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Ground Subsidence in the City of Tuzla (Bosnia & Herzegovina)

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ABSTRACT

Since the year 1955, when the salt deposits exploitation activities were carried out in the city of Tuzla and surroundings, dramatic ground collapsing phenomena occurred. Up to 10 meters of sinking in the last half century produced several damages with regards to buildings and infrastructures, leading to the demolition of the most compromised part of the city by the inhabitants. Traditional topographic survey was used in order to monitor the land deformations from the 50' till presentwith the establishment of a dense topographic network around the sinking area. The analisys of the huge dataset of altimetric data, the correlation with the boreholes activities and the introduction of more productive modern technologies (satellite technologies, GPS for geodesy) for repeated land monitoring are the object of this paper.

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1. Introduction

The paper deals with the ground collapsing phenomena over an area including the city of Tuzla occurring as a consequence of the salt deposits exploitation activities carried out since the beginning of the last century. Since the Roman age, the town of Tuzla is known for the salt extraction; the town's name arise from "tuz", the Turkish word for salt, as the Ottomans renamed the settlement in the 15th century following their conquest of the medieval Bosnia. The ellipsoidal shaped salt deposits beneath the city of Tuzla cover an area of 2 square km approximately. At the beginning, the exploitation has been carried out by the method of the uncontrolled solution mining (brine exploitation) by means of boreholes and hundreds of brine wells. More recently, since the year 1967, the classical dry exploitation has been used. The intensity of brine exploitation over the years, is one of the most important factor which produced cavities formation and caused subsequent ground deformation. Although first geodetic measurements were carried out in the year 1914, a systematic approach for determining the subsidence rate, started in the year 1956 with yearly trigonometric and spirit levelling. During the mentioned period, the topographic survey has pointed out a maximum sinking rate of around 10m in the downtown area of the city that caused serious damages to the water supply system, to the sewage network as well as on the traffic lines and the urban planning activities. In the last decade the urban management was characterized by a great effort towards a decreasing in salt exploitation activities in order to reduce the ground deformations and the related effects. Modern space geodesy methodologies, such as static relative GPS (Global Positioning System) and high resolution satellite remote sensing, are nowadays employed to monitor the modern subsidence rate and to delimitate the risk zone where the urban planner has to take into account past and present effects of salt mine exploitation.

2. Methodology of the Occurrence of Ground Surface Movements

The Tuzla salt deposit is located under an urban area and extends over 2 km2 (Figure 1(a)). The horizontal projection of the deposit has the shape of an ellipse, with a length of about 2500 m and a width of about 900 m. The geological features have been investigated by several authors (Cicic, 2002; Hrvatović, 2006; Jovanović, 1980; Katzer, 1903; Redžepović et al., 2006; Soklić, 1959, 1964; Stevanović, 1977; Tari and Pamić, 1998; Vrabac, 1999). The deposit consists of five separated salt series, or stratigraphic layers, which contain salt rocks embedded in a syncline with one of the limbs close to the surface of the city's center (Figures 1(b) and 1(c)). The maximum thickness of the salt formation is about 600 meters. It is composed of marls and clayey sandstones, salt rocks, banded marls, and anhydrite rocks, as shown by the vertical cross section of X-X' in Figure 1(c).

