Overview of Passive Seismic Characterization and Monitoring Recommendations for High Priority Salt Jugs near the Irsik & Doll Elevator, BNSF Railroad, and William Street in Hutchinson, Kansas

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Executive Summary

This applied research project correlated measured shear-wave velocities with the condition of rock above dissolution voids, targeting the stress as approximated from the shear-wave velocity of the overburden. Shear-wave velocities were estimated during this study using passive surface wave methods with data acquired along two profiles located on or near two key abandoned brine production wells. Multichannel analysis of surface waves (MASW) was used to estimate the shear-wave velocity, loosely map stratigraphic contacts above the top of the "three finger" dolomite, and evaluate the relative difference in the rock above possible salt jugs associated with the wells compared to rocks above undisturbed salt. Comparison of shear-wave velocity profiles over time (time lapse) was used to provide insight into void dynamics and overburden stability.

Passive MASW profiles were acquired near the Irsik & Doll grain elevator, along William Street, and south of the BNSF Railroad in Hutchinson, Kansas, in 2015. In total, five lines and a 2-D grid of receivers were positioned over wells 2A, 4A, 4B, 6B, 7A, 7B, 52, 53, 59, and 60. Continuous sampling was utilized to record and allow for evaluation of all available sources of passive source energy, ensuring optimal source orientation and surface wave characteristics for each line. Surface waves with frequencies as low as 4 hertz (Hz) were recorded with an average depth of investigation 55 meters (m), and in some places exceeding 80 m, successfully sampling deep beneath the bedrock surface at a depth of around 20 m.

With shear-wave velocity being a function of shear modulus and density, and shear modulus the ratio of stress over strain, it is possible to estimate relative stress of overburden rocks (shear modulus) by shear velocity values. Local increases in shear velocity without changes in lithology can be equated to increased stress associated with overburden roof load over dissolution jugs. Relative shear velocity lows may be associated with collapse features whose vertical movement has been arrested by bulking, reduced stress to within roof rock strength, or changes in strength due to geologic features related to natural variation in deposition or erosion.

Reasonable consistency in the surface-wave dispersion patterns over well 2A between November 2014 and May 2015 surveys suggests the obvious change observed in key elastic physical properties of the overburden between the March 2013 and November 2014 is real. The disturbed volume from approximately 25 m below ground surface, down to the maximum sampling depth of these studies, appears to have stabilized since the November 2014 survey. An incremental change appears to have resulted in reduced strength and/or redistributed stress in the overburden above the well 2A void between the November 2014 and May 2015 surveys. This change in strength or stress appears to be limited to depths greater than 25 m (~10 m beneath the top of bedrock). A marked reduction in apparent velocity between the November 2014 and May 2015 surveys is prominent in bedrock between wells 2A and 4B. The velocity trend south of well 4B is consistent with the March 2013 baseline survey, suggesting a normal/stable stress regime in this area. In this transition zone between wells 2A and 4B, the reduced velocity may be related to interference of multiple surface-wave modes as the wavefield transitions from low velocity at well 2A to normal velocity south of well 4B.

Changes in dispersion patterns representative of subtle drops in sub-bedrock shear velocity at well 52 along the William Street line between October 2012 and June 2015 suggest some kind of incremental change has occurred above the old dissolution jug that may have reduced strength and/or redistributed stress in the overburden, such as a failure related to a vertically migrating void. This change in strength or stress appears to currently be confined to depths greater than 28 m below ground surface—approximately 18 m beneath the top of bed-rock—and may have a lateral extent of up to 50 m, although this is uncertain and likely an over-estimate. Shear velocity of bedrock at well 53, although elevated in the June 2015 survey, is consistent with the October 2012 survey. This suggests that the void at this well was stable during the time between surveys.

No significant increases or decreases in shear velocity were observed along the BNSF railroad line that intersects wells 7A and 4A or any wells sampled along William Street, with the exception of well 52 as noted previously. A decrease in surface-wave penetration depths coincident with well 7A (BNSF railroad line) may be related to a localized zone of reduced shear velocity at depths of 45 m or greater. However, this interpretation is relatively low-confidence and reduced surface-wave penetration likely represents natural geologic variation. Overall, there appears to be no change above wells 6B and 7B previously surveyed in the vicinity of the Irsik & Doll elevator and the first-time surveys over BNSF railroad proximity wells have no indications of elevated shear velocity relative to surrounding rock layers that exceed reasonable variations for this area.

Future monitoring of the subsurface around wells 2A and 4B near the Irsik & Doll elevator and wells 52 and 53 along William Street is advisable in lieu of invasive investigations, providing direct measurements and the potential for remediation, if necessary. We propose a new field layout designed to incorporate all designated wells near the Irsik & Doll grain elevator, William Street, and south of the BNSF Railroad using optimal acquisition parameters (i.e., line lengths) determined during previous surveys. Considering the changes in shear velocity observed between surveys, it would be advisable to perform repeat MASW surveys on an annual basis. If change is observed and appears to be accelerating or migrating vertically, then shorter lags between surveys would be advisable. In light of the history of the jugs in question, proximity to surface structures near wells 2A and 4B, and known or suspected migration into the shale overburden near wells 52 and 53, an annual monitoring program continuing through 2018 should be considered before reevaluating subsurface condition. Future evaluations should focus on consistency between annual surveys and relative shear velocity over the jugs compared to native areas around the site.

