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Observation of Surface Subsidence above Workings in a Salt Diapir: Case Studies from the Wapno and Kłodawa Mines

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Abstract

Surface subsidence above salt mines reflects the complex interaction of elastic and viscous deformation processes in rock salt, as well as hydrogeological and structural changes within diapiric formations. This study evaluates long-term ground movements above two Polish salt diapirs: Wapno, affected by catastrophic flooding in 1977, and Kłodawa, where mining continues in selected panels. High-precision levelling records collected over several decades were analysed to determine subsidence magnitude, trough geometry and time-dependent deformation behaviour. In Wapno, suffosion and dissolution caused extensive discontinuous failures, whereas in Kłodawa, deformation remains primarily continuous and controlled by chamber convergence. By introducing and applying the concept of observational capacity, the research highlights the necessity of maintaining geodetic monitoring networks capable of capturing evolving deformation fields. The findings support the implementation of sustained levelling campaigns to ensure infrastructure safety, validate geomechanical models and enhance land-use planning in salt-mining regions.

Keywords: salt mining, subsidence, precise levelling, surface deformation, diapir, degradation of levelling networks

1. Introduction

Surface displacements induced by rock-salt extraction are governed primarily by the progressive closure (convergence) of underground chambers. The magnitude and spatial distribution of vertical displacements characterize both the rate of convergence processes and the lateral dispersion of mining influences. Together with underground convergence surveys, surface-levelling observations constitute a fundamental source of information on rock-mass movements in the vicinity of workings and, indirectly, on mine safety.

Measurements of vertical displacements within areas affected by salt mining aim to quantify the impact of post-mining voids. They also enable linking the consequences of extraction with environmental protection requirements (Kortas et al., 1997). Accurate vertical-displacement estimates are further needed for assigning land-use suitability categories and for validating geomechanical models.

The dispersion of mining influence depends, among other factors, on extraction depth, dip of the diapir flank, and geodynamic movements (Kortas et al., 2008). Greater extraction depth tends to widen the subsidence trough; a dipping diapir margin shifts the trough maximum away from the extraction centre. Local uplift sometimes observed over salt diapirs distorts the apparent trough geometry and remains insufficiently understood.

Despite the adoption of modern techniques for mapping ground-level changes (Kim et al., 2021; Rapiński et al., 2024; Arif et al., 2025), precise geometric levelling remains the preferred method in salt-mining environments. In practice, common pitfalls arise at the stages of network design, measurement, and interpretation, the most significant including:

- inappropriate distribution of benchmarks—over-densification within plant premises and excessive sparsity farther from the centre of activity;
- failure to cover the full extent of the influence area;
- lack of network replenishment after benchmark loss;
- tying the network to benchmarks located within zones affected by mining;
- non-uniform adjustment strategies across campaigns;
- insufficient analysis linking observed effects to their physical causes.

2. Influence of Workings at the Wapno Salt Mine

In plan view, the Wapno salt diapir is approximately elliptical/ovoid, with axes of ~900 m and ~350 m. The salt roof occurs at a depth of ~160 m. A gypsum caprock directly overlies the deposit and reaches the ground surface in the central part. Chamber-and-pillar mining was conducted from 1920 at depths between 380 and 540 m below ground level (bgl). The cumulative volume of workings reached 5.5 million m³.

On 5 August 1977 a catastrophic water inflow flooded the mine. Despite complete inundation, the brine-filled voids have continued to affect the ground surface.

2.1. Levelling Network in Wapno

Elevations of individual benchmarks were first determined in Wapno in 1918 in connection with railway construction, then again in 1937 and sporadically in the 1940s. A large-area monitoring network designed to observe mining impacts at the surface was established only in 1951 and was subsequently expanded. In 1951, benchmarks were stabilized along Świerczewskiego and Sportowa streets and along a parallel line between them. Additional benchmarks along Staszica Street were installed in 1963, and along Świerczewskiego, Pocztowa, and Bema streets in 1972. Ground benchmarks were added in 1973 and 1975. A substantial number of benchmarks were installed immediately after the 1977 inflow. The network continued to be supplemented thereafter and currently comprises 126 benchmarks (Fig. 1).

