

*XX Congresso Brasileiro de Mecânica dos Solos e Engenharia Geotécnica*  
*IX Simpósio Brasileiro de Mecânica das Rochas*  
*IX Simpósio Brasileiro de Engenheiros Geotécnicos Jovens*  
*VI Conferência Sul Americana de Engenheiros Geotécnicos Jovens*  
*15 a 18 de Setembro de 2020 – Campinas - SP*



## Subsidence control in solution mining areas: a systematic review

Renathielly Fernanda da Silva

Doctoral student, Federal University of Paraná, Curitiba, Brazil, renathielly@ufpr.br

Alessander Kormann

Professor, Federal University of Paraná, Curitiba, Brazil, alessander@ufpr.br

**ABSTRACT:** For centuries, subsidence have occurred in salt mining regions. These events can be triggered by anthropogenic action, geological processes or by the association of these factors. When such problems cannot be avoided the development of control techniques (prevention, monitoring, and remediation) is required. The main objective of this study is to list the subsidence control tools presented in the literature to subsidize decisions in mine management. This research applies the Method Ordinatío to sorting out the most important works on subsidence in brine extraction areas. In the selected studies, 10 control techniques were identified and the main considerations about these methodologies are summarized in this paper. Additionally, all cases of subsidence in salt mining areas are presented, indicating the locality, maximum settlement rate, period of subsidence and occupation of the area. Finally, we point out which techniques we consider have the potential to be improved and used together for better control of subsidence in salt mining areas.

**KEYWORDS:** Halokinesis, Rock salt, Ground movement.

**RESUMO:** Durante séculos subsidências tem ocorrido em áreas de mineração de sal. Estes eventos são deflagrados pela ação antropogênica, processos geológicos ou associação destes fatores. Quando estes eventos não podem ser evitados técnicas de controle (prevenção, monitoramento e remediação) são requeridas. O objetivo principal deste trabalho é listar as ferramentas de controle de subsidência apresentadas na literatura para apoiar decisões no gerenciamento de minas. Esta pesquisa aplica a metodologia Ordinatío para ranquear os trabalhos mais importantes sobre subsidência em áreas de extração de salmoura. Foram identificadas 10 técnicas de controle de subsidência e as principais considerações feitas nestes trabalhos sobre estas metodologias são apresentadas. Adicionalmente os casos de subsidência em áreas de mineração de sal apresentados nestes trabalhos são elencados, indicando a localidade, taxa máxima de subsidência, período de subsidência e ocupação da área. Por fim, é sugerida uma combinação de técnicas para melhor controle de subsidência em áreas de mineração de sal por dissolução.

### 1 Introduction

Salt material exploitation, underground energy storage in salt caverns and nuclear waste disposal in rock salt deposits increase the necessity to study the behavior of strength and deformation rock salt (WANG et al., 2014). The salt creep deformations occur in three stages. First, there is a rapid and transient response (primary creep), then a continuous flow stage (secondary creep) and sometimes there is an increase in the strain rate before rupture (tertiary creep) (NEAL, 1991).

This paper focuses on the control techniques of a specific geohazard: subsidence in solution mining areas. The solution mining technique consists of dissolving the salt by circulating solvent (usually water) through a well and pumping out the brine by the recovery well or single well (RAUCOULES et al., 2003).

Before mining operation the saturated brine is generally in equilibrium within these geological formations. With presence of openings, caused by anthropogenic activities, introduction of freshwater can lead to the dissolution of salt strata, mechanical changes, instabilities and finally surface subsidence (QUANG; GOURDIER; BAZARGAN-SABET, 2018).



There are many articles that present techniques of ground movement control in salt mining areas. however, this is the first work that uses a systematic methodology to point out the existing gaps in the study of this type of engineering geology problem. This paper describes control techniques used in cases of terrain deformations in salt solution mining regions. The objective of this paper is to gather knowledge about the subject, pointing out the difficulties found in previous works and suggest tools for managing subsidence.