Introduction

Material properties (specifically strength and stress accumulations) measured as a function of depth above abandoned salt jugs in Hutchinson, Kansas, appear related to the mobility and upward migration potential of these jugs. Localized escalation in stress (as indicated by increased shear-wave velocity) above subterranean voids is one indicator of an increased potential for roof failure and void migration (Eberhart-Phillips et al., 1989; Dvorkin et al., 1996; Khaksar et al., 1999; Sayers, 2004). Previous studies, using both active and passive seismic wavefield characteristics, suggest perturbations in the shear-wave velocity field immediately above voids can be correlated to characteristics of the unsupported roof spans of salt jugs in the Hutchinson area (Sloan et al., 2010).

The strength of individual rock layers can be qualitatively described in terms of stiffness/rigidity and empirically estimated from relative comparisons of shear-wave velocity measurements. Shear-wave velocity is directly proportional to stress and inversely related to non-elastic strain. Since the shear-wave velocity of earth materials changes when stress and any associated elastic strain on those materials becomes "large," it is reasonable to suggest load-bearing roof rock above mines or dissolution voids may experience elevated shear-wave velocities due to loading between pillars or, in the case of voids, loading between supporting side walls. This localized increase in shear velocity is not related to increased strength, but to increased load as defined by Young's Modulus. High-velocity shear-wave "halos" encompassing low-velocity anomalies are suggested to be key indicators of near-term roof failure. All these phenomena have been observed within the overburden above voids in the Hutchinson Salt Member in Hutchinson at depths greater than 30 m below the bedrock surface.

Previous research projects at the Carey Boulevard Research Area (CBRA) correlated measured shear-wave velocities with the condition of dissolution voids and the physical properties of the overburden at selected locations on Vigindustries legacy solution mining property in Hutchinson. Shear-wave velocities were estimated from passive surface-wave data acquired along eight profiles that intersected 13 wells. Two of these 13 wells had been the target of a previous seismic investigation completed in 2008. As a result of that 2008 study it was determined that the integrity of the overlying strata could be reasonably estimated using shear-wave seismic imaging. The 2008 study quantified the effectiveness of shear-wave velocity to estimate local stress above voids of the size and depth prevalent at the Vigindustries site.

The lack of necessary ultra low-frequency surface waves in the recorded wavefield have negated attempts to use active source multi-channel analysis of surface waves (MASW) to estimate shear velocity in the lithified rocks near the top of bedrock (Miller et al., 2009). Uncontrolled, local industrial and transportation activities represent sound sources that have produced the necessary low frequencies and, when recorded and processed using passive methods, have extended the imaging depth to over 60 m (Miller, 2011). Key to this method is the ability to estimate shear-wave velocities to depths more than double those possible with standard active sources at a particular site (Park et al., 2004). Results of passive MASW studies near this site suggest that this method is effective in identifying jugs with heightened risk for upward migration (Miller, 2011; Ivanov et al., 2013).

Wells 2A and 4B are located in proximity to the Irsik & Doll grain elevator. Three previous surveys were acquired at approximately eight-month intervals over these wells: August 2012 (well 2A only), March 2013, and November 2014. Passive MASW processing resulted in three two-dimensional (2-D) shear-wave velocity (Vs) profiles. Individually, each profile represents a snapshot in time that lacks any measure of the dynamics of void migration or change in time. A relative decrease in Vs centered on well 2A between March 2013 and November 2014 suggests a possible reduction in shear strength of the overlying bedrock (Peterie et al., 2015).

Wells 6B and 7B are located in relative proximity to the Irsik & Doll grain elevator. Seismic surveys were acquired over both wells in August 2012 and over 6B in October 2012. MASW processing resulted in three two-dimensional (2-D) shear-wave velocity (Vs) profiles. At the time of those surveys, 2-D Vs profiles above these wells suggested a normal stress regime with natural geologic variation. Wells 52, 53, and 59 are located near William Street. Active shear-wave reflection and passive surface-wave surveys were acquired over these wells in August 2008 and October 2012. In 2008, a decrease in shear-wave reflection stacking velocity and drop in coherency of bedrock and dolomite reflections at well 52 indicated reduced stress and possibly rock failure and collapse. Elevated Vs at well 53 suggested that a domed roof was gently distributing gradually increasing stress.

In 2015, four lines centered on wells 2A, 4B, 6B, 7B, 52, 53, and 59 were acquired to monitor for and evaluate further changes in Vs to provide insight into void dynamics and overburden stability. Additionally, baseline profiles were acquired over wells 4A, 7A, and 60 to estimate the shear-wave velocity, loosely map stratigraphic contacts above the top of the “three finger” dolomite, and evaluate the relative strength of the rock above possible salt jugs associated with these wells. In this report, we present data acquisition, analysis, and discussion in two sections based on acquisition dates: first, wells 2A and 4B acquired in May 2015, followed by wells 4A, 6B, 7A, 7B, 52, 53, 59, and 60 acquired in June 2015.

Geologic and Geophysical Setting

The Permian Hutchinson Salt Member occurs in central Kansas, northwestern Oklahoma, and the northeastern portion of the Texas Panhandle and is prone to and has an extensive history of dissolution and formation of sinkholes (Figure 1). In Kansas, the Hutchinson Salt Member possesses an average net thickness of 75 m and reaches a maximum of over 150 m in the southern part of the basin. Deposition occurring during fluctuating sea levels caused numerous halite beds, 0.2 to 3 m thick, to be formed interbedded with shale, minor anhydrite, and dolomite/magnesite. Individual salt beds may be continuous for only a few miles despite the remarkable lateral continuity of the salt as a whole (Walters, 1978).

