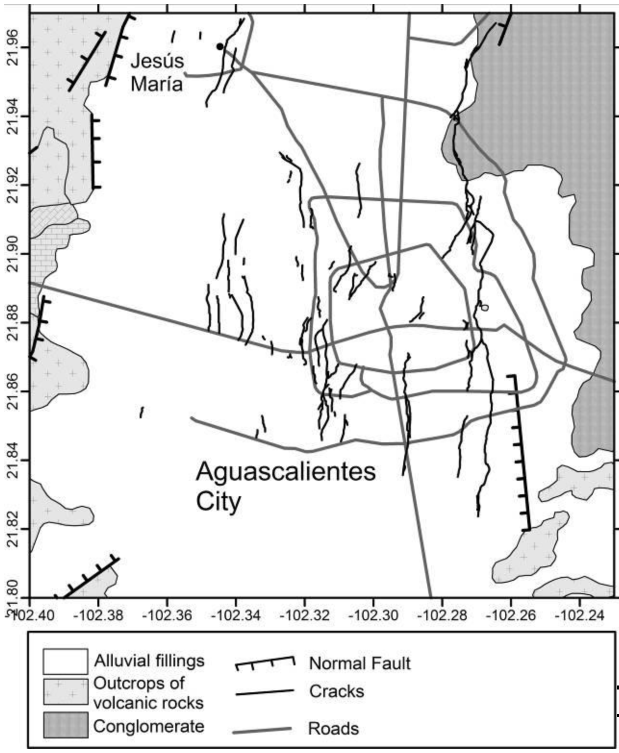

Figure 2. Soil cracks in the urban zone of Aguascalientes city

2 MAIN STRUCTURAL DAMAGES OF HOUSING AFFECTED BY LAND SUBSIDENCE

In relation with the magnitude of the problems associated with the land subsidence in Aguascalientes Valley, Romero-Navarro et al. (2010) estimated that the area affected by subsidence due to pumping of ground water and formation of surface cracks in the AGSV is near to 900 km2. Previously, Zermeño-De-León et al. (2004) calculated an accumulated subsidence of 1.3 m in 18 years using data of relative sinking of a surface fault in the AGSC. The latest authors, measured a sinking velocity of 11 cm/year in a point monitored with GPS in the AGSC.

In the figure 3 it is shown an example of soil crack and the differential sinking between the two generated blocks.

Figure 3. Ramp developed by a soil crack at the northwest of the City of Aguascalientes. The vertical displacement of the blocks generated by the rupture is evidenced by the gate.

According with SIFAGG (2009), in the AGSV there are at least 207 cracks, with a total of accumulated length of 322 km. They affect directly or indirectly nearly 1820 properties, from which 1438 are in the AGSC. The affected properties are mainly dwellings of different typology which present different degrees of affectation, including dwellings affected in a very negligible way, to others with serious structural damages which put in risk the stability of the construction. The table 1 shows some statistics about the cracks in the different municipalities of the AGSV.

Table 1. Statistics about cracks in the municipalities of the Valley of Aguascalientes

Municipality	Total length (m)	Cracks
Aguascalientes	81927	65
Asientos	7718	2
Cosío	30620	14
Jesús María	60292	47
Pabellón de Arteaga	42534	35
Rincón de Romos	47275	27
San Francisco de los Romo	25231	12
Tepezalá	25562	5
Totales	321160	207
Pabellón de Arteaga	42534	35

Along with the damage to private buildings, it has been observed that superficial cracks have affected urban infrastructure mainly streets and highways, distribution lines of freshwater and wastewater, etc. (Romero-Navarro et al. 2010). Furthermore, cracks are affecting public buildings of the city, such as churches with historic value, and other places which are in the national catalogue of historic buildings.

Since 2008 our research group started the inspection of damaged housing structures affected by land subsidence in some cities of Mexico, i.e. Aguascalientes and Tuxtla Gutierrez, in the State of Chiapas, among others. These inspections were done together with colleagues of the Construction and Structures Department of the Autonomous University of Aguascalientes, and the Engineering School of the Autonomous University of Chiapas, as well as the Public Works Office of Aguascalientes.

