SINKHOLE IMAGING AND IDENTIFICATION OF FRACTURES WITH S_H -WAVE REFLECTION SEISMIC

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Abstract

Subrosion can result in depressions and sinkholes, which are a geohazard. To improve the knowledge of subrosion processes, high-resolution geophysical imaging and a detailed characterization of subsurface structures are required. One of the main subrosion areas in Germany is along the Kyffhäuser-Southern-Margin-Fault (KSMF) in Thuringia. Two shear wave (S_H) reflection seismic profiles of 300 m length in total were carried out along two sinkholes. The near-surface down to ca. 100 m depth was imaged with a resolution of less than 1 m down to 15 m depth and a resolution of 1 m to 3 m at 50 m depth. The internal structures of the leached anhydrite and gypsum were imaged. The reflection patterns indicate a heterogeneous near-surface geology around the sinkholes, with mainly lateral and vertical variations of discontinuous reflectors and small-scale fractures, which are necessary for percolation of meteoric water and sinkhole development, especially in areas with a deep groundwater table and no faults. This is the case for one of the two sinkholes. The other is located at a fault with a shallow groundwater table at 37 m depth. The sinkhole margins are characterized by reflectors, which dip towards the focal points of the sinkholes. Previous sinkholes probably generated fractures, which act as additional fluid pathways. As a result, a collapse can be triggered more easily. Indicators for continued collapse are observed in the profile of the fracture-induced sinkhole by the continued migration of focal points of consecutive collapse events over time.

Introduction

Subrosion, the underground leaching of rocks, requires the presence of soluble rocks (e.g., evaporites), water (e.g., groundwater), and fractures or faults enabling water flow through the subsurface to form cavities (Smyth, 1913; Martinez et al., 1998). Different kinds of structures can evolve, and the two main types are (1) sinkholes and (2) depressions (for a detailed classification see Waltham et al. (2005); Gutierrez et al. (2008)). Subrosion is a natural process, but it can be influenced by, e.g., manipulation of the aquifer system (Bell, 1988) and extraction of saline water (Getchell & Muller, 1995). Reflection seismic (e.g., Steeples et al., 1986) delivers a high-resolution image of the underground for a detailed characterization of the subsurface structures, especially using shear-waves, because the near-subsurface surrounding sinkholes often consists of loose sediments and strongly fractured, and therefore not compacted rocks (Krawczyk et al., 2012; Wadas et al., 2016).

Germany suffers from widespread sinkhole problems because soluble deposits, exposed to natural and man-made subrosion processes, are close to the surface in many areas. One of the main subrosion areas is located along the Kyffhäuser-Southern-Margin-Fault near the town of Bad Frankenhausen in Thuringia. For a detailed analysis of the local subrosion processes, two shear wave (S_H) reflection seismic profiles with a total length of 300 m were carried out along two sinkholes. The aim was to obtain detailed images of the sinkhole structures and to detect possible fluid pathways.

Geological Setting

Bad Frankenhausen is a town in northern Thuringia in Germany located at the southern border of the Kyffhäuser hills (Figure 1). The southern part of the hills is bounded by the northward-dipping and W-E striking Kyffhäuser-Southern-Margin-Fault (KSMF), a major thrust fault in this region (Schriel & Bülow, 1926a,b).

The sediments in the south of the Kyffhäuser hills are deposits of the Zechstein Sea, an epicontinental ocean during the Permian. The main Zechstein formations are the Werra-, Staßfurt- and Leine Formations (z1–z3) consisting of anhydrite, gypsum, limestone, shale, and conglomerates, which were cyclically deposited (Richter & Bernburg, 1955). The anhydrite and gypsum of the Staßfurt and the Werra Formations represent the main subsidence horizon in the research area. Triassic deposits are only found at isolated locations, and Cretaceous and Jurassic rocks were completely eroded. Tertiary deposits are exposed only at a few locations at the southern and western margins of the Kyffhäuser hills, e.g., brown coal. Quaternary sediments, like silt and loess, cover a large area (Schriel & Bülow, 1926a,b; Reuter, 1962; Beutler & Szulc, 1999).

