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Calculated and actual seismic consequences of geodynamic processes during the activation of salt karst within the Stebnyk potash deposit

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SUMMARY

The Stebnyk potash salt deposit is one of the largest in Ukraine. The inflow of drainage waters into the mining chambers of Mine No. 2 led to the formation of three large sinkholes. The aim of the study was to analyze geological observation data and seismic monitoring under conditions of salt karst activation and the formation of a hydrogeological system in the area affected by the largest karst sinkholes. During the design of a temporary seismic monitoring system, which initially included one and later three seismic stations, global experience in applying seismological methods to investigate the condition of emergency salt mines was employed. For data interpretation, nearby stations of the Carpathian regional seismological network were also used. Weekly urgent reports on seismic events in the area of the Stebnyk deposit were su Based on the results of the study, seven types of geodynamic processes accompanying technogenically activated karst within the delineated model of pillar undercutting were substantiated. A connection was established with the geological, mining-geological, and hydrogeological characteristics of the development of technogenically activated salt karst. A potential correlation between the mine collapse events and tectonic activity near the deposit is acknowledged. Conclusions were drawn regarding the types of geodynamic processes. The energy released during one of the largest rock collapses in the mine was assessed, and other geodynamic processes were ranked. A combination of direct geological observation methods and seismic monitoring was applied to assess the state of the geological environment and forecast potential catastrophic events.

Introduction. The Stebnyk potash salt deposit is one of the largest in Ukraine, and for many centuries, brines were extracted from its territory and evaporated to obtain salt. Over the past 70-100 years, it has been developed as a significant source of mining and chemical raw materials for the production of agrochemical products, where potash-magnesium ores were extracted and processed, potash-magnesium fertilizers were produced, and substantial volumes were supplied to various regions of the country. However, such extraction has not been without consequences for the geological environment and the ecosystem: the primary karst voids formed during brine extraction eventually merged into a single network of karst channels, which, during periods of water inflow into the mine workings (discharge zones), became feeding and transit zones of the karst hydrogeological system (Haidyn and Diakiv, 2010).

Method and Theory. The prolonged functioning of the karst hydrogeological system and the inflow of drainage waters, aggressive to potash salts, into the mining chambers led to the undercutting and collapse of pillars, the formation of stable equilibrium vaults, their subsequent destruction, and the formation of three large sinkholes – No. 27, 30, and 32 – within seam No. 10, at a short distance from one another. These features have undergone transformations over the past eight years during the flooding process and the formation of the post-mining landscape within the mining allotment of Mine No. 2.

Figure 1 *Current appearance of the three largest karst sinkholes No. 27, 30, and 32*

The aim of the study was to analyze geological observation data and seismic monitoring under conditions of salt karst activation and the formation of a hydrogeological system in the area influenced by the largest karst sinkholes within the Stebnyk potash salt deposit (Diakiv, 2007). To achieve this aim, the following tasks were addressed: analysis of the dynamics of water inflows over time, landscape changes, karst deformations and sinkhole formation, substantiation of models, and identification of stages of geodynamic processes based on a set of indicators (Diakiv et. al., 2024).

Methods applied included spatial analysis of cartographic materials – maps, diagrams, mining plans; remote sensing using the multifunctional software package Google Earth Pro; field verification of geodynamic process manifestations; photographic documentation of karst formation consequences; measurements of dimensions and volume calculations; and comprehensive analysis of seismic data.

Examples. The global experience in applying seismological methods to assess the condition of emergency salt mines, particularly at the mine in Bernburg (Germany), demonstrates their high effectiveness in forecasting the development of events, as described in more detail in ((Thoma, 2000). After reviewing the studies conducted by researchers from Limited Liability Company "GIRHIMPROM" (Zozulja et. al., 2003), proposals were made to the management of "Polimineral" as early as 2007-2008 to employ seismic monitoring for the integration of various research methods. A concept project for the monitoring system was developed, and trial series of seismic recordings were carried out (Verbitskij et. al., 2008), however, due to certain organizational reasons, the project was not implemented.