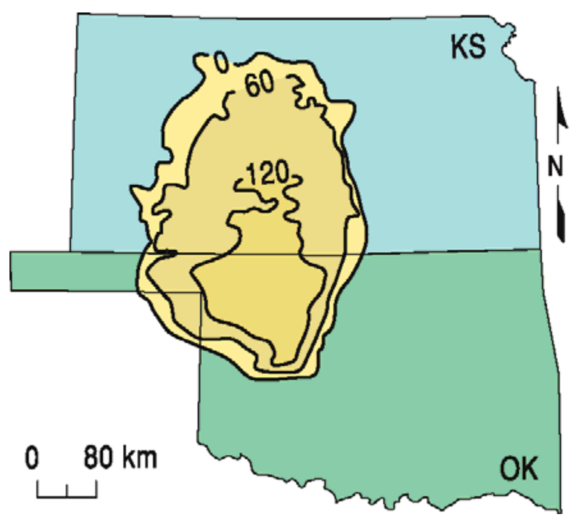

Figure 1. Approximate extent of salt formation, with contour intervals expressed in meters.

The distribution and stratigraphy of the salt is well documented (Dellwig, 1963; Holdoway, 1978; Kulstad, 1959; Merriam, 1963). The salt reaches a maximum thickness in central Oklahoma and thins to depositional edges on the north and west, erosional subcrop on the east, and facies changes on the south. The increasing thickness toward the center of the salt bed is due to a combination of increased salt and more and thicker interbedded anhydrites. The Stone Corral Formation (a well-documented seismic marker bed) overlies the salt throughout Kansas

(McGuire and Miller, 1989). Directly above the salt at this site is a thick sequence of Permian shale.

The upper 760 m of rock at this site is Permian shale (Merriam, 1963). The Chase Group (top at 300 m deep), lower Wellington Shale (top at 245 m deep), Hutchinson Salt (top at 120 m deep), upper Wellington Shale (top at 75 m deep), and Ninnescah Shale (top at 25 m deep) make up the packets of reflecting events easily identifiable and segregated within the Permian portion of the section (Figure 2). Bedrock is defined as the top of the Ninnescah Shale with the sediment. The thickness of Quaternary alluvium that fills the stream valleys and paleo-subsidence features goes from 0 to as much as 90 m, depending on the dimensions of the features.

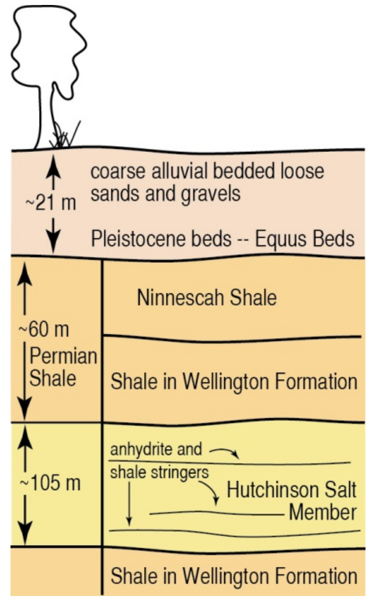

Figure 2. Generalized geology.

Recent dissolution of the salt and resulting subsidence of overlying sediments forming sinkholes has generally been associated with mining or saltwater disposal (Walters, 1978). Historically, these sinkholes can manifest themselves as a risk to surface infrastructure. The rate of surface subsidence can range from gradual to very rapid. Besides risks to surface structures, subsidence features potentially jeopardize the natural segregation of groundwater aquifers, greatly increasing their potential to negatively impact the environment (Whittemore, 1989; 1990). Natural sinkholes resulting from dissolution of the salt by localized leaching within natural flow systems that have been altered by structural features (such as faults and fractures) are not uncommon west of the main dissolution edge (Merriam and Mann, 1957).

Caprock and its characteristics are a very important component of any discussion concerning dissolution, subsidence, and formation of sinkholes. The Permian shales (Wellington and Ninnescah) that overlay the Hutchinson Salt Member are about 60 m thick in this area and are characterized as generally unstable when exposed to freshwater, being susceptible to sloughing and collapse (Swineford, 1955). These Permian shales tend to be red or reddish-brown and are commonly referred to as “red beds.” Permian red beds are extremely impermeable to water and have provided an excellent seal between the freshwaters of the Equus beds and the extremely water-soluble Hutchinson Salt Member. The modern-day expanse and mere presence of the Hutchinson Salt is due to the protection from freshwater provided by these red beds.

Isolating the basal contact of the Wellington Formation provides key insights into the general strength of roof rock expected if dissolution-mined salt jugs (salt jugs are the jug-shaped cavities or voids in the salt that form after salt has been dissolution mined in proximity to the wells) reach the top of the salt zone. Directly above the salt/shale contact is approximately 6 m-thick dark-colored shale with joint and bedding cracks filled with red halite (Walters, 1978). Once unsaturated brine comes in contact with this shale layer, these red halite-filled joints and bedding planes are rapidly leached, leaving an extremely structurally weak layer.

