Workshop on Mechanisms, Monitoring and Modeling Earth Fissure Generation and Fault Activation Due To Subsurface fluid exploitation (M3EF3)

Alicante, Spain, 16-17 November 2017

ABSTRACTS

- **10:00-11:00 h. Meeting talks (session I: Case studies 1)**

1. **Earth Fissures and Surface Faults Accompanying Aquifer-System Compaction and Land Subsidence in the USA.** Devin L. Galloway

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ABSTRACT

Earth fissures and surface faults in areas affected by aquifer-system compaction and land subsidence in the USA are presented. The occurrence of earth fissures is discussed generally with respect to susceptible hydrogeologic settings, and specific examples are provided showing the relation to aquifer-system compaction and land subsidence accompanying subsurface fluid extraction. Various examples of spatio-temporal measurements of ground motion across earth fissures and surface faults are presented.

KEYWORDS: earth fissure, aquifer-system compaction, land subsidence

2. **Mapping and characterisation of ground fracturing in Mexico City.** D. Carreón-Freyre[1], M. Cerca[1], R. Gutiérrez-Calderón[2], C. Alcántara-Durán[2], F. Centeno-Salas[1],

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ABSTRACT

Land subsidence was first reported in in Mexico City in the early 20th century but the effects and the risks that fracturing implies for its inhabitants have not yet been accurate assesed. The subsidence of land and fracturing cause persistent damage to buildings and urban infrastructure (roads, water pipes for drinking and drainage, housing) in the short, medium and long term; that involves high costs of mitigation and maintenance.

In this work, the susceptibility to deformation and fracturing of sediments in volcanic areas are considered a multifactorial phenomena conditioned by a combination of physical variables that can be measured and integrated into a deterministic analysis, by he use of thematic maps. The spatial relation between the parameters determining nucleation and propagation of fractures should be evaluated for each study case. The main variables considered in the analysis are: lithological variations, terrain slope, subsidence gradient, piezometric depletion and geomechanical properties of the media. The interplay of these variables determine the fracture stress states and hence the type of fracturing.. A systematic methodology for the filed mapping and characterisation of fracturing is presented by the integration of structural and physical data with high precision geophysical prospecting of the subsoil. The spatial analysis of variables allowed the estimation of a Physical Vulnerability Index to Fracture (FVI), easy to use for decision-making, to the design of adequate monitoring systems and risk zoning.

KEYWORDS: land subsidence, groundwater extraction, ground fracturing, regional faulting.

3. **A world map of ground ruptures due to groundwater pumping.** P. Teatini[1] and S. Ye[2]

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ABSTRACT

One of the main outcomes of the IGCP641 project "Mechanisms, Monitoring and Modeling Earth Fissure generation and Fault activation due to subsurface Fluid exploitation (M3EF3)" is the realization of a world map with the location of the main occurrences of ground rupture. To accomplish this goal, an in-depth bibliographic and literature review has been carried out to find the major sites threatened by this geo-hazard. More than 45 sites have been listed, mainly located in China, USA, Mexico, and Iran. The sites have been added to a Google Map-based page (http://www.igcp641.org/?page_id=45) in the M3EF3 project website. Two levels of detail are planned to be used in presenting the rupture sites. Initially, each site has been identified by a single marker. Then, the trace of the fissures, properly georeferenced, will be added where available. The sites will be complemented by the following metadata: latitude, longitude, number of ruptures, rupture trend, rupture total length, characteristic slippage and/or opening, rate of land subsidence, cumulative subsidence, mechanisms, time occurrence, and specific scientific references. Obviously, the mapped sites are not intended to provide an exhaustive list. The map will be easily populated by other sites when new information will become available.

KEYWORDS: ground rupture, mapping, webmap

- **11:20-13:00 h. Meeting talks (session II: Characterization and modelling of earth fissures)**

1. **Potential use of 3D datasets for the analysis and monitoring of earth fissures.** A. Riquelme, R. Tomás, M. Cano, J.L. Pastor