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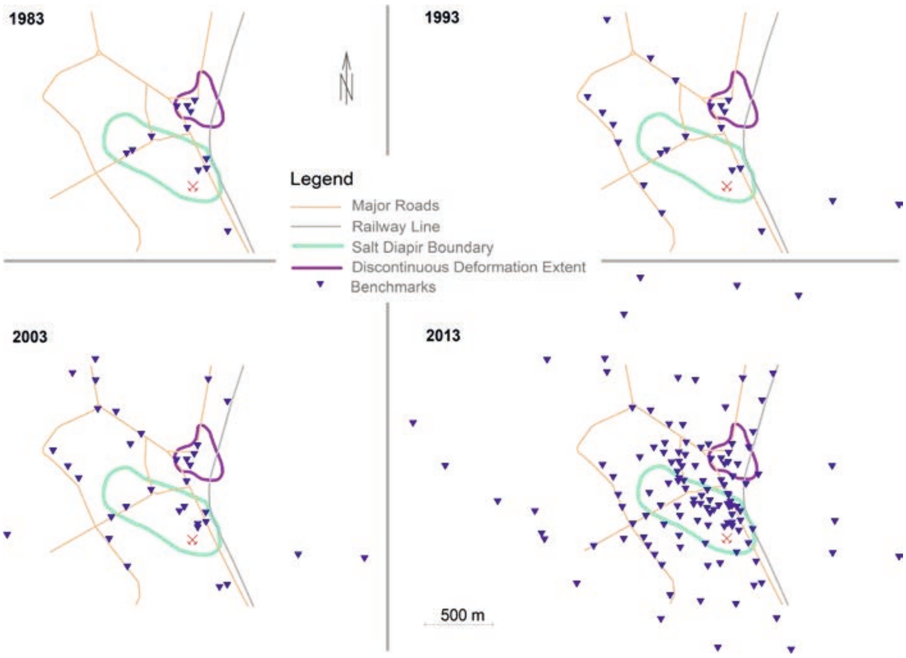

Fig. 1. Development of the benchmark network after the 1977 water inflow in Wapno in 1983, 1993, 2003, and 2013 (own elaboration)

Measurements initially relied on technical levelling and later on precise levelling. A characteristic feature of the dataset is the variability of network ties and adjustment strategies between campaigns, as well as differences in the interpretation approach.

2.2. Surface Subsidence above the Wapno Mine

Prior to the 1977 inflow, i.e., in 1937–1976, the oldest benchmarks subsided at rates up to –14.5 mm/yr. The subsidence trough was regular, with its centre over the main workings. Due to the absence of benchmarks to the north and east, the mapped trough appeared elongated towards the NW.

The formation of the trough before 1937 cannot be quantified; however, it was likely less pronounced—mining was limited to a single level in a rock mass not previously stress-relieved by extraction. Displacements were probably proportional to those of benchmark 8/1067, the oldest point (observed since 1918) mounted on the wall of the railway station building.

Whereas mining-induced influence on the surface had been continuous, the 1977 catastrophic inflow, caprock drainage, and leaching of unconsolidated material produced a broad subsidence trough with numerous discontinuous deformations—fissures, scarps, and sinkholes—typical of suffosion and liquefaction processes (Rogoż, 1998; Poborska-Młynarska and Misiek, 2006). Within this broad trough, maximum observed subsidence reached –5.5 m. At its centre, a large collapse sinkhole exceeded –20 m in depth, and the area enclosed by the –700 mm isoline was a zone of discontinuous deformation (faults, steps, fractures). Most benchmarks in this area were destroyed, implying that actual maxima were likely even greater.

Until about 1980, ground lowering proceeded at relatively high rates due to block falls and loosening within the "great sinkhole" zone and to dissolution of rock in the course of brine saturation. Thereafter, the rate decreased to about –7 mm/yr, and from 1991 stabilized near –4 mm/yr (Fig. 2). The slowdown relative to the pre-inflow period is attributed to brine support of cavity roofs.

In recent years, the subsidence trough has developed two centres: one over the central diapir and another in the area of the former sinkhole (Fig. 3). The trough geometry to the NE of the diapir is less reliable due to the lack of benchmarks. Maximum recent subsidence rates reached up to –4.5 mm/yr.