A new stage of development in this direction began in 2017. Temporary seismic observations using a single seismic station, installed in a service facility of the “Zakhidnyi” ventilation shaft of Mine No. 1 (designated as PNT3 SHE UA) in the area of the Stebnyk Potash Plant, commenced on October 10, 2017 (Verbitskyj and Sapuzhak, 2017). When possible, for processing the instrumental recordings of the “Stebnyk” seismic station, data registered at the nearby seismic stations “Skhidnytsia” and “Morshyn” of the Carpathian Regional Seismological Network of the Institute of Geophysics of the National Academy of Sciences of Ukraine were used.

During the observation period, numerous seismic events of various origins were recorded by the PNT3 SHE UA seismic station, excluding seismic noise of known types (railway, motor transport, anthropogenic disturbances, etc.). In the subsequent data processing, it was possible to identify recordings with features characteristic of local seismic events; however, their localization based on data from a single seismic station was challenging.

To improve the localization of local seismic events within the mining allotment of Mine No. 2, the topology of a seismic network was developed, and by the end of August 2019, two additional seismic stations were put into operation. Subsequently, based on the data from the seismic monitoring system, which consisted of the aforementioned stations and the “Stebnyk” station (PNT3 SHE UA, PNT4 SHE UA, and PNT5 SHE UA), and with the support of the Carpathian Regional Seismological Network stations “Morshyn” and “Skhidnytsia,” reliable determination of the epicenters and hypocenters of local earthquakes and anthropogenic seismic events was carried out. The relevance of the obtained results was also confirmed by the Main Department of the State Emergency Service of Ukraine in Lviv Region, in accordance with whose requirements urgent weekly reports on seismic events in the area of the Stebnyk potash deposit were provided during the period of temporary seismic observations.

Results. Based on the research results, seven types of geodynamic processes accompanying technogenically activated karst in the defined model of pillar undercutting were substantiated:

- dissolution and destruction of inter-chamber pillars under flooding conditions in an aqueous environment;
- destruction of pillars and chamber ceilings with the formation of stable equilibrium vaults in a dry environment;
- collapse sinkholes during the subsidence stage of the surface;
- cylindrical sinkholes caused by the failure of stable equilibrium vaults;
- rapid post-collapse centripetal cave-ins and landslides;
- slow post-collapse centripetal cave-ins;
- slow post-collapse multi-amplitude, multi-phase, centripetal landslides.

All of these processes are associated with the geological, mining-geological, and hydrogeological characteristics of the development of technogenically activated salt karst, in particular, the close interaction between surface and subsurface water inflows, the solubility of salt rocks, the dimensions and morphology of mine workings, locations of water inflow, and other factors. Analysis of seismograms over the observation periods showed that the dissolution and destruction of inter-chamber pillars under flooding conditions in an aqueous environment exhibit virtually no seismic activity. This is due to the

buffering effect of the water column, which dampens potential noticeable seismic events. In contrast, the destruction of pillars and chamber ceilings with the formation of stable equilibrium vaults in a dry environment is characterized by significant seismic events associated with the fall of large blocks from heights of 50-100 meters. A similar situation is observed for collapse sinkholes during the surface subsidence stage: large blocks falling from considerable heights generate both isolated and series of seismic events.

The most significant seismic events are associated with cylindrical sinkholes resulting from the failure of stable equilibrium vaults. In particular, the cylindrical sinkhole that occurred on September 30, 2017 (sinkhole No. 27) resulted in a technogenic earthquake and a hydraulic shock. The exact date and time of the collapse were determined – 00:46. The mass of the collapsed ground was approximately 1 million tons, with a height of about 100 meters. The estimated impact energy at the moment of collapse (E) was approximately 10^{13} kg·m²/s² (kJ), which corresponds to 1,000 tons or 1 kiloton in TNT equivalent. During the formation of sinkholes Nos. 30 and 32, the cylindrical collapses similarly exhibited the greatest seismic manifestations. However, these were buffered by a significantly smaller mass and by the partial (sinkhole No. 30) or complete (sinkhole No. 32) flooding of Mine No. 2.