The entire area south of the Kyffhäuser hills is affected by subsidence. The presence of salt springs and the occurrence of numerous sinkholes and depressions at the surface are indicators for the long lasting and still

ongoing subsidence processes. The Äbtissinnengrube sinkhole (Figure 2b) that developed in the 16th Century, is one of the largest sinkholes of the region with a diameter of 160 m x 120 m and a depth of ca. 40 m. The forest sinkhole has a diameter of ca. 20 m and a depth of ca. 7 m. Other famous subsidence-induced tourist attractions are the Barbarossa Cave situated in anhydrite of the Werra Formation westward of the town and the leaning church tower of Bad Frankenhausen.

Field Survey

Two shear wave reflection seismic surveys were carried out (Figure 1), the first, with a length of 180 m, along a sinkhole in a forest north of the town (Figure 2a), and the second, with a length of 120 m, west of the town of Bad Frankenhausen at the Äbtissinnengrube sinkhole (Figure 2b). To generate horizontally polarized shear-waves (S_H), we used the micro-vibrator ELVIS 7 (Polom, 2003; Druivenga et al., 2011) with a sweep frequency of 20 Hz to 120 Hz and a duration of 10 seconds, as seismic source. As receivers, we utilized 120 horizontal geophones in 1 m spacing combined to a landstreamer and Geometrics Geodes recorded 12 seconds of raw signal. For the profile of sinkhole 1, we used a variable split-spread geometry with the source and the receivers moving forward, which is designed for near-surface reflection seismic profiling. For more information about the equipment, see Krawczyk et al. (2013); Polom et al. (2013).

Figure 1. Geological map of Bad Frankenhausen (after Schriel & Bülow, 1926a,b). Red circles mark the investigated sinkhole areas and the insert map shows the location of Bad Frankenhausen in Germany.

Figure 2. Digital elevation models (DEM; TLUG, 2017b) with positions (red circles) of the investigated sinkhole 1 (forest sinkhole) and sink hole 2 (Äbtissinnengrube sinkhole). Sinkholes nearby are marked orange and white dots indicate bore hole locations.

Data Processing

S_H -wave reflection seismic data processing was carried out using the VISTA software (version 10.028) by Gedco (Schlumberger).

The vibroseis correlation using the pilot sweep was applied to the recorded traces to compress the time-stretched signal to a short wavelet such as an impulsive signal (Figure 3a). This is followed by amplitude and spectral editing with automatic gain control (AGC) of 200 ms, bandpass filter (16/18–120/122 Hz) and trace normalization to enhance the reflection response and to attenuate noise to improve the resolution and the data quality. Improvement of signal-to-noise ratio is important

for investigations of subsrosion structures, in order to image the small-scale vertical and lateral variations, which are typical for these kind of structures. Two records of each source location were vertically stacked subsequently to reduce statistically distributed noise and to amplify the seismic response (Figure 3b). The survey geometry setup was applied using a crooked-line binning with a 0.5 m bin interval. A top mute was used to remove data irrelevant for further data processing, in this case signals above the first breaks. The processing steps described above were applied identical to profile 1 and profile 2 (Äbtissinnengrube sinkhole).

This was followed by individual filtering in the frequency-wavenumber domain (FK filter) and an additional bandpass filter (p1: 16/18 Hz–100/102 Hz, p2: 16/18 Hz–94/96 Hz) to remove surface Love waves, harmonic distortions, and noise. To compensate for attenuation and energy loss of the seismic waves an offset-dependent, time-variant logarithmic scaling was applied on profile 1 (Figure 3c). The loss of reflected energy and the reduced amplitudes result from the fractures and possibly small-scale cavities induced by subsrosion, which lead to scattering of the seismic waves and attenuation of especially higher frequencies (Boadu & Long, 1996; Barton, 2007). Since the energy loss with increasing offset was less pronounced for sinkhole 2, an offset-dependent and time-variant logarithmic scaling was not required for profile 2. After sorting the data by common midpoints (CMP), a manual, interactive velocity

Figure 3. Pre-stack data processing of profile 1 using vibroseis correlation (a), vertical stacking, amplitude and spectral editing (b), and FK filtering and offset-dependent, time-variant logarithmic scaling (c).

analysis was carried out using semblance, offset gathers and constant velocity stacks. The lateral intervals for the velocity analysis were generally 2 m to 10 m in order to resolve the lateral velocity variations. After normal-moveout (NMO) correction and residual statics correction, a CMP-stacked section in time domain was generated (Figures 4a, 5a). To remove remaining noise, an additional FK filter was applied to the stacked data. To compensate the frequency attenuation, spectral balancing was applied on profile 1 (Figure 4b). The main parts of the reflection signals were between ca. 20 Hz and 60 Hz for profile 1 and ca. 20 Hz and 80 Hz for profile 2. The spectral balancing boosted the frequency range of profile 1 to 20 Hz to 75 Hz, which improved the resolution.