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ABSTRACT

Earth fissures are tension cracks that opens as a result of soil surface tension due to land subsidence. The characterization of his geometry and their evolution could be of high interest for scientists. Consequently, during field inventories efforts are made to capture as much information as possible. Remote sensing techniques enable the capture of digital datasets for further detailed analysis. Airborne or terrestrial 3D laser scanners are widely used nowadays and can capture millions of points in few seconds with high accuracy and resolution. Structure from Motion (SfM).is an alternative remote sensing technique which is currently acquiring high popularity. This technique uses commercial digital cameras and enables the reconstruction of a surface applying certain strategies. By means of the use of Remotely Piloted Aircraft Systems (RPAS), ground based restrictions of this technique are overcomed since digital photos can be captured from almost any point of view, even inside the fissure. This fact enables the generation of geo-referenced digital models. Such models lead to the extraction of different features from the earth fissures such as cross sections and volumes. Moreover, the comparisson of models captured on different dates enables the detection and quantification of changes. In this work two remote sensing techniques are presented, 3D laser scanning and SfM. Additionally, as a case study, an earth fissure is modelled using a 2:45 video downloaded from Youtube of a fresh earth fissure captured by the Arizona Geological Survey. Different frames of this video's were extracted and processed in order to generate a 3D model of the earth fissure. This case study shows the high potential of the presented techniques for the detailed analysis of earth fissures.

KEYWORDS: remote sensing, earth fissures, RPAS, sfm, youtube

2. **Geotechnical characterization and mapping of two earth fissures appeared in the Guadalentin Valley after the September 2012, 28th flooding.** J.L. Pastor[1], J. Mulas[2], R. Tomás[1], G. Herrera[2], J.A. Fernández-Merodo[2], M. Béjar[2], L. Jordá[2], J.C. López-Davalillos[2], R. Aragón[2], R.M. Mateos[2]

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ABSTRACT

Southeast of Spain was affected by a heavy downpour on 28th September 2012. That day, up to 212 litres of rain per square metre were reported in Murcia province. The flooding caused by this event caused three fatalities in the region and destroyed more than 200 agricultural exploitations and had a catastrophic impact to many infrastructures, collapsing, amongst others, a main highway bridge. After the flood, two new earth fissures appeared in the Guadalentin Valley. One fissure was located in Puerto

Lumbreras and the other one in Totana, being both towns in the Murcia province. The Puerto Lumbreras fissure was 400 m long and 2 to 3 m depth, showing some piping erosion and collapses. The fissure showed a straight line direction approximately parallel to the main geological structures of the Guadalentin Valley. The soil at this site is a low plasticity silt with some sand and clay, being classified as ML according to the USCS. Five samples were collected along the fissure, obtaining a percentage of silt of 48-68%, a clay content of 12-30% and a sand content of 2-40%. The plasticity index was smaller than 9.2 for all the samples. Pinhole tests, crumb tests and some geochemical test were done in order to evaluate the internal erosion and piping susceptibility of the soil. Crumb and Pinhole tests showed a non-dispersive soil, while the pH, Sodium Adsorption Ratio and Exchangeable Sodium Percentage tests showed that this process could be important at some points. The collapsible potential of the soil was also studied, obtaining that only one sample located on the south end of the fissure showed a medium to high potential. Regarding the Totana fissure, this fissure was about 190 m long and appeared with different branches and holes instead of as a rectilinear pattern. The soil at this site is also a silty soil although has not been as deeply characterized as for the Puerto Lumbreras fissure. Finally, INSAR data, GPS, GPR and land subsidence maps have been used to study the possible origin of these fissures.

KEYWORDS: earth fissure, geotechnical characterization, mapping, Guadalentín

3. **Stress / strain analysis caused by groundwater pumping in the faulted basin of Queretaro, Mexico. Insights from a 3D FE groundwater flow and geomechanical modelling approach.** G.H. Ochoa-González[1], D. Carreón-Freyre[2], A. Franceschini[3], M. Cerca[2], and P. Teatini[3]

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ABSTRACT

The City of Querétaro, Mexico, is located on a graben structure that formed a continental basin filled with lacustrine and alluvial sediments, pyroclastic deposits, and interbedded fractured basalts. The basin is crossed by two major N-S oriented faults. Important differences of hydraulic and mechanical properties characterize the various geologic units. Groundwater was been strongly withdrawn over the last three decades in the study area, with a piezometric level decline exceeding 100 m in some areas. Because of the high variability of the geologic deposits, the piezometric decrease, and consequently of the effective stress increase, are characterized by a large space variability. The variable distribution of the deformation and effective stress increase has caused large differential subsidence causing ground fracturing that has damaged the urban infrastructures of the City of Querétaro. This complex geological setting has been properly accounted for into a three-dimensional (3D) finite-element (FE) flow and geomechanical model aimed at quantifying the displacement, deformation, and stress fields caused by fluid withdrawal. The model has been calibrated using observed groundwater levels and land settlement records, with the simulations spanning the period between 1970 and 2010. The

modelling results highlight that the areas where large differential subsidence and horizontal displacements developed correspond to the portions of the city where earth fissuring have been observed. The spatial relationship between major withdrawals, discontinuities of geologic structure, and accumulation of large stress and strain fields clearly emerged from the outcomes of the 3-D geomechanical model.