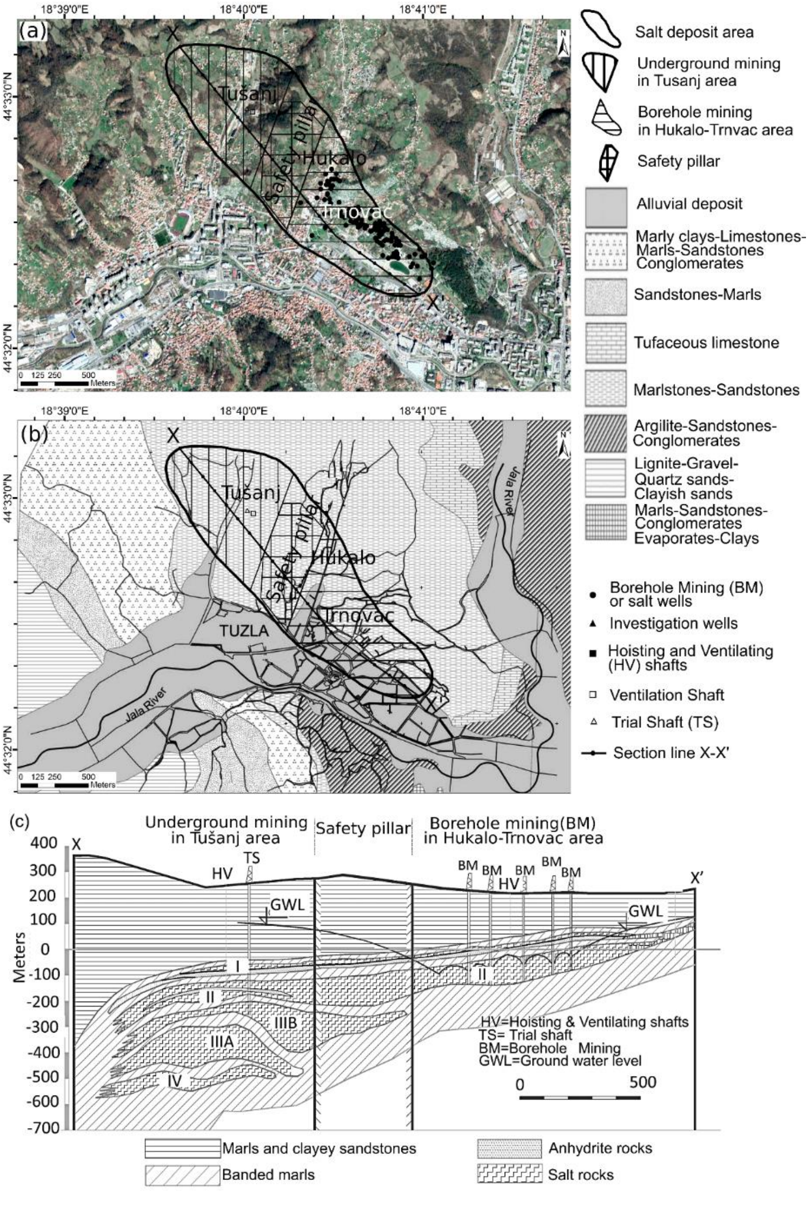

Figure 1. Geological conditions of Tuzla: (a) plan view using background aerial photo from Google Earth Pro and location of salt wells, (b) plan view (modified from Mancini et al., 2009), and (c) vertical X-X' cross section

Primitive salt exploitation was achieved by natural brine and shallow salt water wells in the Neolithic period 6000 years ago. This was confirmed by the discovery of the ceramic fragments of holders from 3500 BC used to boil saltwater above hot charcoal (Stecchi, 2008). During the Ottoman-Turkish Empire, salt water exploitation was achieved by shallow wells, at depths of about 60 m, and the production of salt in that period amounted to 2500 kg/day. Extensive exploitation of the deposits began in 1886, in the eastern part of the salt deposits in Trnovac-Hukalo, by pumping salt water through deep wells (Figure 1(b)) and using the uncontrolled leaching method. The exploitation of rock salt through pits began in 1967. In the period from 1983 to 1991, the so-called controlled leaching of the existing parts of the mine "Tušanj" was carried out (Ferhatbegović, 2004).

The intensive production of salt water by means of the uncontrolled leaching method caused extensive subsidence of up to -12 m of the terrain in the urban area of Tuzla. It induced serious damage to buildings and the infrastructure, such as water supply systems, sewage networks, and electric powerlines (Stecchi et al., 2009). For this reason, more than 2000 buildings collapsed or needed to be demolished and about 15,000 people had to evacuate the most affected area (Stecchi, et al. 2009). Another report (Ibreljic, et al. 2007) mentioned that 2300 apartments had been destroyed between 1965 and 1990 due to the subsidence phenomenon.

In the period from March 2006 to May 2007, a gradual suspension of the salt well exploitation was carried out. The official date of the termination of the exploitation of Tuzla's salt deposits was May 29, 2007 (Čeliković et al., 2014; Čeliković & Imamović, 2016).

3. Result of Previous Surveys and Modern Technologies for Monitoring

3.1. Spatial Distribution From 1956-2007

The first geodetic survey was conducted in Tuzla in 1914, and systematic geodetic surveys in the area of subsidence in the city of Tuzla were started in 1956. In order to monitor the actual process of the subsidence at the surface of the terrain and to determine the limits of the impact of the exploitation, a network of fixed points for geodetic surveys was set up in 1955. From 1956 to 1991, geodetic surveys were performed annually to measure the subsidence in Tuzla and to determine the spatial coordinates or position changes of the fixed points. The number of measurement points has changed over time. By 1991, about 1200 measurement points had been set, as a considerable number of them had been destroyed over time. Between 1956 and 1991, there were over 300 points with a known vertical displacement in the zone of subsidence, while there were about 40 points with a known horizontal displacement (Ministry of Industry, Energy and Mining in cooperation with Tušanj Salt Mine and Mining Institute Tuzla).