Irsik & Doll Grain Elevator: Wells 2A and 4B

Field Layout and Data Acquisition

To ensure the highest quality data, receivers were deployed during the day and train data were recorded at night when cultural and industrial noise was minimal to provide an optimum signal-to-noise ratio. Analysis of the previous seismic energy sources captured during passive recording at this site clearly indicated trains from a distance of 3 kilometers (km) or more away provided the best broad spectrum, low-frequency seismic energy (Miller, 2011). Because seismic energy with characteristics best suited for the purpose of this study may arrive when trains are at a distance greater than they can be detected by spotters, seismic records were recorded continuously during acquisition to ensure that optimum data was recorded.

Data were acquired over the course of the night on May 28, 2015. Two seismic lines were deployed directly over well 2A and near well 4B (Figure 3). Seismic receivers were single GeoSpace GS11D 4.5 Hz geophones spaced at 3 m intervals. The seismic lines totaled approximately 0.5 km in length. A 2-D grid of receivers to monitor passive seismic energy was

Figure 3. Aerial photo with GPS locations of seismic lines and wells in the study area.

deployed nearby. This monitoring grid consisted of 144 receivers spaced at 5 m intervals and was configured to form four concentric expanding squares with 10, 30, 50, and 70 m sides. Data were recorded during one night with a 300+ channel 24-bit Geometrics Geode distributed seismic system. Seismic records were 30 seconds (s) long with a 2 millisecond (ms) sampling interval. In total, 916 seismic records equivalent to 16.1 gigabytes (Gb) of data were recorded.

Processing and Analysis

Data were processed using algorithms developed at the Kansas Geological Survey (KGS). The passive method used for this study is well published and provides good quality results at a similar nearby site (Park et al., 2004; Ivanov et al., 2013). Continuous data acquisition records energy from nearby energy sources at various orientations with respect to the seismic line. The 2-D grid was deployed to evaluate and optimize source alignment with respect to each 1-D seismic line to effectively identify void roofs with elevated stress and an elevated risk of vertical migration.

For each line, the surface wave amplitudes recorded by the 2-D grid were plotted as phase velocity versus frequency for a range of azimuths from 0 to 360 degrees with respect to the seismic line to determine which record had the best broad band, low frequency source with an azimuth near parallel to the line (Figure 4). The seismogram with optimum source characteristics was selected and divided into the shortest groups of receivers ("spread length"), which provided dispersion patterns on phase velocity versus frequency plots with high amplitude

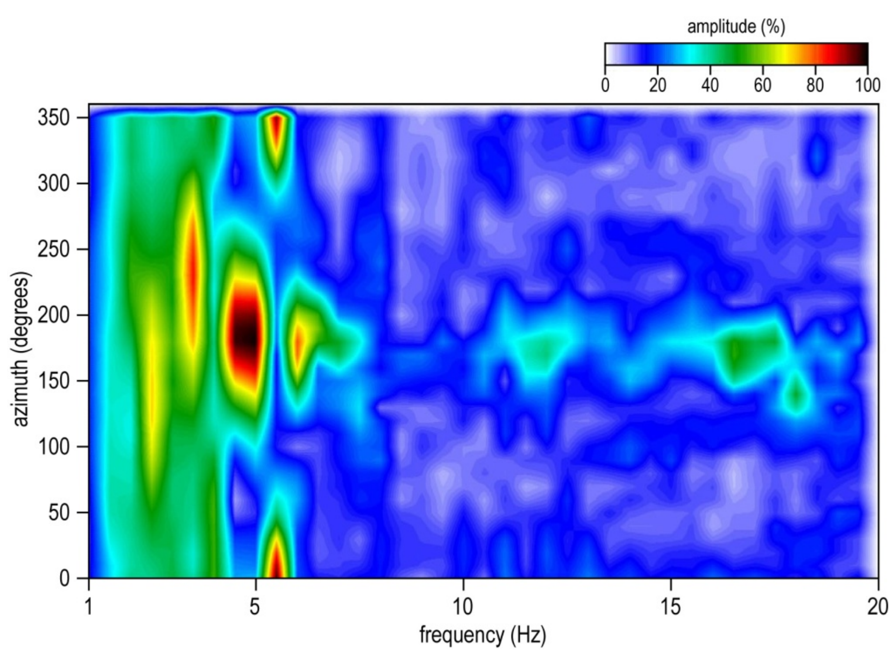

Figure 4. Azimuth plot indicating the direction of the dominant passive source energy (in degrees counter-clockwise from east). Here, the dominant passive source energy is centered on approximately 180°.