Nowadays, we have inspected more than 61 houses with structural damages in AGSC, and most of them present structural pathologies caused mainly due to differential settlements by land subsidence. However, in some cases it was found that the structural damages were caused by a combined effect of land subsidence, poor quality of construction materials, and an inadequate construction process.

Table 2. Observed pathologies in the constructions affected by land subsidence due to groundwater withdrawal in the Aguascalientes City.

No	Pathology	Frequency
1	Diagonal cracks in bearing walls due to diagonal tension.	61
2	Cover detachment in concrete elements.	47
3	Cracks in floors due to ground gaps by differential settlements.	43
4	Multiple cracks in bearing walls, having mainly diagonal trajectories due to diagonal tension.	23
5	Horizontal cracks of short length in bearing walls.	20
6	Vertical cracks in corners of columns due to excessive compressive load.	19
7	Reinforcing steel bars exposed in concrete elements.	17
8	Distortions in door and window frames.	16
9	Diagonal cracks in reinforced concrete beams due to shear forces by differential settlements.	16
10	Vertical cracks in bearing walls due to excessive compressive load.	12
11	Horizontal cracks in the connection of bearing wall and slab by differential settlements.	12
12	Cracks in slabs due to tension stress in the bottom part by bending.	10
13	Detach of connection between column and wall.	8
14	Cracks in the corners of windows.	6
15	Cracks in the corners of doors.	5
16	Cracks in beams due to tension stress in the bottom part by bending.	5
17	Horizontal cracks in bearing walls in the whole length.	5
18	Horizontal cracks in the connection of bearing wall and floor by differential settlements.	5
19	Throw out of plumb of vertical elements (walls and columns).	3

These houses are structured based on different structural typologies within masonry system: confined masonry made of clay bricks, reinforced masonry of concrete blocks, non-confined masonry of clay bricks and stone, as well as hybrid systems using also reinforced concrete. The most relevant results of this study are presented in the table 2, which shows the frequency distribution of the structural pathologies found in the inspected housing inventory.

The inspection of the damage houses consisted in apply a methodology of inspection and evaluation (Ortiz-Lozano et al. 2010), in order to estimate the state of the condition of damaged structures with the purpose of establishing a diagnosis of its structural state. The standard methodology allowed unifiying the criteria for the inspection and evaluation tasks, which in other words means that the diagnoses issued by inspectors were more objective and accurate. In the figure 4 to 6 it is presented some photographs of some structural elements damaged by the differential settlements caused instead by the soil cracks.

Figure 4. Caused damage to a bearing wall by differential settlement

Figure 5. Diagonal cracks in a bearing wall due to diagonal tension.

Figure 6. Vertical cracks due to differential settlement in non-reinforced walls

3 MECHANISM OF LAND SUBSIDENCE AND CRACKS GENERATION IN THE AGUASCALIENTES VALLEY

The occurrence of cracks in the AGSV is attributed to a combination of two factors: one is natural and the other is anthropogenic: The first factor is the geology of the valley which consist in a graben refilled by granular and poorly consolidated sediments conforming the aquifer system. This system lies over a rocky basement and is flanked by outcrops consisting in volcanic rocks, mainly rhyolites (figure 7). The second factor is the drop in the ground water level due the over exploitation for domestic, industrial and irrigation uses. This last factor is considered the trigger factor of the subsidence.

The mechanism explaining better the subsidence and soil cracks occurring en el AGSV, considers that the drop in the water level of the aquifer system, has induced a gradual compaction of the sedimentary filling causing superficial sinking. When the sinking is uneven, superficial cracks and scarps are formed. Furthermore, it was observed in the AGSV that both the trace and shape of the cracks are controlled by the depth and shape of the rocky basement (Aranda, 1989; UAQ-UNAM, 2002; Zermeño et al. 2006). This correlation was first reported for a region of superficial cracks en Arizona by Jachens and Holzer (1979 and 1982), and it has been reported by others authors en several regions with land subsidence in the Mexican Plateau (Aguirre Diaz et al. 2000; Rojas et al. 2002; Ávila-Olivera and Garduño-Monrroy, 2008).