KEYWORDS: Queretaro, faulted basin, ground fissures, FE modelling, 3D stress/strain investigation

4. **Earth fissures caused by extensive aquifer exploitation in China and a novel approach to model earth fissure.** Shujun Ye[1]*, Andrea Franceschini[2], Yan Zhang[3], Carlo Janna[2],

Xulong Gong[3], Jun Yu[3], Pietro Teatini[2*]

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ABSTRACT

Earth fissures accompanying aquifer-system compaction and land subsidence induced by excessive groundwater withdrawal in China are introduced. Earth fissures do not occur in all the subsidence-affected regions. They mainly develop in three regions, i.e. Fenwei Basin, North China Plain, and Yangtze Delta. The most severe earth fissure geohazard occurs in the Fenwei Basin. Since the 1950s, about 500 earth fissures have occurred in more than 50 cities in the Fenwei Basin. Earth fissures occur in the North China Plain more than elsewhere in China. The majority developed in the Hebei Plain which covers part of Beijing and Tianjin, and includes Baoding, Cangzhou, Hengshui, Langfang, Handan, Xingtai, and Shijiazhuang. The most special earth fissures are found in the Su-Xi-Chang area in the Yangtze Delta. Indeed, the Fenwei Basin and North China Plain are semiarid areas, i.e. the typical environment and condition where earth fissures usually develop. Conversely, the Su-Xi-Chang area is in a humid climatic region. Earth fissures in the Fenwei Basin and the North China Plain are in part related to the pre-existing faults; however, those in the Su-Xi-Chang area are not. The features of earth fissures in the three regions were described respectively. Understanding the generation of earth fissures and modelling their occurrence and propagation are still far to be achieved. A novel modelling approach to simulate earth fissure generation and propagation in three dimensional complex geological settings is proposed. A nested two-scale approach associated with an original non-linear elasto-plastic finite element / interface element simulator allows modeling the mechanics of earth discontinuities, in terms of both sliding and opening. The model is applied on a case study in the Su-Xi-Chang area of Yangtze Delta, China, where groundwater pumping between 1980 and 2004 has caused land subsidence larger than 2 m. The model outcomes highlight that the presence of a shallow (~80 m deep) bedrock ridge crossing the Yangtze River delta is the key factor triggering the earth fissure development in this area. Bending of the alluvial deposits around the ridge tip and shear stress due to the uneven piezometric

change and asymmetrical shape of the bedrock have caused the earth fissure to onset at the land surface and propagate downward to a maximum depth of about 20-30 m.

KEYWORDS: earth fissure, aquifer exploitation, numerical simulation, China

5. **A parametric FE-IE modeling analysis on factors controlling ground ruptures due to groundwater pumping.** M. Frigo[1], M. Ferronato[1], D. Carreon-Freyre[2], S. Ye[3], D. Galloway[4], and P. Teatini[1]

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ABSTRACT

A hypothetical modeling analysis was used to investigate the relative susceptibility of various geologic configurations to rupture generation. A geomechanical Finite Element (FE) - Interface Element (IE) modeling approach is used to simulate rupture generation and propagation for three typical processes: i) reactivation of an existing fault caused by horizontal displacements; ii) tensile fracturing above a bedrock ridge; and iii) differential compaction due to heterogeneous thickness of aquifer/aquitard (sand/clay) layers. A sensitivity analysis was used to address various factors of the rupture processes, including the thickness of the compacting layers, their depth below the land surface, the ratio between compressibility and thickness of sand/clay layers in heterogeneous formations, and the height of the bedrock ridge with respect to the thickness of the compacting alluvial sequence.