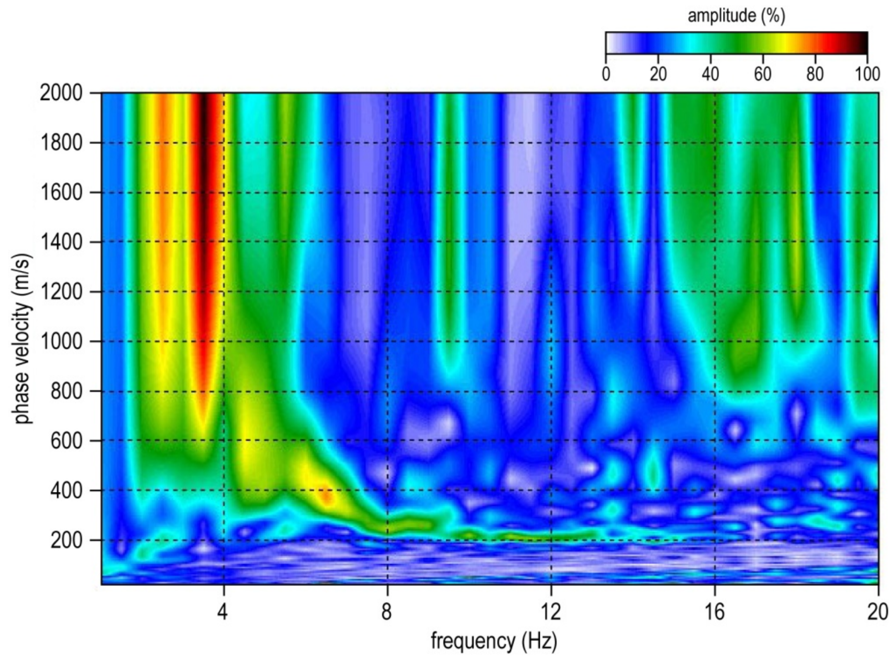

Figure 5. Dispersion pattern with high signal-to-noise ratio of the fundamental mode Rayleigh wave.

fundamental mode Rayleigh wave energy and minimal higher-order surface wave interference (Figure 5). Fundamental mode dispersion curves were picked and inverted to obtain a 2-D section of shear-wave velocity as a function of depth. The apparent velocity (v_{app}) is:

$$v_{app} = \frac{v_{act}}{(\cos\theta)} \tag{1}$$

where v_{act} is the actual seismic velocity and θ is the azimuth of the source with respect to the seismic line determined from the azimuth versus frequency plot. Thus, the increase in velocity (Δv) is:

$$\Delta v = \frac{1}{\cos\theta} - 1 \tag{2}$$

Equation 2 was used to calculate the increase in velocity due to the source azimuth for each line (Table 1).

Table 1. Directions of the passive seismic sources and the seismic lines (in degrees counterclockwise from east), the angle of the source with respect to the line (θ), and the percent increase in apparent velocity (Δv) attributable to oblique source orientations.

	source orientation	**line orientation**	***θ***	**Δv**
line 10	163°	160°	3°	< 1%
line 11	180°	175°	5°	< 1%

Results and Observations

Line 10 is oriented W-E and is centered on well 2A, located at station 10042. The velocity of the upper layer is approximately 175 meters per second (m/s) (Figure 6a), which is consistent with the shear-wave velocity of unconsolidated sediment. The velocity gradient at approximately 15 m depth is indicative of top of bedrock. An approximately 20% decrease in Vs relative to adjacent stations is observed at a depth of 35-50 m from stations 10038-10045, centered at the location of well 2A. An apparent increase in depth to bedrock is also observed within this range of stations. Dispersion patterns across the line are relatively consistent within the frequency range that corresponds to the top of bedrock (approximately 8 Hz). Although variability in the top of bedrock above well 2A cannot be ruled out, the apparent variability is low confidence and may be an artifact of the inversion process.

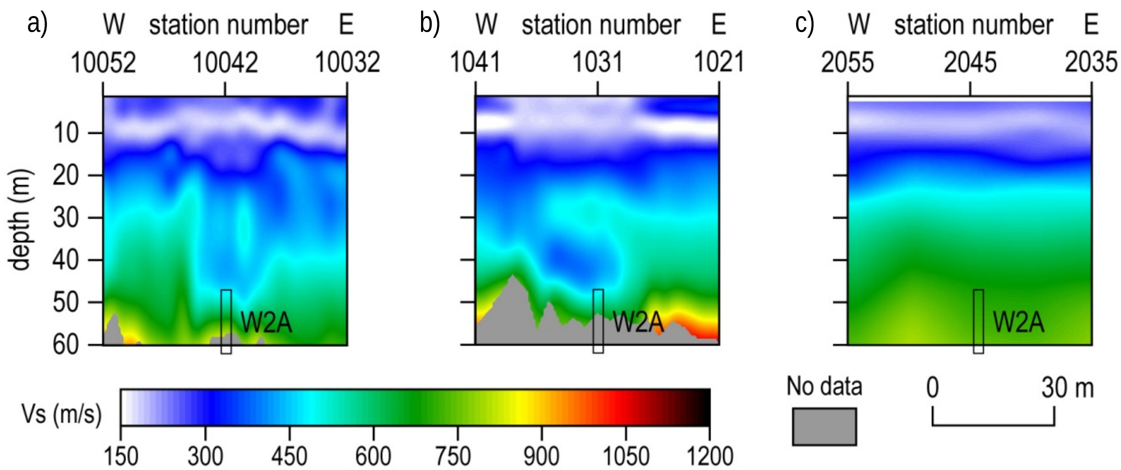

Figure 6. Shear-wave velocity profile of line 10 from (a) the present study, (b) November 2014, and (c) the baseline study in March 2013. Approximate well locations are indicated at the bottom of the profile.

Line 11 is oriented N-S and is centered on wells 2A and 4B, located at stations 11061 and 11038, respectively. The velocity of the upper layer is approximately 175 m/s (Figure 7a), which is consistent with the shear-wave velocity of unconsolidated sediment. The velocity gradient at 10-15 m is indicative of top of bedrock. An approximately 20% decrease in Vs is observed from stations 11054 to 11065, centered on well 2A, relative to bedrock velocity on the north and south ends of the line. A 15% decrease in Vs is observed between well 2A and 4B from stations 11040 to 11054.