## 2 Methodology

This systematic review is conducted by a methodology to select and rank relevant scientific papers encompassing the impact factor, number of citation, and year of publication (PAGANI; KOVALESKI; RESENDE, 2015). The research protocol (Appendix A) show (A) research questions that these works intend to answer; (B) databases select to this systematic review; (C) research criteria to include an article; (D) search terms used; (E) exclusion criteria and (F) search results. After exclusions exhibited on step E from Research Protocol, it was selected 25 articles considered relevant to this work. In other geological or geotechnical areas, this number of articles would be considered small, however, it is important to note this is a very specific subject.

## 3 Systematic review

The systematic review elaborated in this paper analyzed the articles selected by six aspects: type of control, technique/method, location, maximum subsidence rate, the period in which the maximum subsidence occurred and land occupation in the subsidence district. Articles are introduced in Table 1 ordered according to the relevance ranking established by the Method Ordinathio. Table 1 presents the journal name, reference, type control, and method.

Table 1. Selected articles.

[#]	Reference	Control type	Control method
1	(PERSKI et al., 2009)	Monitoring	[1][3]
2	(RAUCOULES et al., 2003)	Monitoring	[1][3]
3	(YERRO et al., 2014)	Monitoring	[1][3][4]
4	(KIM; LU, 2018)	Monitoring	[1]
5	(PIPIA et al., 2009)	Monitoring	[1]
6	(KALIA; FREI; LEGE, 2017)	Monitoring	[1] [4]
7	(KIM; LU; KAUFMANN, 2019)	Monitoring	[1][7]
8	(GEE et al., 2019)	Monitoring	[1][3][4]
9	(QUANG et al., 2019)	Prevention	[2]
10	(MANCINI et al., 2009a)	Monitoring	[6]
11	(VAN DER SPEK, 2018)	Prevention	[5]
12	(PIPIA et al., 2013)	Monitoring	[1]
13	(MANCINI et al., 2009b)	Monitoring	[4]
14	(ZHANG et al., 2017)	Prevention	[6]
15	(ZIDANE et al., 2014a)	Prevention	[2]
16	(ZIDANE et al., 2014b)	Prevention	[2]
17	(DE WAAL et al., 2012)	Prevention	[6]
18	(LAND, 2013)	Monitoring	[8][9]
19	(CONTRUCCI et al., 2011)	Monitoring	[4][9]
20	(COOPER, 2002)	Prevention	[5]

[#]	Reference	Control type	Control method
21	(STECCHI; ANTONELLINI; GABBIANELLI, 2009)	Monitoring	[3]
22	(AUTIN, 2002)	Prevention	[5]
23	(ZIJL; HENDRIKS; HART, 2005)	Prevention	[2]
24	(BAUER et al., 1997)	Prevention	[2][8][10]
25	(BELL, 1975)	Monitoring	[5]

Figure 1 shows the number of articles over time. We can observe an increase after 2000, especially after 2010. This fact can be explained by the development of methods that allow analyses de subsidence phenomenon and mainly due new subsidence cases that occurred, including mines out of operation.

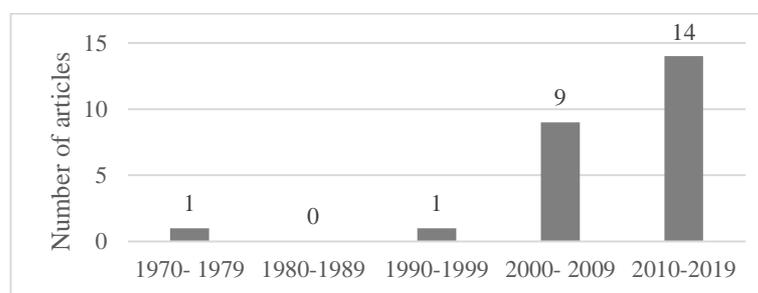


Figure 1. Amount of articles over time.

Regarding the type of control, it was found that 15 articles (60%) are related to the monitoring of subsidence already noticed, 10 articles (40%) are related to the prevention of subsidence and none presents remediation techniques. Articles addressing monitoring techniques stand out in both quantity and ranking.