Figure 2(a) shows the contour lines for the subsidence from 1956-2003 presented by Mancini et al. (2009). The figure reveals that the maximum subsidence reached -12 m. It was found that the large subsidence extended to the north of the city, including a residential area, and was shaped like a trough. Figures 2(b), (c), and (d) show the subsidence distributions measured at four different times by static GPS surveys, namely, in 2004, 2005, 2006, and 2007 (Mancini et al., 2009; Stecchi, 2008). The survey network was composed of six reference points and 60 densification measurement points (Mancini et al., 2009).

The GPS results for 2004-2005 show that the subsidence continued at a rate of -12 ~ -22 cm/year in the north part of Pannonica Lakes (Figure 2(b)), although the rate had largely decreased compared to that of the previous period (1956-2003). A considerable area of the northeast part of the city was subjected to subsidence rates of -2 ~ -5 cm/year. In the period of 2005-2006, the subsidence rate decreased to -8 ~ -22 cm/year around Pannonica Lakes (Figure 2(c)). Mancini et al. (2009) and Stecchi (2008) stated that the GPS results from 2006-2007 showed that the subsidence was heading to the end almost everywhere, except for the area near Pannonica Lakes where the subsidence rate was still about -10 cm/year (Mancini et al., 2009; Stecchi, 2008) (Figure 2(d)).