The modeling results suggest that rupture inception typically occurs at two specific depths: the top of the pumped aquifer, and at the ground surface, in correspondence with the geologic discontinuities. Indeed, a high stress state is induced within the aquifer by contraction, which can create favorable conditions for rupture generation. Conversely, although the magnitude of the stress effects of water extraction are smaller in the shallowest deposit, the potential for triggering rupture is still high because of the limited natural stress regime, so failure is even more likely. The evolution of rupture was analyzed and can be summarized in two cases. In the first case the rupture does not propagate and remains confined either at the aquifer top or at land surface. In the second case, the rupture expands from the aquifer top toward the surface and/or from the land surface downward. The aquifer depth is the most important factor controlling the occurrence of these behaviors. Specifically, the probability of a significant rupture propagation (and enlargement) is higher when the two inception zones are closer. Several simulations were carried out to address the possible ranges of parameter variations associated with the processes listed above, and the numerical results were elaborated by a statistical regression analysis. The model can be used to provide a preliminary evaluation of the possible mechanisms generating ground ruptures in subsiding basins.

KEYWORDS: ground fissure, numerical modelling, finite elements- interface elements

- **15:00-16:20 h. Meeting talks (session III: Case studies 2)**

1. **Land Subsidence and Earth Fissures Caused by Groundwater Exploitation in Quetta valley, Pakistan.** Najeebullah kakar[1], Din Mohammad kakar[2], Abdul S.Khan[3], Shuhab D. Khan[4]

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ABSTRACT:

Land subsidence is effecting several metropolis in the developing as well as develop countries around the world such as Nagoya (Japan), Shanghai (China), Venice (Italy) and San Joaquin valley (United States). This phenomenon is attributed to natural as well as anthropogenic activities that include extensive groundwater withdrawals. Quetta is the largest city of Balochistan province in Pakistan. This valley is mostly dry and ground water is the major source for domestic and agricultural utilization. The unplanned use of ground water resources has led to the deterioration of water quality and water quantity in the Quetta valley. Water shortages in the region was further aggravated by the drought that hit the area forcing people to migrate from rural to urban areas. Refugees from the war torn neighboring Afghanistan also contributed to rapid increase in population of the Quetta valley. The population increased from 0.26 million in 1975 to 3.0 million in 2016. The objective of this study was to measure the land subsidence in Quetta valley and identify the effects of groundwater withdrawals on land subsidence. To achieve this goal, data from five Global Positioning System (GPS) stations were acquired and processed. Furthermore the groundwater decline data from 41 observation wells during 2010 to 2015 were calculated and compared with the land deformation. The results of this study revealed that the land of Quetta valley is subsiding from 20mm/y on the eastern flank to 120 mm/y in the central part. The subsidence is causing rapid development of earth fissures that were observed at different localities in Quetta valley, those fissures were 3 meters wide and 5 meters deep covering an area of several kilometers. Several buildings were completely damaged due to the passage of these fissures. The level of groundwater drops at a rate of 1.5-5.0 m/y in the area where the rate of subsidence is highest were also recorded. So the extensive groundwater withdrawals in Quetta valley is considered to be the driving force behind land subsidence and earth fissures.

KEYWORDS: Land Subsidence, Earth Fissures, Water Depletion, GPS, Pakistan.

2. **Impact of the 19th September 2017 earthquake on slip of ground fractures related to land subsidence in Mexico City.** Mariano Cerca[1], Dora Carreón-Freyre[1], Raúl Gutiérrez-Calderón[2], Penélope López-Quiroz[1], Carlos Alcántara-Durán[2], Félix Centeno Salas[2]

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ABSTRACT

Land subsidence and ground fracturing affects the Mexico City basin since the early 1900. Fracture vertical slip during a recent strong earthquake (19th September 2107) suggests that the fractures are at effective stresses critical state and can respond instantaneously to strong motions. Measurements of the ground movements, in situ and constructed using radar interferometry data for the period 2002 and 2007, and fracture slip by monitoring in the time period 2007-2015, reveals coexistence of brittle and creep behavior in the fractures. Different orders of magnitude of slip are conditioned by local and regional factor such as: regional structures, variations on groundwater withdrawal, sedimentary variations, volcanic buried structures and differential physical properties of the volcanic and sedimentary filling of the basin (compressibility, permeability, void ratio and shear strength). Here we present the distribution of ground fractures and their spatial relation with damages reported after the 19/09/17 intraplate earthquake in central Mexico.