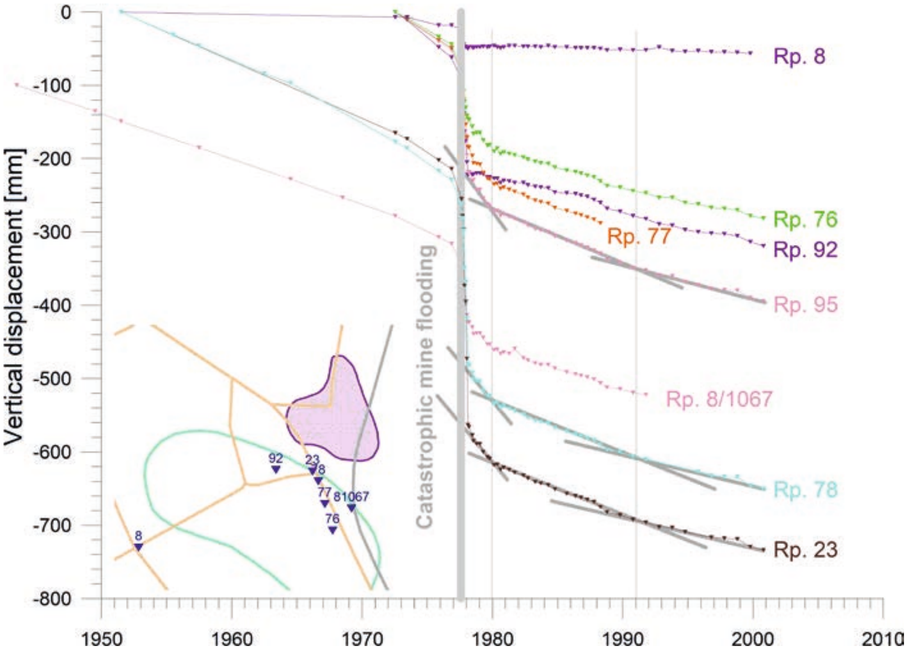

Fig. 2. Decay of benchmark subsidence rates (own elaboration)

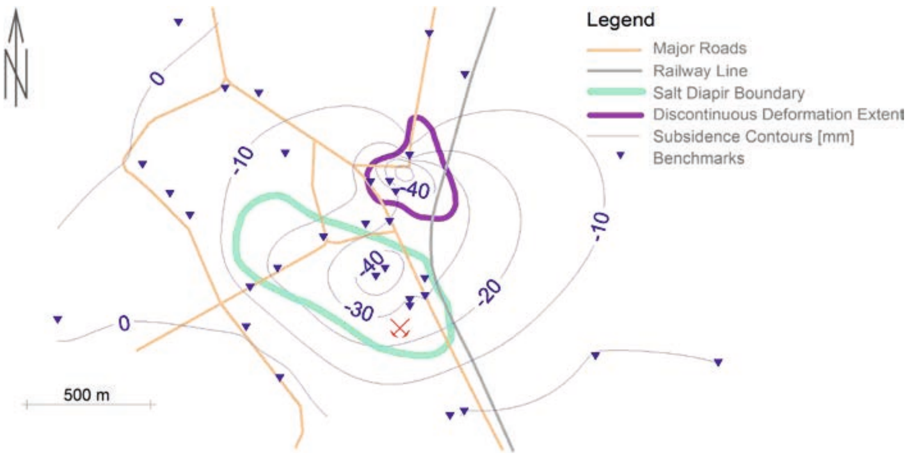

Fig. 3. Subsidence trough in 2003–2013 (own elaboration)

Short-term accelerations up to –18 mm/yr were observed in 1999, 2001, 2007, and 2013, followed by phases of deceleration. Such local rate changes may signal hydrogeological phenomena; minor or short-lived disturbances may, however, also reflect occasional measurement errors, differences in adjustment, or in the network ties.

It should be emphasized that surface lowering above salt mines is not solely the result of chamber closure; other processes contribute, including hydrogeological and hydrological effects, salt karst, diapirism, and regional vertical crustal motions (Rasała, 2005, 2006; Kowalczyk, 2007; Manea et al., 2021; Szczerbowski and Gawałkiewicz, 2023).

3. Influence of Workings at the Kłodawa Salt Mine

The Kłodawa diapir forms the central ~30-km segment of the extensive Izbica Kujawska–Kłodawa–Łęczyca salt structure (~60 km long, trending NW–SE). In cross-section, it is an asymmetric salt wall with an overhang on the NE flank, rising from ~6 km depth to ~25 m a.s.l. (salt roof). The diapir attains a width of ~2 km in its highest part and ~5–8 km within the overhang developed at ~2 km depth. Above the diapir lies an anhydrite–gypsum–clay caprock ~40–220 m thick.