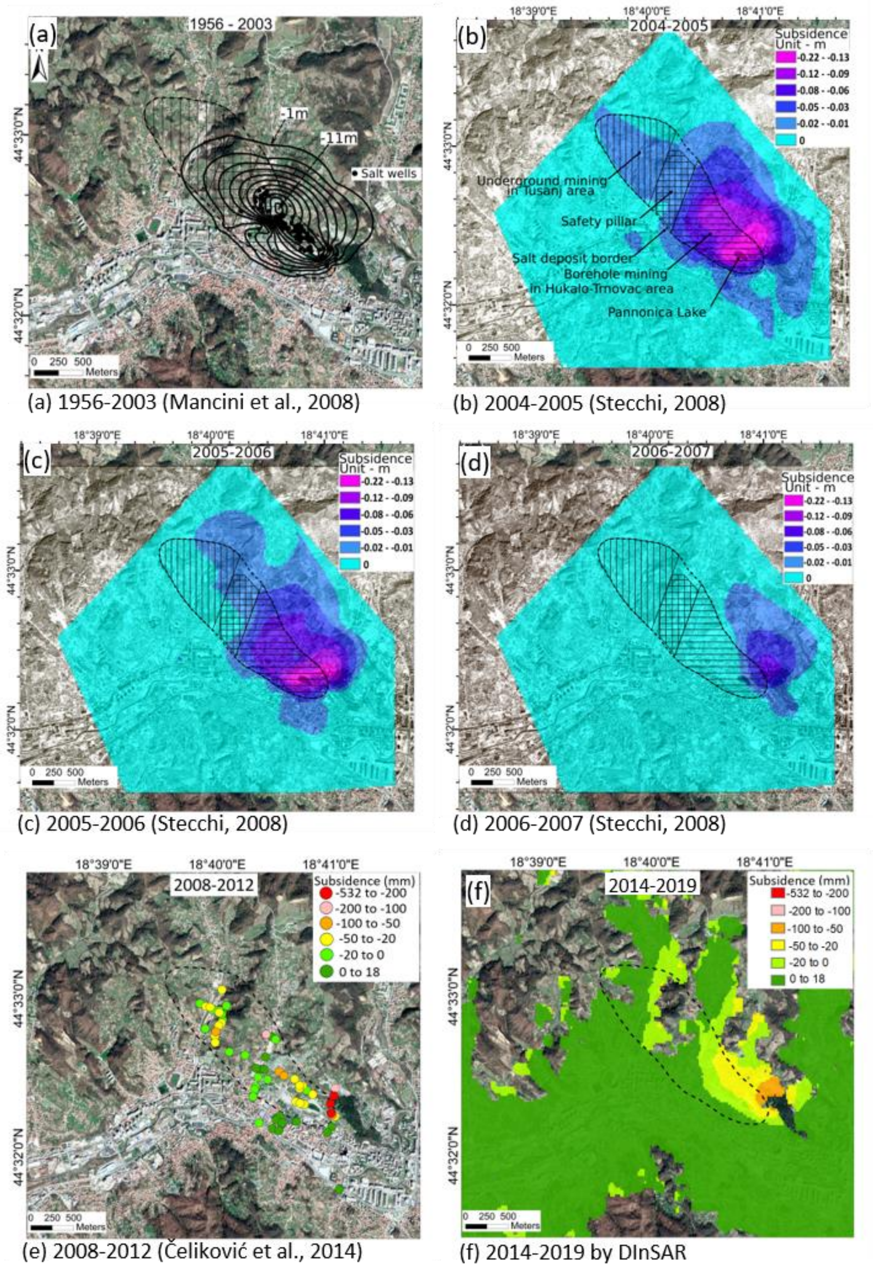

Figure 2. Time transition of spatial distribution of subsidence in Tuzla from 1956: (a) cumulative subsidence obtained by traditional topographic surveys from 1956-2003 presented by contour lines (dashed line indicates salt deposit border added by the authors), (b) subsidence in Tuzla obtained by GPS surveys from 2004 – 2005, (c) subsidence in Tuzla obtained by GPS surveys from 2005 – 2006, and (d) subsidence from 2006 to 2007 (modified from Stecchi (2008), (e) Subsidence from 2008 to 2012 obtained by GNSS and geodetic methods (Čeliković et al. 2014), and (f) Subsidence from 2014 to 2019 obtained by SBAS-DInSAR. (salt deposit border, safety pillar, and mining region were added by the authors).

3.1.1.Ikonos data

An high resolution Ikonos image, acquired on the 2000, was purchased and othorectified to be used as reference map. One meter resolution panchromatic data is suitable for the characterization and extrapolate of geometric features whereas the four meters resolution multispectral channels allow the separation between urbanized and vegetated area with a fine spatial resolution. The image was used for the visualization of historical sinking rates, which were processed by gridding and contouring of altimetric data. The production of maps, showing the subsidence rates over the last half century, is fundamental for the delimitation of the most sinking area along with the evaluation of time varying phenomenon and its relation with wells activity. Figure 3 shows a portion of the Tuzla urbanized area (above) as 321 RGB multispectral data and a detail (below) of collapsing phenomena occurred from the year 1981 to the year 1986 superimposed to 1-meter panchromatic data. As can be seen from Figure 3 over the 5 years the sinking reaches the considerable rates of 3 meters with a risk area showing a typical ellipsoidal shape corresponding to the most intensively exploitation area. The contouring of rates processed in the period spanning from the year 1955 to the year 1990 shows a very similar sinking rates with a decreasing trend until the year 1990, as a consequence of the reducted salt extraction by the wells. In addition it should be pointed out that a certain number of benchmarks were destroyed by the deformation itself. In the most damaged zone, a green and recreational area was created after the demolition of damaged buildings. As obvious, in that part of the city data were not collected anymore.