The differential sinking related to ground water exploitation is generated when on the zones where the bedrock is shallower, the strata of sedimentary fillings develops a minor compaction. Whereas in the zones of deeper bedrock, the strata of fillings develops a bigger compaction. This induce the sediments with bigger compaction to pull down at the sediments of the zones with less compaction.

In the AGSV, three configurations of the rocky basement that can generate cracks due to differential compaction have been indentified (Arroyo, 2003; Arroyo et al. 2004; UAQ-UNAM, 2002; Zermeño et al. 2006; Romero-Navarro et al. 2010). Each of these three configurations can generate a different kind of cracks with different width of influence or width of affectation (figure 8).

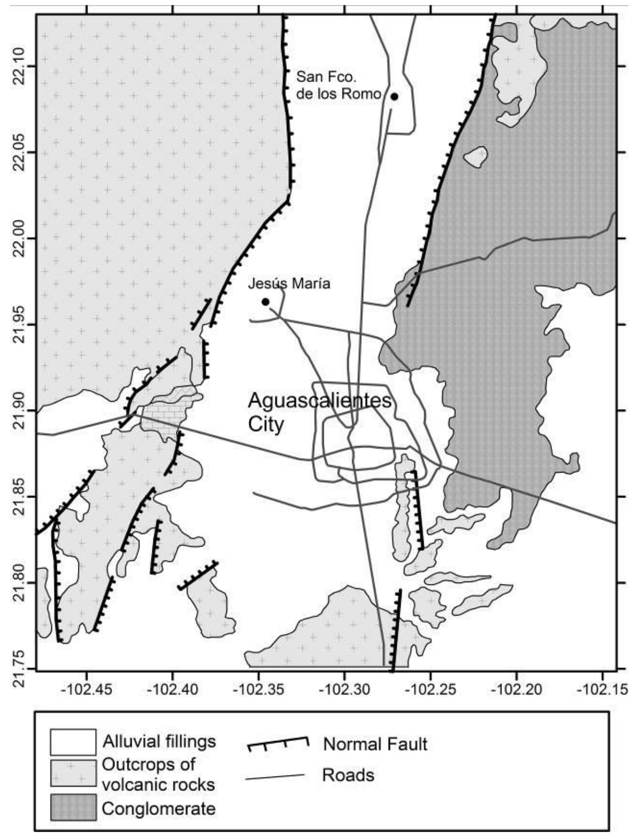

Figure 7. Simplified geology of the Aguascalientes city and its surroundings into the Graben of Aguascalientes.

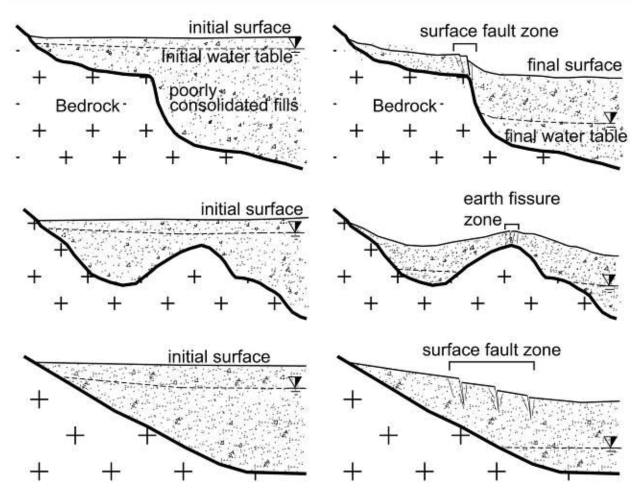

Figure 8. Configuration of rocky basement for earth fissures and surface faults. Modified of Carpenter (1999)

Additionally, other kind of soil cracks in the AGSV has been observed. This kind of cracks does not align with the geological structures or with the topographic features of the bedrock. This can be caused because the uneven sinking apparently is related to the drag of fine sediments. These cracks develop near to the San Pedro stream, and their length are not more than 100 metres, furthermore the sinking area seem like the projected shape of a buried fluvial stream.