On September 29, a tectonic earthquake occurred near the village of Modrychi in the area of the Stebnyk potash deposit at 21:46:09.7 UTC, at a depth of H = 0-2 km, with a magnitude of M = 2.63. The epicenter coordinates, determined from the data of the Carpathian seismic network stations, were: $\varphi = (49.310 \pm 0.015)^{o}$N, $\lambda = (23.480 \pm 0.023)^{o}$E. The accuracy of coordinate determination in this case, when converted to linear distance, amounted to ±1.5 km in latitude and ±2.3 km in longitude. The event was recorded not only by the closest seismic stations “Skhidnytsia” and “Morshyn” (the “Stebnyk” station had not yet been installed at that time), but also by other stations of the Carpathian network – located in the cities of Berehove, Brid, Kamianets-Podilskyi, Lviv, Mizhhiria, Novodnistrovsk, Nyzhnie Selyshche, Rakhiv, Starunia, Trosnyk, Uzhhorod, Kholmtsi – as well as 3 Polish, 2 Slovak, and 1 Hungarian seismic stations (Sapuzhak, 2019). It remains uncertain whether the tectonic earthquake triggered the collapse of rock in the mine, or whether the collapse in the mine acted as a "trigger mechanism" for a preconditioned tectonic earthquake .

Rapid post-collapse centripetal cave-ins and landslides, which occurred following sinkhole No. 27 on September 30, 2017, generated an elevated seismic background after the most powerful centripetal collapse. Slow post-collapse centripetal cave-ins were visually documented by video recordings; however, their seismic manifestations were weakly expressed during the formation of sinkhole No. 30, as this event involved the fall of blocks in a dry environment from a considerable height (approximately 50 meters), and were practically unrecorded during the formation of sinkhole No. 32, since the blocks fell into water. We consider slow post-collapse multi-amplitude, multi-phase, centripetal landslides to be the least seismically expressed geodynamic events documented by us during the activation of salt karst at the Stebnyk deposit.

Conclusions. Based on the results of the study, the following conclusions can be drawn:

1. Within the model of pillar undercutting, seven types of geodynamic processes with varying seismic manifestations were identified.
2. The most significant seismic events are associated with cylindrical sinkholes resulting from the collapse of stable equilibrium vaults. In particular, the cylindrical sinkhole of September 30, 2017 (sinkhole No. 27) may have resulted in a technogenic earthquake and hydraulic shock. The exact date and time of the seismic event were determined – 00:46. The collapse involved approximately 1 million tons of material, with a fall height of about 100 meters. Based on these parameters, the calculated impact energy was approximately 10^{13} kg·m²/s² (kJ), equivalent to 1,000 tons or 1 kiloton in TNT equivalent. During the formation of sinkholes No. 30 and No. 32, the cylindrical collapses likewise exhibited the greatest seismic manifestations, but were buffered by a

significantly smaller mass and by the nearly full (sinkhole No. 30) or full (sinkhole No. 32) flooding of Mine No. 2.

3. The remaining geodynamic processes are ranked as follows:
    - rapid post-collapse centripetal cave-ins and landslides;
    - destruction of pillars and chamber ceilings with the formation of stable equilibrium
    - vaults in a dry environment;
    - dissolution and destruction of inter-chamber pillars under flooding conditions in an aqueous environment;
    - rapid post-collapse centripetal cave-ins and landslides;
    - slow post-collapse centripetal cave-ins;
    - slow post-collapse multi-amplitude, multi-phase centripetal landslides.
4. The integration of direct geological observation methods with seismic monitoring enables the assessment of the geological environment and the forecasting of potential catastrophic events, including post-collapse multi-amplitude, multi-phase centripetal landslides.

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