### 3.1 Subsidence cases

Exception made to article 23 (ZIJL; HENDRIKS; HART, 2005), all other articles applied their methodologies to some existing mine. Table 1 shows the subsidence cases reported in articles selected. The maximum subsidence rate reported in the article, the period in which this subsidence occurred and soil occupation of the region is presented in this table.

Subsidence rate is an important parameter on subsidence study, however the settlement does not have always a constant rate (PERSKI et al., 2009). The subsidence rate is directly related to the volume of salt extracted. In Tuzla, a decrease in subsidence rates was detected, related to the reduction of salt exploitation (Mancini et al., 2009b). In Seville, three micro seismic regimes were observed, each well correlated with changes in surface subsidence rate and brine level in the cave (CONTRUCCI et al., 2011).

In Wieliczka, Poland two principal types of subsidence were observed: slow, due to the convergence of chambers and fast caused by groundwater inflows into the mine (Perski et al., 2009). In Catalonia, four types of ground movements were identified. With progress of the salt extraction, active shifting subsidence occurs. On abandoned galleries, residual subsidence is triggered with a decreasing rate of closure. Resurgence is identified due to the intrusion of the salt dome. And rapid ground collapses caused by the dissolution of soluble materials laying close to the ground surface (YERRO et al., 2014).

The decrease in subsidence rate also relates to the total volume of chambers. In Wieliczka, the subsidence rate reduced due to filling with sand in some caves, while the volume of others is decreasing with convergence (PERSKI et al., 2009).

The maximum subsidence rate is very variable, depending on the subsidence mechanism. Slow ground movement is typical for regions where there is salt rock with creep behavior. Articles 18 and 24 (Bauer et al., 1997; Land, 2013) present cases in which there was certainly no creep deformation, but a plastic deformation, because the ground movement occurred abruptly and with a high magnitude.



Article 11(VAN DER SPEK, 2018) stands out to be the only one that shows predictions of future subsidence rates and presents the interference of settlement on climate change in coastal regions. It is important to mention that many cases occurred in urban areas and thus can cause economic losses and risk lives.

Table 1. Subsidence cases reported in the selected articles.

[#]	Location	Maximum subsidence rate (cm/year)	Period	Soil occupation
1	Wieliczka, PL	72	1962	Urban area
2	Vauvert, FR	2,1	1995-1998	Rural area
3	Suria, ES	30	1995-2000	Urban area
4	Grandfalls/Wink, EUA	23/40	2014-2017	Rural area
5	Sallent, ES	5	2006-2007	Urban area
6	Germany	0,67	1992-1999	Urban area
7	Winkler County, EUA	53	2015-2016	Native vegetation
8	Veendam/Frisia, NL	1,83/1,38	2015-2017/2016-2017	Rural area
9	Dombasle, FR	14	-	-
10	Tuzla, BA	25	1982	Urban area
11	Vlie/Pinkegat/Zoutkamp, NL	0,01/0,02/0,01	2030	Coastland
12	Vila de Sallent, ES	-	-	Urban area
13	Tuzla, BA	25	1982	Urban area
14	Jintan, CN	-	-	Urban area
15	Switzerland	12	-	-
16	Switzerland	10	-	-
17	Netherlands	-	-	All country
18	New Mexico, USA	Abruptly (45m)	-	Native vegetation
19	Cerville, FR	1 m/h	2008	-
20	UK	-	-	All country
21	Tuzla, BA	30	1956 - 2003	Urban area
22	Five Islands, EUA	-	-	-
24	Weeks Island, EUA	Abruptly (9 m)	1992	Urban area
25	Cheshire, UK	-	-	Urban area

### 3.2 Control methods

Analyzing the articles, ten control subsidence methods were observed: Interferometry [1], numerical methods [2], topographic leveling [3], GNSS [4], literature review [5], assessment of risk [6] aerial photography [7], geophysics [8], seismometer [9] and drilling [10].