Lopez-Doncel et al. (2010) and Pacheco-Martínez et al. (2010), reported some cracks with the same features in the Valley of San Luis Potosí, 140 kilometres NE from the AGSV . According with these authors, the formation of these cracks start by the drag of fine sediments through buried paleochannels, forming voids that induce the collapse of the cavity´s roof (Figure 9).

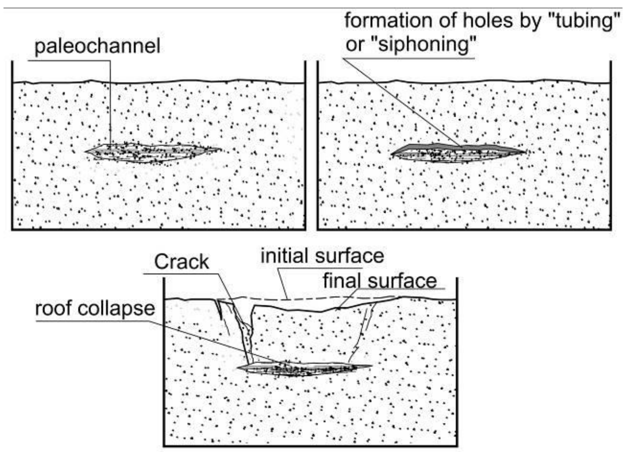

Figure 9. Formation stages of cracks related with paleochannels. After Pacheco et al. (2010)

According with this explanation, there are four geological setting in which a soil cracks in the Aguascalientes Valley can be generated, three of them are related to the configuration of the rocky basement, and one is related with the presence of paleochannels. This is summarized in the figure 10.

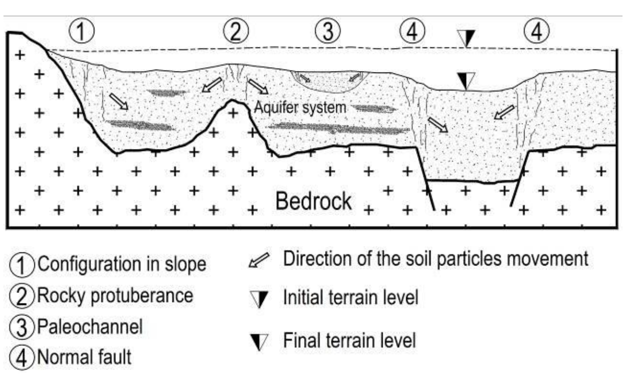

Figure 10. Geological setting in which cracks in the Valley of Aguascalientes can be generated.

The photograph of the figure 11 shows a crack that is related to an irregularity in the bedrock with shape of stair or normal fault (point number 4 in the figure 10). This kind of crack develops a ramp or scarp in the surface that can reach until 1.1 metres high according to observations on the surrounding area of Aguascalientes City. On the other hand, the figure 12 shows a photograph of a crack related to a paleochannel.


Figure 11.- Surface fault related to differential sinking in the Aguascalientes City.


Figure 12. Cracks related to formation of caves by drag of fine material through paleochannels

4 GEOTECHNICAL CHARACTERISTICS OF SUBSOIL IN THE VALLEY OF AGUASCALIENTES.

In general, the subsoil of Aguascalientes City has very good geotechnical properties. Even though there is not a geotechnical zonification map, the geotechnical studies carried out from different building projects show a homogeneous stratigraphy in the whole city. The typical stratigraphy of the subsoil of the AGSC is shown in the figure 13.

