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Time-lapse monitoring of subsidence features within the Hutchinson Salt in Kansas

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Summary

Since 2013, time-lapse passive surface wave surveys have been conducted annually in south-central Kansas providing measurements of stress-field changes in the Permian shale bedrock indicative of potential failure. The shale is underlain by the Hutchinson Salt Member, which has been solution mined in this area. Since shear-wave velocity is directly related to the shear modulus, (e.g. rigidity), 2-D shear-wave velocity profiles from inverted passive surface wave energy provided a measure of material competency. From 2014-2015 profiles, a shear-wave velocity anomaly was observed indicating a disruption to the laterally uniform shear-stress state of the shale caprock. Although the magnitude of this anomaly's shear wave velocity increased in 2017, the area had a bulk velocity that was lower compared to 2013 when the investigation was initiated. Based on these observations, the shale caprock is undergoing stoping, a process where segments of roof rock progressively collapse as the overlying stress conditions exceed the elastic limit of the roof rock.

Introduction

The development of subsidence features and sinkholes due to rapid migration of salt-dissolution voids is a well-documented hazard that continues to threaten specific areas in the state of Kansas (Johnson, 1997; Merriam and Mann, 1957a, b; Miller and Xia, 2002). Compared to sinkholes that develop in carbonate environments, evaporite karst (e.g. salt, gypsum) processes have been known to accelerate more quickly because of their higher rate of solubility and decreased material strength (Waltham et al., 2005; Gutiérrez et al., 2008). If the natural environment's stress field is being disturbed by human-induced changes processes such as surface loading for engineering investigations (Waltham and Fookes, 2003; Waltham et al., 2005), removal of subsurface materials for mining exploration (Lucha et al., 2008; Singh and Dhar, 1997), or dewatering and irrigation (Sinclair, 1982) the level of risk continues to increase.

In south-central Kansas, under-regulated mining during the early twentieth century of the Hutchinson Salt member has led to the evolution of salt-dissolution voids and subsequently ground failure in some areas (Ivanov et al., 2013; Walters, 1978). As the salt continues to dissolve, the void grows laterally, forming a longitudinal cavity. However, the removal of salt alters the distribution of stresses in the overlying bedrock creating a tensional dome in the roof rock structure (Fig. 1). This tensional dome

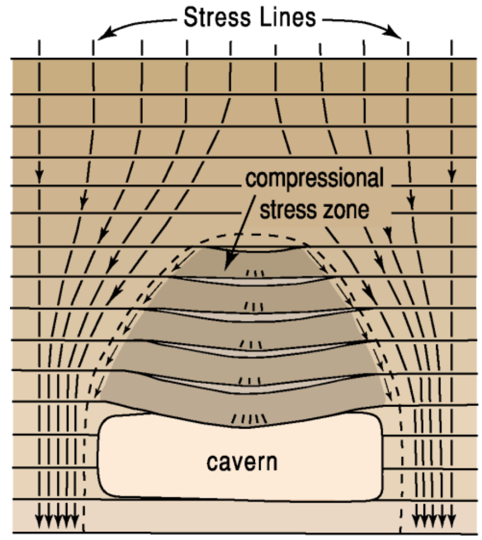

Figure 1: Tension dome and the distribution of stresses above and around a void opening in layered strata. (modified from Davies, (1951).

consists of multiple layers of roof rock strata, but as the size of the void grows, the amount of unsupported weight also increases causing the roof to sag (Davies, 1951). If the weight of the roof rock exceeds the ultimate strength or the elastic limit of the material, the cavity roof and walls will ravel and potentially collapse until the stresses reach a state of equilibrium. As salt-dissolution continues, the void will undergo stoping, or the progressive collapse of roof rock material, which can lead to vertical void migration and ground surface failure (Waltham et al., 2005). The rate of subsidence within a material depends on its material strength and the type of salt deformation (Miller and Xia, 2002; Gutiérrez et al., 2008; Waltham and Fookes, 2003). Ductile deformation can induce subsidence more gradually whereas brittle deformation can lead to rapid subsidence because of the increased rate of fracturing within the rock (Anderson et al., 1995; Steeples et al., 1986; Rokar and Staudtmeister, 1985)

In order to mitigate ground surface failure, these subsidence features need to be accurately detected with enough time to remediate or relocate overlying structures and populations. However, if an area is known to have an increased susceptibility to dissolution processes, invasive testing procedures may expedite cavity wall and roof breakdown

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(Lucha et al., 2008; Gutiérrez et al., 2008). To minimize the level of disturbance to the stress field, non-invasive seismic techniques have been widely used to successfully image and detect subsidence features in and outside of Kansas; examples include surface wave (Almalki and Munir, 2013; Ivanov et al., 2013; Parker and Hawman, 2012) and reflection methods (Miller and Xia, 2002; Dobecki and Upchurch, 2006; Lambrecht et al., 2004). For the purpose of this work, a time-lapse passive surface wave technique was annually used to extract dispersion information and invert for 2-D shear-wave velocity (Vs) profiles from 2013-2017 at a site in south-central Kansas. Pre-existing subsidence features and ground failure were observed at the start of this work, indicating that subsidence may be ongoing. From these 2-D Vs profiles, the development of a subsidence feature was qualitatively interpreted and implications were made concerning the bedrock material's structural behavior.