Rock salt extraction in the Kłodawa Salt Mine began in 1956 from the 450 m mining level. Between 1960 and 1967, two lower production levels – 525 m and 600 m – were developed. Further expansion of the Kłodawa Salt Mine took place during the 1970s and 1980s, when successive mining levels intersected the salt deposit (Chwałek, 2010).

At present, the mine comprises seven mining fields and twelve production levels (450, 475, 500, 525, 550, 575, 600, 630, 660, 690, 720, and 750 m), situated at depths ranging from 322 to 625 m below ground level. Extraction is by the chamber-and-pillar method. The cumulative volume of workings exceeds 20 million m³.

The continuation of mining operations is planned until 2052, along with the development of rock-salt extraction at greater depths across all mining fields. In mining panels 2, 3, 5, and 7, extraction is projected to extend to depths of 657–698 m b.g.l., corresponding to the 780 m and 820 m mining levels. Development works providing access to the 780 m level were initiated in 2014 (Cała et al., 2017).

3.1. Levelling Network in Kłodawa

A surface network of benchmarks spans the area above panels 1 and 2 and its NW–SE continuation. Following the catastrophic flooding at Wapno, the Kłodawa network was expanded to encompass the full anticipated influence area, by reusing existing benchmarks and densifying the grid with additional wall and ground marks. Measurements have been conducted by second-order precise leveling. In terms of spatial coverage and dispersion, the network became more functional. However, the 1983 survey showed that some benchmarks previously assumed stable did not meet this criterion, diminishing the value of earlier results.

Over several decades, many benchmarks were destroyed or temporarily not found, hampering year-to-year comparison of individual point behaviour and of the trough as a whole. Of 324 benchmarks observed in 1978 during network expansion, ~40% were no longer measured twenty years later. Consequently, 50 new benchmarks were stabilized in 1999 and measured in the same campaign. Figure 4 shows the benchmarks observed in characteristic years for the network's development: 1952, 1978, and 1999.

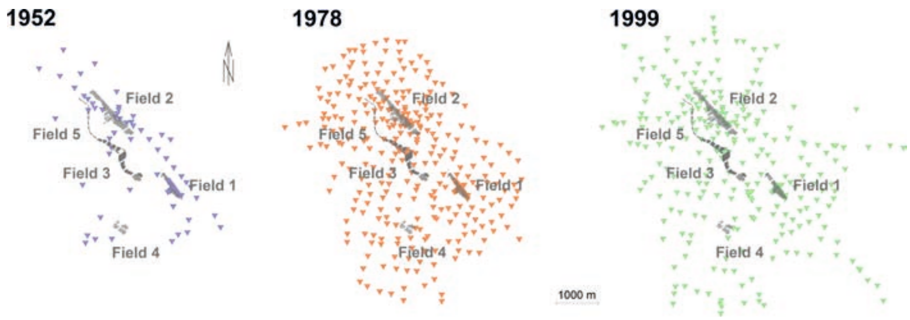

Fig. 4. Development of the levelling network for delineation of the subsidence trough (own elaboration)

3.2. Surface Subsidence above the Kłodawa Mine

Levelling data over mines allow estimation of subsidence rates and of the extent and shape of the trough (see Section 4.2), and they provide additional insights. Among simple rheological representations of rock salt, the Maxwell model—instantaneous (elastic) response followed by viscous creep at an approximately constant rate—is often used. Geodetic observations over fields 1 and 2 reveal such behaviours at rock-mass scale. While the increase in trough volume characterizes both processes, limitations of the network motivate the use of simpler indicators, e.g., the increase in maximum subsidence.

A trough with two centres develops over field 1 and field 2 (Fig. 5). The influence of other panels is not evident in the surface measurements.