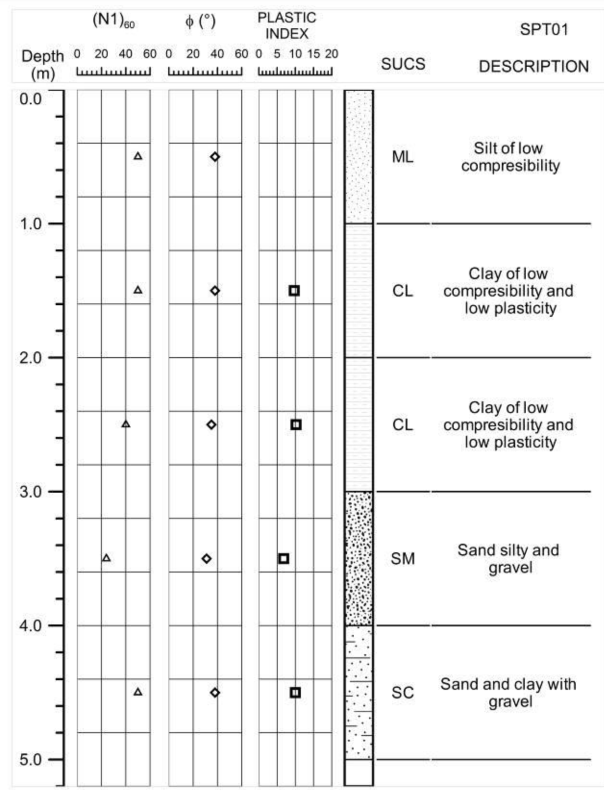

Figure 13. Typical stratigraphy of the City of Aguascalientes.

On the top of the sedimentary sequence, it is common to find a top layer with a thickness of no more than 50 centimetres with different percentage of sand, silt and clay and with high content of organic material. Beneath this layer, there is a stratum with very good geotechnical properties. This deeper layer is locally known as "tepetate" and corresponds to a "hard stratum" composed by volcanic particles of sand and silt, or occasionally by sand and clay of low compressibility. In general the number of blows from the Standard Penetration Test performed on the “tepetate” is higher than 50. Additionally, its plastic index usually does not exceed the value of 15, and the angle of internal friction is in general higher than 30°.

In addition to the geotecnical properties described above, we measured the velocities of the seismic waves through the subsoil, reaching depths of 30 metres. The average velocity of the shear wave in the first 8 metres is of 336 m/s. This value was calculated on the base of 905 measurements made in 77 point at the west of the city (figure 14).

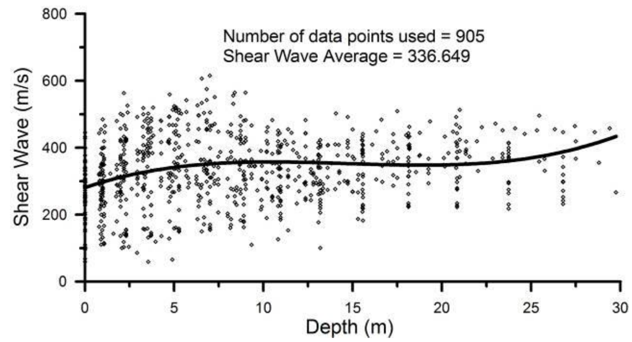

Figure 14. Velocities of shear wave for the subsoil of the Aguascalientes City.

5 PROFFESSIONAL PRACTICE RELATED TO LAND SUBSIDENCE AND SOIL CRACKS IN THE AGUASCALIENTES VALLEY.

Before soil cracking and sinking appeared for first time in the AGSV, the subsoil of the Aguascalientes city did not present geotechnical complications, as a consequence, the professional practice had not had significant progress after the 80´s. The requirements for the common geotechnical studies were limited to determine the bearing load capacity of the soil at deeps no more than 2 meters, for this, it was sufficient to perform either a plate load test or a Standard Penetration Test, in order to find the bearing load capacity and the expected settlements of the subsoil. However, after massive proliferation of soil cracks over the Valley, the geophysical and geological studies have been carried out to complement the geotechnical surveys.