Geologic Setting

The Permian Hutchinson Salt formation, which is predominantly in central Kansas and Oklahoma, has an increased susceptibility to dissolution processes that can lead to rapid void migration and sinkhole collapse. In Kansas, oscillating sea levels during deposition created fluctuating beds of anhydrite, shale, and dolomite for a net average thickness of 75 m (Walters, 1978). Although the Hutchinson Salt is largely susceptible to sloughing and collapse, it is bounded by the Wellington Shale Formation and the Ninnescah Shale that theoretically protects it from permeating groundwater; above the shale is approximately 21 m of alluvial coarse materials and Pleistocene beds with an average water table depth of 4.5 m. However, the shale caprock contains red halite joints that leach in the presence of unsaturated brine, subsequently compromises its structural competency (Merriam and Mann, 1957b; Swineford, 1955). Mining and saltwater disposal in this region have contributed to reported cases of salt dissolution and subsidence features (Walters, 1978). Given that evaporite karst (e.g. salt-dissolution karst) has an increased rate of development compared to other types of karst in conjunction with jointing in the caprock, these dissolution processes put overlying infrastructure at greater risk of failure (Waltham et al., 2005).

Field Method and Data Processing

Passive surface wave seismic data were collected annually from 2013-2017 (with the exception of 2016) at a site in south central Kansas to monitor ongoing migration potential of Hutchinson salt-dissolution voids in the shale caprock. Surface wave energy was excited by trains (<2 km away) and recorded overnight using fixed arrays of 4.5 Hz vertical geophones at 3 m receiver intervals (Ivanov et al., 2013; Park et al., 1999). An additional 2-D grid array consisting of four concentric squares was deployed in order to determine the azimuth of the passive sources (i.e. trains; Leitner, (2015)). Passive source files were selected if their recorded azimuths corresponded to the orientation of the fixed 1-D linear arrays and exhibited high phase velocity information. If these criteria were met, rolling spreads were decimated from the selected source file for conventional multichannel analysis of surface wave (MASW) processing (Park et al., 1998; Xia et al., 1999).

Time-lapse Seismic Data Results

Since source and signal quality vary from year to year, the decimated rolling-spread length varied as well. For the west-east line discussed in this paper, Line 10, the spread length remained relatively consistent, ranging from 84-96 m, or +/- four receivers (Table 1). Although the Hutchinson Salt exists below 80 m, the purpose of this investigation is to monitor the overlying Ninnescah Shale for changes in its Vs structure caused by the vertical migration of stress field associated with an under-supported void roof. 2-D Vs inversion results near well 2A from each year are shown in Figure 3.

Table 1: Line 10 Survey Spread Length by Year

Year	Spread Length	No. Receivers
2013	90 m	31
2014	87 m	30
2015	96 m	33
2017	84 m	29

In 2013 (Fig. 2a), a laterally homogenous 2-D Vs profile was generated whose velocity layers were consistent with the expected geologic conditions and borehole logs. The Ninnescah Shale bedrock was imaged from approximately 30-60 m and did not display any anomalous features that would indicate concerns regarding the competency of the shale. However, in 2014 (Fig. 2b) and 2015 (Fig. 2c), a low-velocity anomaly within the shale was observed within proximity of well 2A that was not seen the previous year. Within the upper 15 m, a disruption to the low-velocity layer (i.e. coarse sand and gravel alluvium) was also observed that is consistent with the low-velocity feature between 30-50 m. Additionally, increased velocities (>900 m/s) were imaged at the half-space data boundary below 50 m. This abrupt change in the velocity structure reaffirmed the need to continue monitoring.

Two years later in 2017 (Fig. 2d), the amplitude of the localized low-velocity anomaly within the shale became less prominent. Instead, the overall Vs structure exhibited an increased velocity trend below 30 m compared to 2014-2015; however, the average velocity in 2017 is still lower than that seen in 2013. Although the disturbance to the shallow coarse sand and gravel alluvium is no longer evident, the top elevation of the shale is also lower with areas of localized decreased velocity values.