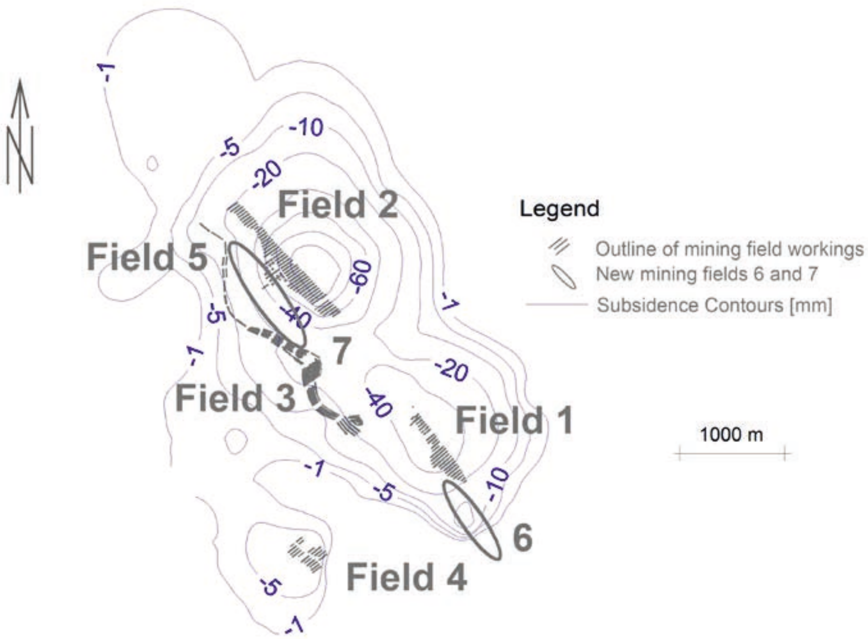

Fig. 5. Subsidence trough over extraction fields in 1978–1999 (own elaboration)

Observations indicate that the maximum increase in vertical displacement above field 2 is correlated with the excavation volume in this field. In the period 1978–1999, the maximum vertical displacement reached 116.5 mm (Fig. 6), corresponding to 4.5 mm/yr, while the excavation volume increased by 4.13 million m³ (0.14 million m³/yr). Unfortunately, for the initial mining period, before the extension of the geodetic network, reliable levelling data are not available. Consequently, the "matching" of the curves of maximum displacement and excavation volume is only possible from 1978 onwards. The relatively strong correlation suggests that, in the case of field 2, the rock-mass response to excavation is governed predominantly by elastic deformation rather than viscous effects. This is attributable to the fact that field 2 has been mined continuously since 1960.

For field 2, an elastic influence coefficient m_e for the surface was determined. It is defined as the ratio of the increment in subsidence to the increment in excavation volume that induces this subsidence. The post-mining influence of field 1 on displacements above field 2 is sufficiently small to be neglected; thus, the elastic influence coefficient is

$$m_e = \frac{\Delta m_{\max}}{\Delta V_{exc}} = \frac{116.5\,\text{mm}}{4.13\times 10^6\ \text{m}^3} = 28.2\ \text{mm per}\ 10^6\ \text{m}^3$$

This implies that creating a void with a volume of 0.1 million m³ results in an instantaneous lowering of the centre of the subsidence trough by 2.8 mm.

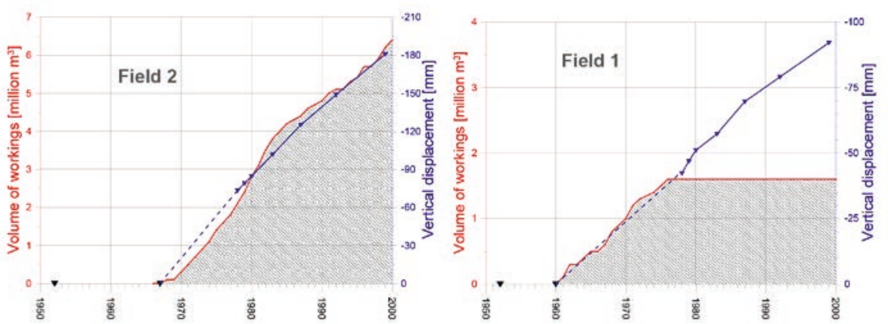

Fig. 6. Vertical displacements due to active extraction (field 2) and rock-mass creep following extraction (field 1) (own elaboration)

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The ground surface above field 1 exhibits a different behaviour. Mining in this field ceased in 1977, i.e. prior to the expansion of the geodetic network. The vertical displacements observed thereafter are no longer associated with ongoing extraction, but instead reflect rock-mass creep manifested as progressive closure of the excavations.