Some articles used more than one methodology (as can be seen in Table 1), however, the papers that approached the subject such as literature review and risk assessment were considered to have used a single methodology. Figure 2 shows the number of applications of each technique in this systematic review.

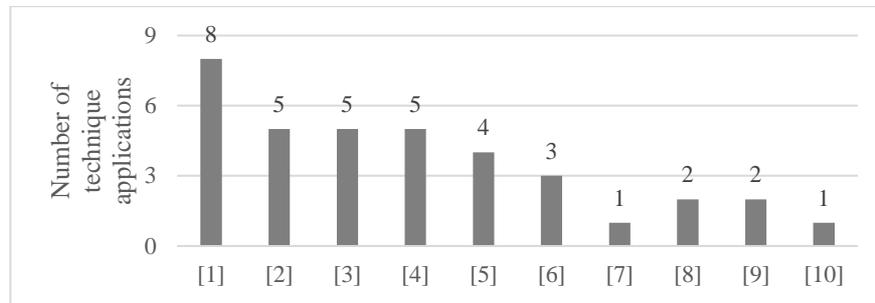


Figure 2. Amount of technique application in selected articles.

Table 3 presents the purposes for which these techniques were used and the main considerations of the authors on such methodologies.

Table 3. Techniques identified in the literature review.

Technique	Key considerations in articles
Interferometry	Remote process allowing to consult past data. Satisfactory for slow ground movements. Main disadvantage is the inability to record sudden ground movements. Interferometry allows to define the most suitable location to install benchmarks for topographic leveling. To eliminate the atmospheric effect in the signal phase, a PSInSAR (Persistent Scatterers) technique was developed. Eventually is necessary to perform a reprocessing that consists of an algorithm to solve unwrapping problems.
Numerical methods	Numerical modeling of subsidence caused by salt dissolution is still used with restrictions due to the difficulty of simulating the creep behavior of salt rock. In the selected articles the saline rock displacement was simulated in the following ways: creep law and Hooke law, Stokes flow law and Darcy flow law coupled with other physical equations that relate to advection dispersion, dissolution and porosity. The most recent article adopts a model that is based on Darcy's law and a simplified equation linking flow, dissolution, and porosity. However, the results do not present a very satisfactory converge with real cases (QUANG et al., 2019).
Topographic leveling	All articles use the information obtained by topographic measurements to compare or calibrate In-SAR information. In Tuzla dissolution salt mining areas, topographic data were used in two methods of curvature analysis: directional curvature and analytical Gaussian curvature for subsidence analysis. The directional curvature presented by the maps generated from the curvature methods showed good agreement with the most pronounced cracks observed in the field. The Gaussian maps were more satisfactory in the representation of the normal subsurface faults (STECCHI; ANTONELLINI; GABBIANELLI, 2009).
GNSS	The static GPS with relative positioning has potential to detect slow deformations. GNSS also has the potential to calibrate interferometric readings. However, the two techniques are not fully comparable because GPS station frequently is installed on top of tall buildings, which has their piles supported in deep layers.
Literature review	Literature reviews are relevant because they are public records of past case experiences, unlike projects and management plans that involve restricted access files.
Assessment of risk	These products could be applicable in public policy to select the mitigation actions. There are several risk assessment techniques. In the selected works probabilistic approaches based on geotechnical tests are used. The use of GIS environment is a good alternative for results representation as it allows the manipulation of data and the production of maps and reports.



Technique	Key considerations in articles
Other techniques	Aerial photography, geophysics, microseismic network and drilling were the least used techniques, with two or fewer applications. Among these, we highlight the seismic tomography and electrical resistivity, geophysical techniques. These techniques make it possible to know subsurface material without the use of invasive procedures that are often more costly and may even affect mine stability or generate drainage paths.