For convenience, two stages in soil cracks detection were differentiated; the first is referred in detecting cracks at their first stage of formation. In this stage, cracks are not visible on the surface because the crack-related damages are negligible (Figure 15), and they can be easily hidden by the erosion or by the activities for prepare the land for the construction.

In order to detect the cracks at this stage of formation, the measurement of electrical resistivity profiles of the subsoil have been carried out. The fractured zones in propitious conditions (homogeneous stratigraphy and undisturbed soil) appear like anomalies of high resistivity and then they are easy to find (Figure 16). However, in unfavorable conditions, such as a subsoil with a complex stratigraphy, deposits of anthropogenic fillings, or in zones with lateral moisture variations, the interpretation presents some ambiguities. In these last cases, the excavation of trenches helps to eliminate the doubts. Therefore by doing a direct exploration in the stretch along the profile where the anomalies are observed helps to distinguish and corroborate the presence of a crack on the subsoil (Figure 17).

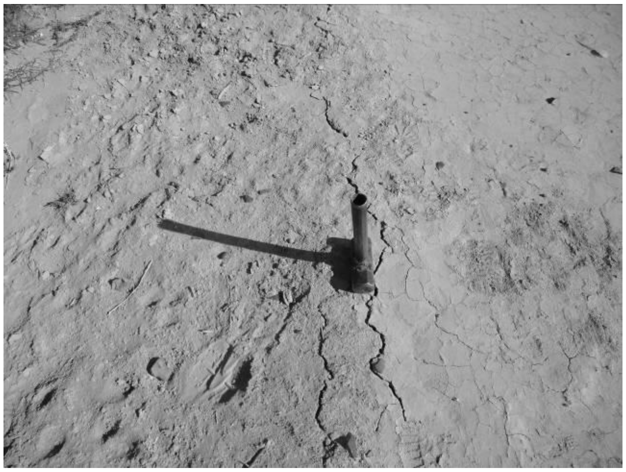

Figure 15. Soil crack in a first stage of formation

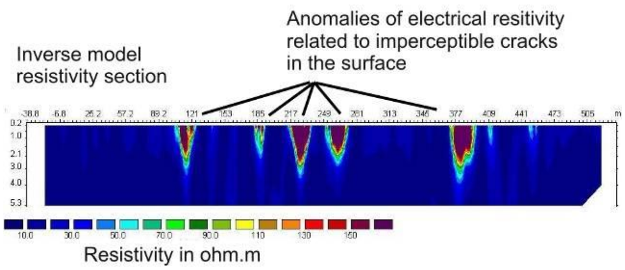

Figure 16. Electrical resistivity profile used for detection of imperceptible soil cracks

The other problem in soil crack detection, is when the crack does not develops. In this case the problem consist in evaluating the potential occurrence of a crack, this is in evaluate whether the crack develops or not. To solve this problem, gravimetric surveys have been implemented in order to define the shape of the bedrock, and localize irregularities of the bedrock associated to the soil cracks generation (see figure 10). Usually, the gravimetric measurements carried out across the soil cracks show an anomaly which is caused by the irregularity in the bedrock. This fact was reported by Jachens and Holzer (1979 and 1982) in a group of cracks in Arizona, U.S.A., and by Pacheco et al. (2006 and 2010) for the soil cracks of the valleys of Querétaro and San Luis Potosí, both cases in México. The figure 18 shows some profiles of gravimetric measurements carried out on some soil cracks in the City of Aguascalientes.

Figure 17. Excavated trench for carrying out a direct exploration in the stretch where the interpretation of the anomalies of resistivity presents ambiguities.