For field 1, assuming constant mining and geological conditions, a viscous influence coefficient m_v can be defined as the ratio of the vertical displacement rate to the excavation volume at the end of extraction. In the years 1978–1999, the maximum vertical displacement above field 1 amounted to 49.8 mm (Fig. 6). The voids remaining after salt extraction in field 1 total 1.61 million m³. Hence, the viscous influence coefficient is

$$m_v = \frac{\Delta m_{\max}}{V_{exc}} = \frac{49.8\ \text{mm}}{1.61 \times 10^6\ \text{m}^3} = 1.5\ \text{mm/yr per } 10^6\ \text{m}^3$$

This coefficient represents the annual lowering of the central point of the subsidence trough and depends on the volume of the extracted workings.

4. Observational Capacity of the Network

As shown by field 1 (extraction ended in 1977) and by the post-mining Wapno case, slow surface movements persist long after extraction ceases. Degradation of levelling networks is a major practical issue extending beyond salt mining and has motivated numerous studies (Kortas and Maj, 1999; Derezińska and Kujawski, 2007; Kurałowicz, 2015; Wolski and Toś, 2017; Bureš et al., 2024).

The usefulness of levelling surveys for defining a subsidence trough depends on multiple factors, notably network condition, measurement method, and adjustment strategy. We can speak of the network's observational capacity: measurements performed on that network must provide sufficient, consistent information on the behaviour of individual points within the trough continuously over time, enabling multi-year analyses of vertical displacements. The analysis should elucidate processes occurring in the rock mass and at the surface. Accordingly, network preparation, survey assumptions, and adjustment procedures should be optimized for such analyses.

Each campaign should be documented with a report that includes—besides the results—evidence of stability of tie points, a list of destroyed or not-found benchmarks, a description of the levelling method, a network sketch with loop closures, and a statement of the adjustment method. Based on this report, each campaign should be followed by an interpretation of mining influences at the surface with conclusions regarding the adequacy of network preparation and survey execution.

Key requirements for determining vertical displacements for geomechanical analysis and for computing surface strains are:

- Fit-for-purpose network design and proper benchmark stabilization. Observation points must be distributed to capture the full influence extent, i.e., to record near-zero subsidence at the trough edge. Ground benchmarks—unless protected or masked (e.g., below grade)—are prone to damage; wall benchmarks are recommended. Each mark must have a topographic description and be mapped.
- Ability to maintain the network during and after extraction. Given the specific mechanical behaviour of salt, adequate protection and replenishment of marks is essential. Maintaining a functional network effectively requires continuous renewal, with replacement of lost marks and prompt post-campaign densification.
- High-accuracy measurements by precise geometric levelling, tied to points whose stability is beyond doubt. Age-resistant (deep) marks should be installed on the periphery of the monitored area at locations

selected for ground conditions, lack of hydrological disturbance, limited traffic-induced vibrations, and practical protection; minimum depth ~3 m. The local network should be tied to the national levelling network.

- Appropriate adjustment of observations. Data should be adjusted so as to enable determination of the extent of mining influence; adjustment to points that are not stable distorts the trough image.
- Mandatory interpretation tailored to local specifics, with geomechanical conclusions and network-related recommendations. Systematic comparative analysis of successive campaigns mitigates errors originating in measurement and adjustment.
- Systematic surveys. Benchmark elevations should be measured by precise geometric levelling in the same month each year. The frequency follows the rate of geomechanical processes and legal requirements.

5. Conclusions

Long-term levelling observations demonstrate that surface subsidence above salt diapirs results predominantly from chamber convergence, yet may also be significantly intensified by hydrogeological disturbances. In Wapno, the catastrophic flooding in 1977 triggered extensive discontinuous deformation, creating a deep collapse sinkhole and accelerating ground movements. Conversely, in Kłodawa, subsidence remains largely continuous, with elastic response dominating in the actively mined Field 2 and viscous creep controlling post-mining deformation over Field 1.

Rock-mass movements persist for decades after extraction ceases, emphasising the necessity of maintaining monitoring networks throughout the full life cycle of a mine. The concept of observational capacity highlights that only a well-designed, constantly replenished and correctly adjusted network can provide reliable subsidence data for geomechanical evaluation and land-use management.

Systematic precise levelling, supported by proper reference and benchmark stabilisation, remains a key tool for ensuring the safety of surface infrastructure and for validating predictive models in salt-mining environments.

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