Figure 4. Post-stack data processing of profile 1 with CMP stack (a), FK filter, spectral balancing (b), and FD time migration (c).

Coherency enhancement and further noise suppression were accomplished by applying a trace weighting function. Finite-difference (FD) time migration shifted the reflectors to their origin subsurface position and removed diffractions (Figures 4c, 5c). The last step was time-to-depth conversion to generate a seismic depth section. All processing steps were performed iteratively, for a detailed description of the processing procedures, see e.g., Hatton (1986) and Yilmaz (2001).

Interpretation

S_H -wave reflection seismic profile 1 (180 m length), was carried out from north to south along sinkhole 1.

Figure 5. Post-stack data processing of profile 2 with CMP stack (a), coherency enhancement (b), and FD time migration (c).

For correlation of reflectors and stratigraphy, borehole Ky 01/1982 (BGR, 2017) was used, located ca. 600 m west of profile 1 (Figures 1, 2a). At ca. 5 m depth, a continuous reflector with high amplitudes is traceable between 0 m and 80 m and between 135 m and 180 m profile length (Figures 6a,b). The strong impedance contrast represents the boundary between silt of the Pleistocene and Werra Anhydrite of the Permian. The

area between ca. 5 m to 70 m depth shows a semi- to discontinuous reflection pattern within the karstic Werra Anhydrite. Shallowly-dipping reflectors, which form three bowl-shaped structures of ca. 30 m to 50 m diameter are visible at three different depths. The three structures are interpreted as subrosion-induced collapses. The deepest collapse is labeled number 1 and the collapse at the surface is labeled number 3. Collapse 1 (at 60 m

Profile 1 – forest sinkhole

Profile 2 – Äbtissinnengrube sinkhole

Figure 6. Depth sections of profile 1 (a,b) and profile 2 (d,e) with interpretation (c,f). Two boreholes were used to correlate reflectors and stratigraphy (g), for borehole location, see Figure 1. Fractures and intraformational faults are shown as black lines.

depth) has a height of ca. 10 m and collapse 2 (at 40 m depth) and 3 (at 15 m depth) have a height of ca. 20 m (Figure 6c). All three collapse structures are formed within the karstic Werra Formation (Figure 6g), while collapses 2 and 3 were generated above the southern margin of the collapse beneath. As a result, a shift of the collapse focal points towards south can be observed. The focal point of collapse 3 shows weak reflectivity and the area directly beneath from ca. 20 m to 40 m depth is almost transparent compared to the neighbouring reflectors at the same depth. The center and the margins of the three consecutive collapse events are characterized by fractures and intraformational faults on the seismic- and probably subseismic scale. They have small-scale vertical offsets of ca. 1 m to 5 m.

S_H -wave reflection seismic profile 2 (120 m length), was carried out along the forest sinkhole. For correlation of seismic reflectors and stratigraphy borehole Ky 02/2014 (TLUG, 2017b) was used (Figures 1, 2b). At ca. 10 m to 30 m depth, partly continuous, high amplitude reflectors are visible. They represent the internal layering and the base of the Quaternary deposits (Figures 6d, e). In contrast the area below, down to 120 m depth, is characterized by a heterogeneous reflection pattern with mostly discontinuous reflectors. Numerous fractures are identified of which only a few are drawn into the interpreted section (Figure 6f). This strongly fractured area is part of the Permian Zechstein Formations (Werra- to Leine Formations (z1–z3)). They are characterized by anhydrite and gypsum (z1An, z2An, z3An). From the surface to ca. 70 m depth the displaced reflectors dip to the south towards sinkhole 2. In this profile only the sinkhole margin is imaged compared to the profile of sinkhole 1, which displays the entire cross-section next to a sinkhole.

Discussion

Shear wave reflection seismic has been shown to be a valuable tool to image sinkholes and the surrounding near-surface like the internal structures of the leached anhydrite and gypsum of the Permian Zechstein Formations z1–z3. The horizontal resolution achieved was less than 1 m at 20 m depth and 1 to 3 m at 60 m depth.