Interpretation and Discussion

Well 2A

The apparent bedrock velocity over well 2A on line 10 is relatively consistent with the previous survey in November 2014. The dispersion pattern at well 2A (Figure 8a) is similar to the dispersion pattern at the equivalent location in the November 2014 survey (Figure 8b), suggesting that no significant change in material properties has occurred in the interim six months. The velocity inversion at 25 m depth observed in November 2014 (Figure 6b) is not observed in May 2015 (Figure 6a), which may indicate a reduction in strength and/or stress

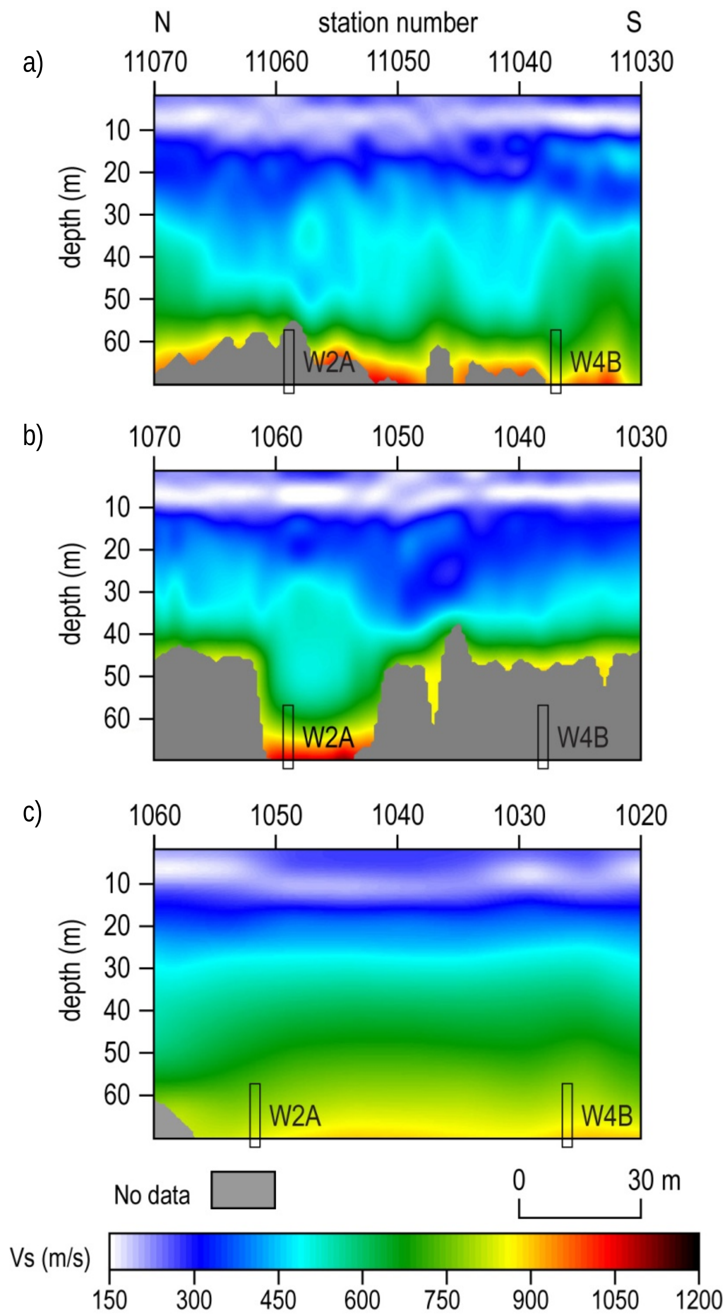

Figure 7. Shear-wave velocity profile of line 11 from (a) the present study, (b) November 2014, and (c) the baseline study in March 2013. Approximate well locations are indicated at the bottom of the profile.