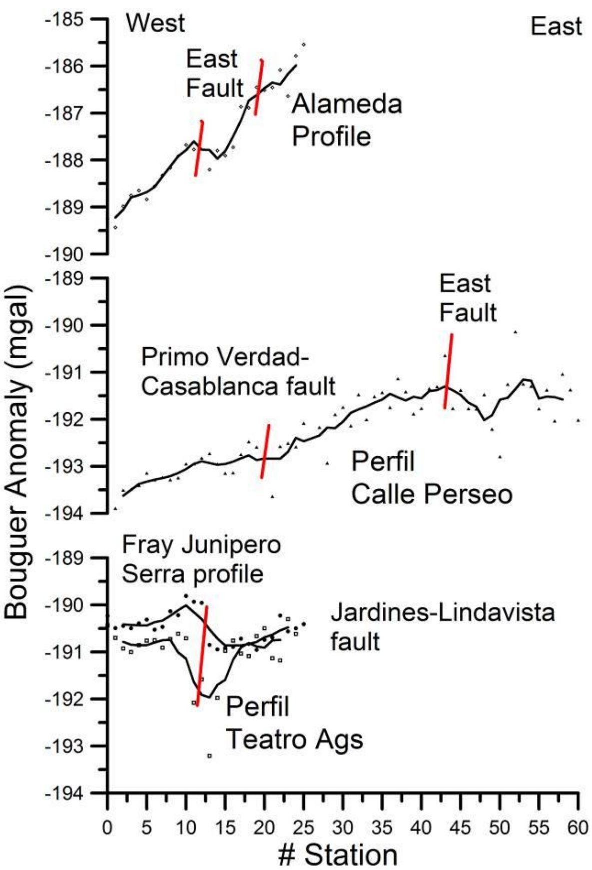

Figure 18. Gravimetric measurements on soil cracks in the City of Aguascalientes

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REFERENCES

Aguirre-Díaz, G. D. J., Zúñiga-Dávila Madrid, R., Pacheco-Alvarado, F. J., Guzmán-Speciale, M., y Niero-Obregón, J. 2000. El graben de Querétaro, México. Observaciones de fallamiento activo. *GEOS,* 201, 2-7.

Aranda-Gómez, J. J. 1989. Geología preliminar del graben de Aguascalientes. *Revista Mexicana de Ciencias Geológicas*, 81, 22-32.

Arroyo-Contreras, G. M., Arzate-Flores, J. A., Rojas-González, E., Martínez-Reyes, J., Vsevolod-Yutsis, V., Pacheco-Martínez, J., Frías-Martínez, O., y Ochoa-González, G. H. 2003. Causas y efectos de las grietas y fallas en el Valle de Aguascalientes. *Cuaderno de Trabajo, Sistema de Investigación Miguel Hidalgo*. SEP-CONACYT, 1-16.

Arroyo-Contreras, G. M., Zermeño-De-León, M., y Castañeda-Alvarado, J. A. 2004. *El agrietamiento en Aguascalientes, causas y efectos*. Universidad Autónoma de Aguascalientes, Aguascalientes, México.

Avila-Olivera, J. A., y Garduño-Monrroy, V. H. 2008. A GPR study of subsidence-creep-fault processes in Morelia, Michoacán, México. *Engineering Geology*, 100, 69-81.

Carpenter M. C., 1999; Land subsidence in the United State: *Circular 1182, U. S. Geological Survey*. Galloway D., Jones D. R. e Ingebritsen S. E. eds. Part I, Mining Ground Water, South-Central Arizona. p. 65-81.

Garduño-Monroy, V. H., Arreygue-Rocha, E., Israde-Alcántara, I., y Rodríguez-Torres, G. M. 2001. Efectos de las fallas asociadas a sobreexplotación de acuíferos y la presencia de fallas potencialmente sísmicas en Morelia, Michoacán, México. *Revista Mexicana de Ciencias Geológicas*, 181, 37-54.

Jachens, R. C., y Holzer, T. L. 1979. Geophysical investigation of ground failure related to ground water withdrawal-Picacho Basin, Arizona. *Ground Water*, 176, 574-585.