#### 4 Conclusions and recommendations

This paper aims to present the control techniques of subsidence in salt mining areas by solution method. The Ordianthio methodology was applied to point the most relevant articles in literature. It is possible to conclude that:

- It was found that interferometry is the most used technique, mainly because it can provide a ground movement history. This technique is considered well established. However, due the time gap between satellite measurements, it faces limitations of application to detect sudden subsidence increase.
- GNSS, topographic leveling, seismograph, aerial photography are techniques widely used in other engineering fields and find application in controlling subsidence.
- We highlight three techniques: *Risk assessment, geophysical methods, and numerical methods*. No articles in the literature used this combination. Together these techniques could form subsidence prevention tool. It would be interesting if numerical modeling were based in real mine geometries, local lithology obtained by geophysical tests and field/laboratory testing to properly characterize salt stress-strain behavior.
- The authors point out that the studies do not present salt mine decommissioning techniques.

#### ACKNOWLEDGMENTS

The authors would like to thank the Postgraduate Program in Civil Engineering from the Federal University of Paraná by scientific support. The author also acknowledge Capes support, a foundation linked to the Brazilian Ministry of Education.

#### REFERENCES

- Albuquerque, P. J. R., Carvalho, D.; Borjaille Alledi, C.T.D.; Polido, U.F. (2007) Behavior of instrumented continuous flight auger piles in sedimentary and residual Soils. In: Panamerican Conference on Soil Mechanics and Geotechnical Engineering, 13, Isla Margarita. *Proceedings...Venezuelan Geotechnical Society*. CD-ROM. 6 p.
- Bauer, S. J.; Ehgartner, B. L.; Neal, J. T. (1997) Geotechnical studies associated with decommissioning the strategic petroleum reserve facility at Weeks Island, Louisiana: A case history. *International Journal of Rock Mechanics and Mining Sciences*, v. 34, n. 3, p. 25.
- Contrucci, I. et al. (2011) Multiparameter monitoring of a solution mining cavern collapse: First insight of precursors. *Comptes Rendus Geoscience*, v. 343, n. January, p. 1–10.
- Cooper, A. H. (2002) Halite karst geohazards (natural and man-made) in the United Kingdom. *Environmental Geology*, v. 42, n. 5, p. 505–512.
- Gee, D. et al. (2019) National geohazards mapping in Europe: Interferometric analysis of the Netherlands.



*Engineering Geology*, v. 256, p. 1–22.