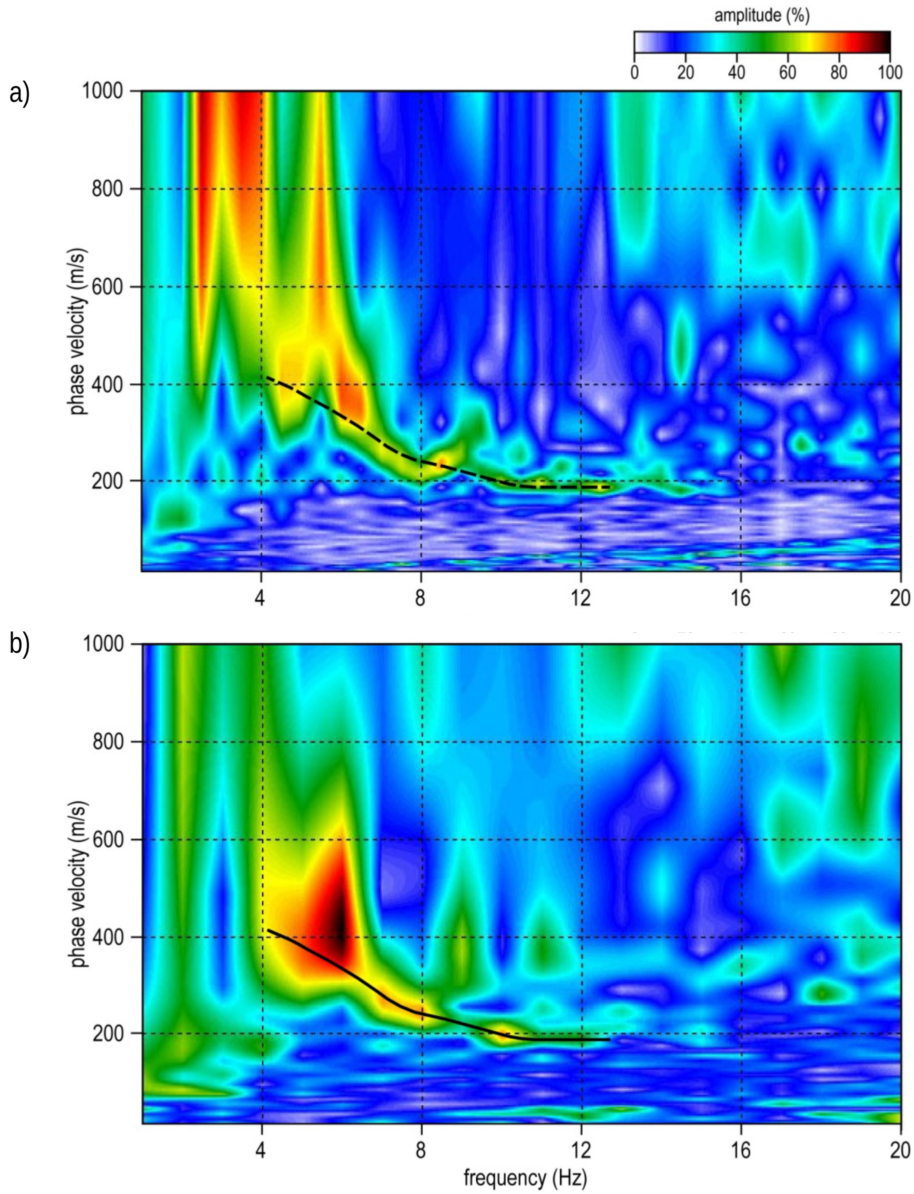

Figure 8. Dispersion patterns at the location of well 2A on line 10 from (a) the May 2015 survey and (b) the November 2014 survey. The dispersion curve from November 2014 (solid black line in (b)) is superimposed in (a).

extending downward from 25 m below ground surface. As described in the previous study, this does not necessarily imply that the roof of the void has physically collapsed. Instead, it may imply that some kind of physical change (possibly a macroscopic failure) has reduced strength in the overburden and/or redistributed stress within bedrock above the well, but at least 10 m below the bedrock surface. An essential observation and a key component to establishing a path forward at well 2A is the demonstrated, highly repeatable nature of this application of the passive surface wave method for measuring shear velocity (related to stress) and therefore the confidence that can be placed in the observed subsurface change in shear velocity that occurred between March 2013 and November 2014.

The apparent velocity above well 2A on line 11 (Figure 7a) is consistent with the velocities observed on line 10 (Figure 6a). Velocities at a depth of 30-40 m are approximately 10% lower at this location relative to November 2014 (Figure 7b). Dispersion patterns from line 11 at well 2A (Figure 9a) indicate that the surface wave phase velocity decreased in the time since the previous survey (Figure 9b). This suggests a change in material properties consistent with incremental failure and/or redistribution of stress in the interim 6 months, supporting the observations from line 10. The change in velocity is relatively small and appears to be limited to 25 m and deeper.

Well 4B

Slightly lower velocities are observed between stations 11040 and 11054 on line 11 (Figure 7a). The dominant surface wave energy transitions from a low-velocity trend at well 2A to a higher-velocity trend south of well 4B, and dispersion patterns between these wells represent surface wave energy from both velocity trends. In a transition zone with multiple surface wave dispersion patterns, the general practice is to select the trend with the dominant amplitude. Although both dispersion patterns have similar amplitudes between stations 11040 and 11054 (e.g., Figure 10), the lower-velocity trend was slightly more dominant and, therefore, inverted to produce the final 2-D Vs profile.

Due to the presence of two surface wave modes between wells 2A and 4B on line 11, confidence in the resulting bedrock velocities is low within this transition zone. The velocity trend south of well 4B is consistent with the baseline survey in March 2013 (Figure 7c), suggesting a stable stress regime south of this well. Although a reduction in bedrock velocity cannot be ruled out, it is possible that the low bedrock velocity between wells 2A and 4B is only apparently low due to superposition of the two dispersion patterns within the transition zone. Future monitoring for dynamic changes may be required to improve confidence in the interpretation.