Jachens, R. C., y Holzer, T. L. 1982. Differential compaction mechanism for earth fissures near Casa Grande, Arizona. *Geological Society of America Bulletin*, 9310, 998-1012.

López-Doncel Rubén, Mata-Segura José Luís, y Pacheco-Martínez Jesús. 2010, Hundimiento y agrietamiento relacionados a la reactivación de paleo-cauces. Ejemplos en la zona conurbada de San Luís Potosí, en Resúmenes del la Reunión Anual 2010 de la UGM. *Geos Boletín Informativo de la Unión Geofísica Mexicana*, A.C, ISSN 0186-1891, No 1, vol. 30, pág. 132, Puerto Vallarta, Jalisco, México.

Ortiz-Lozano, J. O. , Alonso-Farrera F. A., Pacheco-Martínez J., Zermeño-De-León M.E., Araiza-Garaygordobil G., y Mendoza-Otero E. 2010, Assessment of the state of condition of damaged buildings and structures affected by land subsidence, *IAHS Publication 339. Proceedings of Eigth International Symposium* On Land Subsidence, IAHS Press, U.K.,, 449-451.

Pacheco, J., Arzate, J., Rojas, E., Arroyo, M., Yutsis, V., y Ochoa, G. 2006. Delimitation of ground failure zones due to land subsidence using gravity data and finite element modeling in the Querétaro Valley, México. *Engineering Geology*, 843-4, 143-160.

Pacheco-Martínez J., Arzate-Flores J.A., López-Doncel R., Barboza-Gudiño R., Mata-Segura J.L., Del-Rosal-Pardo A., y Aranda-Gómez J.J.. 2010. Zoning map of ground failure risk due to land subsidence of San Luís Potosí, México. *IAHS Publication 339. Proceedings of Eigth International Symposium* On Land Subsidence, IAHS Press, U.K., 179-184.

Rojas, E., Arzate, J., y Arroyo, M. 2002. A method to predict the group fissuring and faulting caused by regional groundwater decline. *Engineering Geology*, 65, 245-260.

Romero-Navarro, M., Pacheco-Martínez, J., Ortiz-Lozano, J., Zermeño-De-León, M., Araiza-Garaygordobil, G., y Mendoza-Otero, E. 2010. Land subsidence in Aguascalientes Valley, México. Historical Review and present situation. *IAHS Publication 339. Proceedings of Eigth International Symposium* On Land Subsidence, IAHS Press, U.K., 207-209.

SiDDiS. 2010. Sistema Digital de Discontinuidades del Subsuelo de la ciudad de Aguascalientes. *Cartografía Digital Interactiva, Secretaría de Obras Públicas del Municipio de Aguascalientes*, Aguascalientes, México.

SIFAGG. 2009. Sistema de Información de Fallas Geológicas y Grietas. *Cartografía Digital Interactiva, Secretaría de Obras Públicas del Estado de Aguascalientes*, Aguascalientes, México.

UAQ-UNAM. 2002. Estudio integral sobre la problemática del agua, subsidencia y sismicidad en el valle de Aguascalientes. *Informe técnico final preparado por el DEPFI de la UAQ y el CGEO de la UNAM para el Instituto del Agua del estado de Aguascalientes*, *INAGUA*, Aguascalientes, México, 433 págs.

Zermeño-De-León, M., Mendoza-Otero, E., y Calvillo-Silva, G. 2004. Medición del hundimiento y modelado para estudiar el agrietamiento de la ciudad de Aguascalientes. *Investigación y Ciencia*, 1231, 35-40.

Zermeño-De-León, M., Pacheco-Martínez, J., Mendoza-Otero, E., Arzate-Flores, J., y Arroyo-Contreras, M. 2006. Fracturamiento y fallamiento de suelos, experiencias en la cd. de Aguascalientes y Santiago de Querétaro, Qro.. *Memorias de la XXIII Reunión Nacional de Mecánica de Suelos*, Tuxtla Gutierrez, Chiapas, México, 793.802.