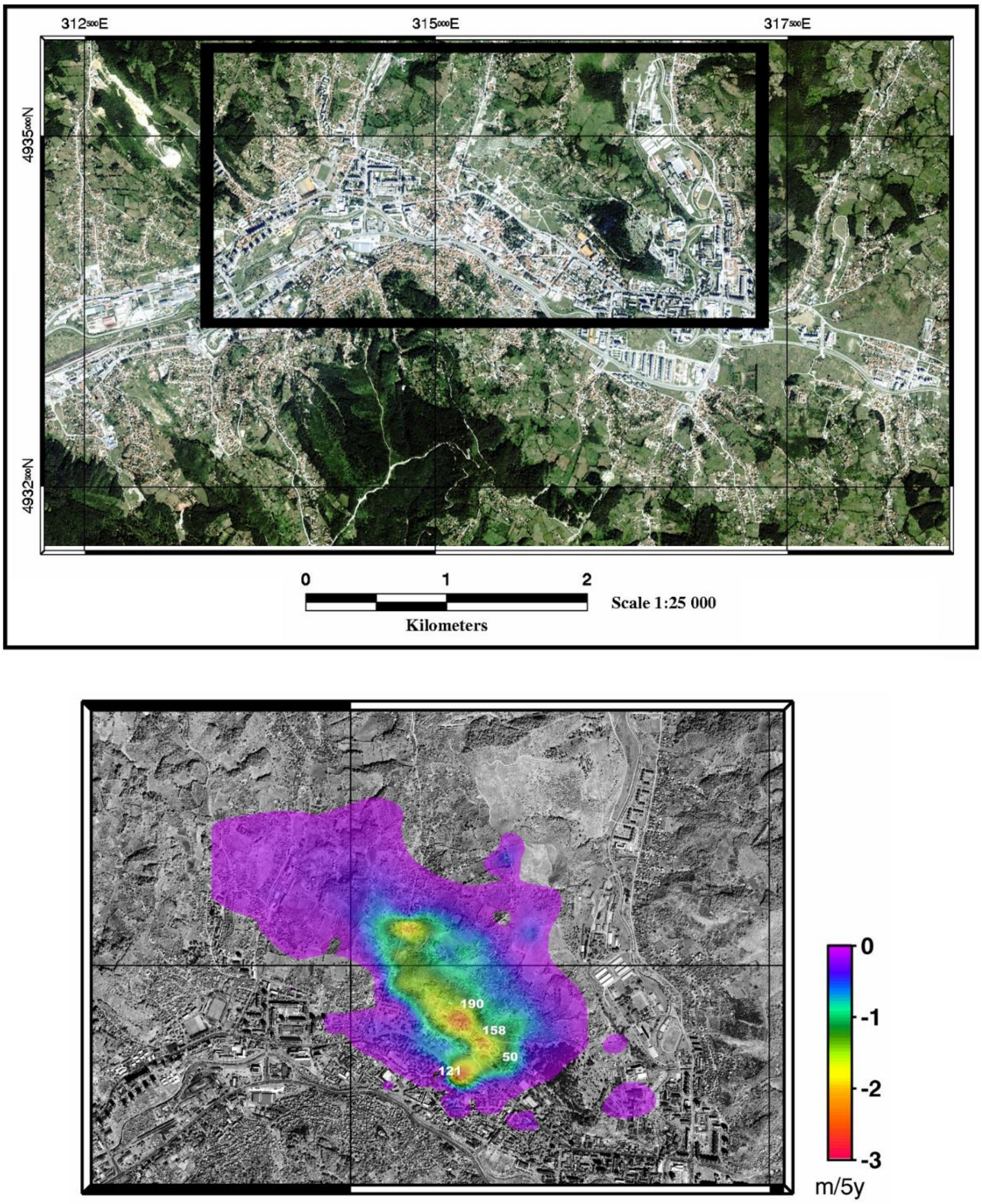

Figure 3. Tuzla observed by using multispectral data (above) and a portion (below) by panchromatic data. Colours represent the subsidence rates between 1981 and 1986.

3.2. Spatial Distribution From 2008-2019

After the suspension of the operation of the salt wells, geodetic surveys of the terrain continued, as the number of points observed was changing. An analysis of the geodetic survey results showed that periodic and systematic surveying needed to be continued even after the suspension of the exploitation.

Figure 2(e) shows the spatial distribution of the subsidence measured by GNSS and geodetic surveys from 2008-2012. The distribution of subsidence is similar to that by GNSS from 2004-2007. Large subsidence was found around the most eastern part of the salt deposit. The subsidence became small toward the northwest parts of the salt deposit. The maximum subsidence of -53.2 cm was found at a point in a hilly area located in the southeast part of the salt deposit.

Figure 2(f) shows the spatial distribution of the subsidence obtained by SBAS-DInSAR for the period of October 2014 to May 2019. This spatial distribution is similar to those by GNSS surveys from 2004-2007 and by GNSS and geodetic surveys from 2008-2012. It means that the subsidence still continued in a similar manner even after the extraction of salt water had been terminated in 2007. However, the absolute value of the subsidence has been decreasing. It is also important to reveal the mechanism of the present subsidence behavior.

From Figures 2(a)-(f), the location of the large subsidence area is seen to have moved to the southeast border of the salt mine deposit (northeast from Pannonica Lakes), while it was located in the center of the salt mine region in the previous period (1956-2003). It should be noted that the complex hydrodynamic groundwater system for the city of Tuzla plays a major role in the creation and speed of the settlement. In the northeast hilly area of Pannonica Lakes, large horizontal displacements were detected (Čeliković et al., 2014; Čeliković & Imamović, 2016) and the complex behavior comprising a combination of landslides and subsidence has appeared.

4. Conclusions

The presented case study has focused on monitoring the subsidence induced by salt mining activities in Tuzla, Bosnia and Herzegovina by means of SBAS-DInSAR, GNSS, and geodetic surveys from 2004 -2019.

The time transition of the subsidence obtained by DInSAR showed a good agreement with the monitoring results by GNSS, and it detected that the subsidence is still on-going at a rate of -10 ~ -40 mm/year in the eastern area of the salt deposit. The location of the large subsidence area has shifted to the southeast border of the salt mine deposit (northeast of Pannonica Lakes), while it was located in the center of the salt mine region in the previous period (1956-2003).

The combination of SBAS-DInSAR, GNSS, and geodetic surveys will be effective for monitoring the subsidence in Tuzla in future periods.

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