Several aspects regarding data acquisition and processing have to be taken into account for investigation of sinkholes or subsrosion areas with

shear wave reflection seismic. For the identification of the lateral, structural variations and steep reflectors a dense receiver spacing should be chosen (e.g., 1 m or smaller). The seismic source must provide a sufficient force and good ground coupling for good energy transmission into the ground, even on unpaved ground. This helps to partly compensate for energy loss due to strong seismic wave attenuation induced by the fractured subsurface.

Important steps of data processing were filtering, spectral balancing and offset-dependent, time-variant logarithmic scaling, due to the poor signal-to-noise ratio and attenuation of especially high frequencies (e.g., 120 Hz). Partly poor reflection hyperbolas due to discontinuous reflectors are another issue. An improvement might be the use of the common reflection surface (CRS) stacking method instead of CMP stacking, because the CRS stack is independent of the velocity model and uses more traces, which can increase the signal-to-noise ratio (Yilmaz, 2001).

Both profiles reveal a heterogeneous near-surface below a sinkhole and in the surrounding area with many fractures and intraformational, non-tectonic, faults induced by subsrosion. These are necessary for percolation of meteoric-water and groundwater and therefore sinkhole development, especially in areas with a deep groundwater level of e.g. 110 m depth (TLUG, 2017a) for the area of sinkhole 1. Neither a tectonic fault nor artesian-confined groundwater are found at this location, as a result the near-surface subsrosion of anhydrite and gypsum is unlikely to be caused by contact with groundwater. Instead meteoric water that percolates through the near-surface dissolved the soluble rocks and generated the three collapses. In contrast the Äbtissinnengrube sinkhole (sinkhole 2) is located at the KSMF with a shallow groundwater level at 37 m depth (TLUG, 2017a). The fault serves as a fluid pathway for groundwater and probably enhanced subsrosion, which eventually resulted in the occurrence of such a large sinkhole with a dimension of 120 m x 160 m. The digital elevation model (DEM; Figure 2b) shows two smaller sinkholes at the northern and western margins of the Äbtissinnengrube sinkhole. Similar observations were made for the seismic profile of the sinkhole 1, but not in the corresponding DEM, due to a poor resolution limit of 5 m.

Three subsrosion-induced collapse structures were identified in the profile of sinkhole 1. Each collapse is suspected to have generated additional fractures within the overlying material, due to stress redistribution in the area surrounding a cavity, because cavities can not transfer stress (Holohan et al., 2015; Schneider-Löbens et al., 2015). In this study, fracture migration is observed especially at the collapse margins (Figure 7), which serve as fluid pathways for e.g., meteoric water.

As a result multiple collapses can be triggered more easily at the margins. The collapse events have consecutively moved to the south, which correlates with the direction of the drainage system of the Kyffhäuser hills. From these observations, we assume that the margins of an underground collapse or a sinkhole are predestined for a subsequent collapse.

Conclusions

Sinkholes and their surroundings are characterized by a strongly heterogeneous near-surface with semi-continuous to discontinuous reflectors, vertical and lateral variations, and fractures and intraformational faults, which result in vertical displacements on the order of ca. 1 m to 5 m. These openings serve as fluid pathways and can trigger a collapse.

Figure 7. Sketch illustrating the process of the upward migrating fractures and collapse events of sinkhole 1.

We have shown that the margins of an initial underground collapse or a sinkhole are predestined to form another collapse event, due to the generation and the upward migration of additional fractures and intraformational faults into the overlying material. They may enhance the percolation of water, and therefore trigger a subsequent collapse. These collapse events can constantly migrate upwards until they reach the surface forming a sinkhole. The migration direction of collapse events follows the general water flow direction of this area, e.g., it follows the direction of the natural drainage system.

Since sinkholes and collapse events form very small features (even <1 m), the chosen imaging method must be capable of resolving these scales. S_H -wave reflection seismic is well suited to image the underground to a depth of ca. 100 m in high resolution, which is an important depth zone for investigation of subsrosion processes.

Acknowledgements

We thank LIAG's seismic field crew for their support during the field surveys and Lutz Katzschmann, Sven Schmidt and Ina Pustal of the Thuringian State Institute for Environment and Geology (TLUG) for supporting this work. We also thank David Tanner for comprehensive discussions and improvement of the English spelling.

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