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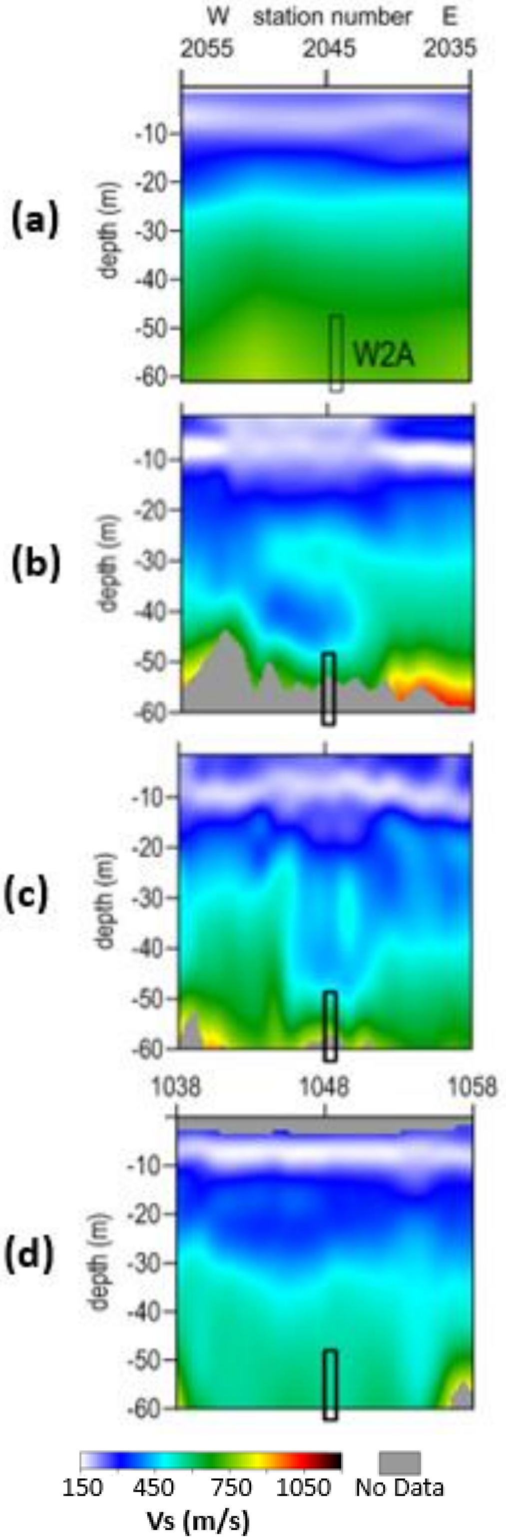

Figure 2: 2-D Vs inversion results from (a) 2013, (b) 2014, (c) 2015, and (d) 2017.