KEYWORDS: Mexico City, ground fracturing, subsidence, earthquake

3. **Triggering of ground subsidence related faults in Mexico City by the Mw8.2 Chiapas and the Mw7.1 Puebla, September 2017 earthquakes.** D. Solano-Rojas[1], E. Havazli[1], E. Cabral-Cano[2], S. Wdowinski[3]

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ABSTRACT

Mexico City recently experienced two large earthquakes only 11 days apart: the Mw8.2 September 8th, 2017 with its epicenter offshore Chiapas, and the Mw7.1 September 19th, 2017 with its epicenter in Puebla. The Mw8.2 earthquake was located over 700 km away from Mexico City and its effects in the city were not significant. However, the Mw7.1 earthquake occurred only ~100 km away and severely damaged it. Mexico City is very susceptible to seismic-induced damage because part of the city is built over a sedimentary basin with clay rich lacustrine sediments up to 400 m thick. This sedimentary unit amplifies the seismic energy making civil structures more vulnerable. On the other hand, due to the same circumstance, coupled with an aggressive ground water extraction, Mexico City is one of the fastest-subsiding metropolis in the world, with rates up to -350 mm/yr, producing an very dynamic process. We examine the effects of both earthquakes on the subsidence process in Mexico City using Sentinel-1data. As a

baseline for pre-seismic deformation, we generated two 24-day SAR interferograms between July 19th-August 12th and August 12th-September 5th. These interferograms, covering the Mexico City Metropolitan area show the high subsidence areas on the eastern and southern sectors of the city, which have been previously described as the fastest subsiding regions within the city. We produced a third interferogram, between September 5th - September 29th, which encompasses the integrated deformation for both the Mw8.2 and Mw7.1 earthquakes. This interferogram shows that the previously mentioned areas underwent an increase in deformation with much larger spatial coverage in comparison to the previous interferograms which are 24 and 48 days older. The change in velocities and areal extent integrated during both seismic events indicates that most of the seismically triggered deformation centered on these rapidly subsiding areas -which are otherwise well known and described on previous works (e.g. Cabral-Cano et al. 2008; Chaussard et al. 2014; Osmanoğlu et al. 2011)- that include Bosques de Aragón, Ciudad Nezahualcóyotl, Canal de Chalco, Tláhuac, and Valle de Chalco neighborhoods. We thus interpret that the energy released during these earthquakes is responsible for a distinctive deformation that is not shared by other sectors of the city where the underlying lacustrine sediment package is either thinner or absent. A closer analysis of this circumstance shows that a large portion of the reported damage in this southern sector of the city clearly correlates with the presence of preexistent, subsidence-related faults that have been identified using a Fast Fourier Transform residual technique (Solano-Rojas et. al, 2017). Moreover, we find evidence of phase discontinuities in the September 5th-September 29th interferogram, which also correspond to these areas around the lower slopes of the Sierra de Santa Catarina. We conclude that the seismic energy from both earthquakes induced a fast soil consolidation and triggered the coseismic faulting of the preexistent subsidence related faults. This circumstance not previously observed 32 years ago during the Mw8.1 September 19, 1985 earthquake creates a new variable that needs to be addressed for any future updates to the building codes and urban zoning considerations in Mexico City.

KEYWORDS: InSAR, subsidence, earthquake, Mexico, faulting, Sentinel-1

4. **Subsidence and fracturing in the municipality of Iztapalapa, Mexico City. Ten years of the Geological Risk Assessment Center.** Raúl Gutiérrez-Calderón[1], Dora Carreón-Freyre[2], Mariano Cerca[2], Carlos Alcántara-Durán[1], Felix Centeno Salas[1]

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ABSTRACT

The city of Mexico, established in the bed of a drained lake delimited by volcanic structures, is affected by subsidence characterized by the generation of subsidence and fracturing. Historically, the territory occupied by Mexico City has been one of the most populated of the country and in the 1960s, demographic growth forced the expansion of urban boundaries towards the periphery, changing the use and morphology of the plain lacustrine. Iztapalapa, a municipality of pre-Hispanic origin established in eastern Mexico City, was annexed to the city by uncontrolled urban growth, increasing the need to pump water from the subsoil to supply the growing region. The municipality is delimited by three volcanic structures: the Cerro de la Estrella to the west, the Sierra de Santa Catarina to the southeast, and the Peñón del Marques to the northeast. The volcanic deposits of piedmont, are interdigitated with clay formations of the old lake of Texcoco, which generates a high mechanical contrast. Currently, the region has subsidence values of between 5 and 40 cm/year, generating deformation and fracturing of the subsoil and, consequently, substantial damages to buildings, infrastructure and urban equipment. The geomorphological changes of the lacustrine plain have generated micro-basins, where in the last decade the floods have been recurrent. We present relevant data applied in the Integral Risk Management to ten years of operation of the Geological Risk Assessment Center.

KEYWORDS: subsidence, geomorphology, floods, fracturing