- Kalia, A. C.; Frei, M.; Lege, T. (2017) A Copernicus downstream-service for the nationwide monitoring of surface displacements in Germany. *Remote Sensing of Environment*, v. 202, p. 234–249.
- Kim, J.-W.; Lu, Z. (2018) Association between localized geohazards in West Texas and human activities, recognized by Sentinel-1A/B satellite radar imagery. *Scientific Reports*, v. 8, n. 1.
- Kim, J.-W.; Lu, Z.; Kaufmann, J. (2019) Remote Sensing of Environment Evolution of sinkholes over Wink , Texas , observed by high-resolution optical and SAR imagery. *Remote Sensing of Environment*, v. 222, n. April 2018, p. 119–132.
- Land, L. (2013) Geophysical records of anthropogenic sinkhole formation in the Delaware Basin region, Southeast New Mexico and West Texas, USA. *Carbonates and Evaporites*, v. 28, n. 1–2, p. 183–190.
- Mancini, F. et al. (2009) Monitoring ground subsidence induced by salt mining in the city of Tuzla (Bosnia and Herzegovina). *Environmental Geology*, v. 58, n. 2, p. 381–389.
- Mancini, F.; Stecchi, F.; Gabbianelli, G. (2009) GIS-based assessment of risk due to salt mining activities at Tuzla (Bosnia and Herzegovina). *Engineering Geology*, v. 109, n. 3–4, p. 170–182.
- Neal, J. T. (1991) Prediction of Subsidence Resulting from Creep Closure of Solutioned-Mined Caverns in Salt Domes. n. 200.
- Pagani, R. N.; Kovaleski, J. L.; Resende, L. M. (2015) Methodi Ordinatio: a proposed methodology to select and rank relevant scientific papers encompassing the impact factor, number of citation, and year of publication. *Scientometrics*, v. 105, n. 3, p. 2109–2135
- Perski, Z. et al. (2009) InSAR analyses of terrain deformation near the Wieliczka Salt Mine, Poland. *Engineering Geology*, v. 106, n. 1, p. 58–67.
- Pipia, L. et al. (2009) Polarimetric differential SAR interferometry: First results with ground-based measurements. *IEEE Geoscience and Remote Sensing Letters*, v. 6, n. 1, p. 167–171.
- Pipia, L. et al. (2013) Polarimetric temporal analysis of urban environments with a ground-based SAR. *IEEE Transactions on Geoscience and Remote Sensing*, v. 51, n. 4, p. 2343–2360.
- Quang, V. C. et al. (2019) A Robust Model Coupling Subsidence with Salt Dissolution. *Mine Water and the Environment*, v. 38, n. 1, p. 166–177.
- Quang, V. C.; Gourdier, S.; Bazargan-Sabet, B. (2018) A Robust Model Coupling Subsidence with Salt Dissolution. *Mine Water and the Environment*, v. 38, n. 1, p. 166–177.
- Raucoules, D. et al. (2003) Monitoring of slow ground deformation by ERS radar interferometry on the Vauvert salt mine (France): Comparison with ground-based measurement. *Remote Sensing of Environment*, v. 88, n. 4, p. 468–478.
- Stecchi, F.; Antonellini, M.; Gabbianelli, G. (2009) Curvature analysis as a tool for subsidence-related risk zones identification in the city of Tuzla (BiH). *Geomorphology*, v. 107, n. 3–4, p. 316–325.
- Van Der Spek, A. J. F. (2018) The development of the tidal basins in the Dutch Wadden Sea until 2100: The impact of accelerated sea-level rise and subsidence on their sediment budget-a synthesis. *Geologie en Mijnbouw/Netherlands Journal of Geosciences*, v. 97, n. 3, p. 71–78.
- Wang, G. et al. (2014) International Journal of Rock Mechanics & Mining Sciences Experimental investigations of the creep – damage – rupture behaviour of rock salt. *International Journal of Rock Mechanics and Mining Sciences*, v. 66, p. 181–187.
- Yerro, A. et al. (2014) Analysis of the evolution of ground movements in a low densely urban area by means of DInSAR technique. *Engineering Geology*, v. 170, p. 52–65.
- Zhang, N. et al. (2017) Comprehensive risk evaluation of underground energy storage caverns in bedded rock



salt. *Journal of Loss Prevention in the Process Industries*, v. 45, p. 264–276.

Zijl, W.; Hendriks, M.; Hart, M. (2005) A velocity-based approach to visco-elastic flow of rock. *Mathematical Geology*, v. 37, n. 2, p. 141–162.

#### Appendix A – Research protocol

<b>A - Research questions</b>					
A1	Which are the papers on salt solution mining areas?				
A2	What are the subsidence cases reported in the literature?				
A3	What are subsidence control techniques applied to salt mining?				
<b>B - Databases</b>					
B1	Science Direct (SD)/ Scopus (S)/ Emerald (E)				
<b>C - Search criteria</b>					
C1	Language	English			
C2	Scientific area	All			
C3	Journal (s)	All			
C4	Article type (s)	Review and research			
C5	Research field (s)	Title, abstract and keywords			
C6	Date of publication	Until present			
C7	Date of search	19 August 2019			
<b>D - Search terms</b>					
	Keywords	Total	Database		
			SD	S	E
D1	"subsidence" AND "salt mining"	48	7	25	16
D2	"subsidence" AND "salt extraction"	16	1	5	10
D3	"subsidence" AND "solution mining"	82	4	28	50
D4	"subsidence" AND "salt dissolution"	86	23	61	2
	Total	232	35	119	78
<b>E - Exclusion criteria</b>					
E1	Inability to download	OR			
E2	Elimination of duplicate	OR			
E3	Editorials or conference proceedings	OR			
E4	Articles related to subsidence triggered by purely geological processes	OR			
<b>F - Search results</b>					
F1	From keywords search	232			
F2	After abstract review	73			
F3	After article review	25			