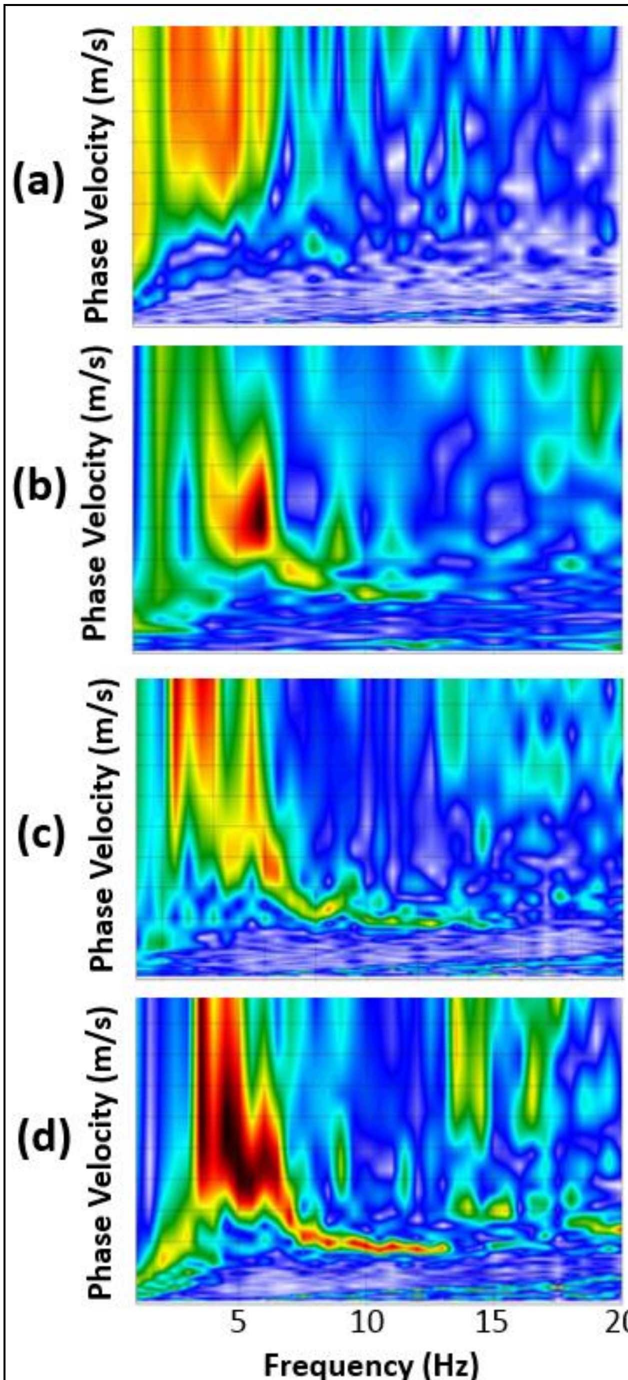

Figure 3: Representative dispersion images from receivers located at the well 2A station from (a) 2013, (b) 2014, (c) 2015, and (d) 2017.

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Starting in 2014, a dominating higher mode surface wave interfered with the fundamental mode between 5-7 Hz (Fig. 3b). These higher modes became more pronounced within the same frequency range in 2015 and 2017 (Fig. 3c-d), which required additional filtering in order to recover the fundamental mode energy trend above 6 Hz. A bow-slice dispersion-curve filter was used (Park et al., 2002) to reduce the contaminating higher mode. This filter uses a user-specified bow-shaped filter zone to dictate where the *f-k* filter will be applied. Dispersion-curve filtering adequately recovered the fundamental mode trend between 5-7 Hz for improved dispersion curve picking and inversion results.

Discussion

Indications regarding the structural competency of the shale caprock were made based on temporal changes in the inverted shear-wave velocity structure proximal to well 2A. Collectively, the altering behavior of the anomaly within the Ninnescah Shale indicates that a subsidence feature was present in 2014 and 2015. This feature is evidenced by the low-velocity anomaly consistent with the location of well 2A from 30-50 m depth (mid-station 1048 in 2017). Coherent dispersion trends support this observation that the shale material velocity exhibited decreased values proximal to the well compared to those observed away from the well. For example, the phase velocity at 5 Hz decreased by approximately 200 m/s within 70 m of well 2A. A higher mode also became more prominent from 2014-2017 within the same 5-7 Hz frequency range in data collected from the eastern portion of each survey line. The presence of higher modes has been documented to represent heterogeneities in the subsurface (Lin and Lin, 2006; O'Neill and Matsuoka, 2005), further supporting a change in the shale material's stress field.

Observations from the 2-D Vs profiles (Fig. 2) and picked dispersion curves (Fig. 4) near well 2A indicate that the Ninnescah Shale is undergoing changes in its stress field that are consistent with the cyclic stoping process. Events such as this are not unprecedented since ground failure and other subsidence features were observed at other areas of this site. The increased velocity trend in 2017 compared to 2014 and 2015 indicates that the shale caprock has rebounded after stoping because the accumulation of compressional stresses above the cavity was released. This cycle of material behavior is supported by the picked dispersion curve trends in Figure 4 such that phase velocities progressively decrease from 2013 to 2015 before recovering back to reduced levels of equilibrium stresses in 2017.

Conclusions

Time-lapse surface wave seismic surveys were conducted from 2013-2017 at a site in south central Kansas with documented susceptibility to sinkhole development. The purpose of these surveys was to monitor voids formed by salt-dissolution within the Hutchinson Salt and detect subsequent changes in the stress field of the overlying shale caprock as the void migrates toward the ground surface. Based on the progression of a localized low-velocity anomaly near well 2A, it was determined that a subsidence feature developed between the 2013 and 2014 surveys. This feature is an implication of the changing material behavior within the shale. In 2017, the magnitude of this anomaly reduced, which has been attributed to stoping. Time-lapse imagine of this area will continue on an annual basis in other to monitor.

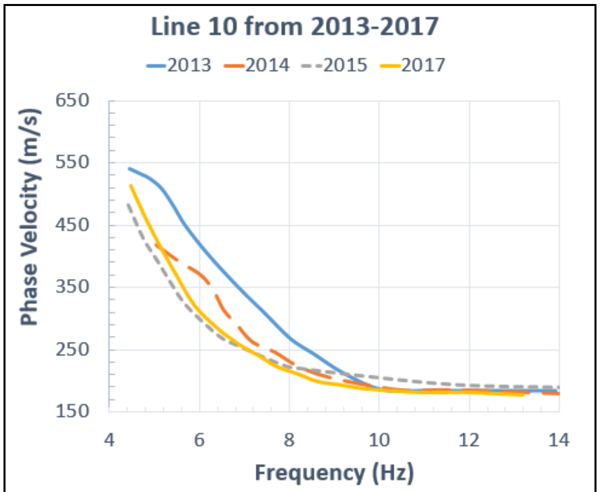

Figure 4: Picked dispersion curve trends from 2013-2017 that represent the development of a subsidence feature.

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