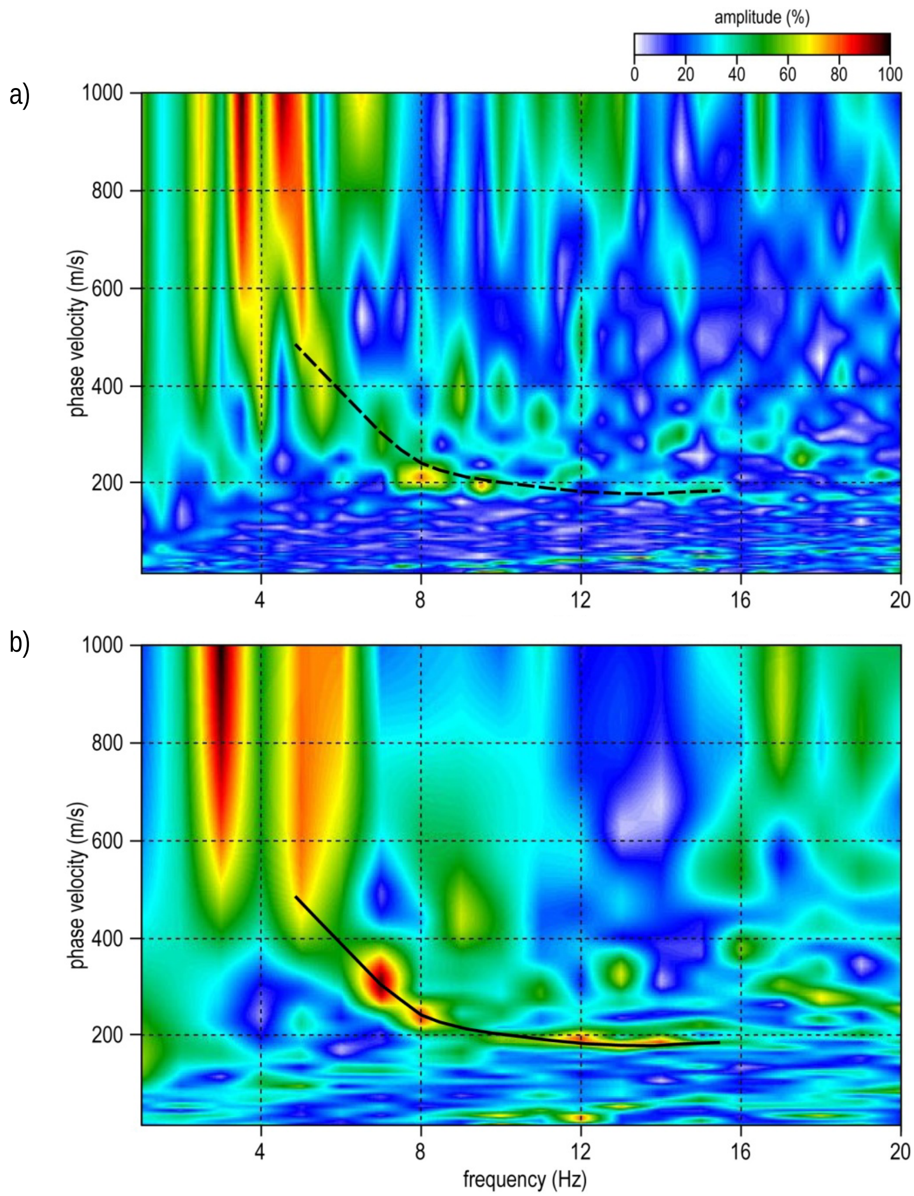

Figure 9. Dispersion patterns at the location of well 2A on line 11 from (a) the May 2015 survey and (b) the November 2014 survey. The dispersion curve from November 2014 (solid black line in (b)) is superimposed in (a).

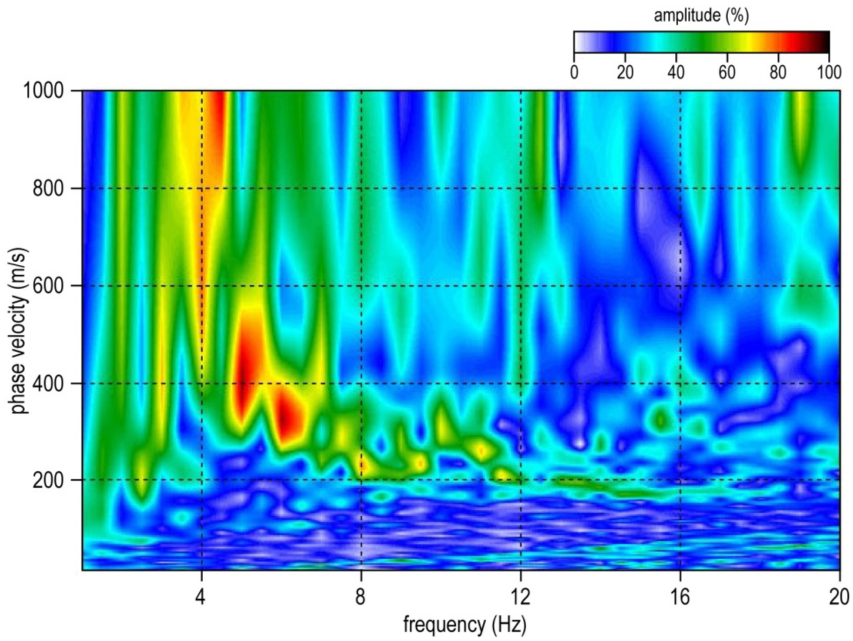

Figure 10. Dispersion patterns at the location of well 4B on line 11 from the May 2015 survey.

I&D Elevator, BNSF Railroad, and William Street: Wells 4A, 6B, 7A, 7B, 52, 53, 59, and 60

Data Acquisition, Processing, and Analysis

In general, data acquisition and processing followed the same general steps outlined in the previous section. Data were acquired over the course of the night on June 22, 2015. A total of three seismic lines were deployed over key wells (Figure 11). Seismic receivers were single GeoSpace GS-11D 4.5 Hz geophones spaced at 3 m intervals. A 2-D grid of receivers to monitor passive seismic energy was deployed nearby. The seismic lines totaled approximately 1 km in length. Data were recorded during one night with a 350+-channel 24-bit Geometrics Geode distributed seismic system. Seismic records were 30 seconds (s) long with a 2 millisecond (ms) sampling interval. In total, 586 seismic records equivalent to 15.1 gigabytes (GB) of data were recorded.

The processing flow consisted of the same general steps outlined in the previous section:

1. Evaluate seismic records and select optimal source energy, surface wave dispersion properties, and source azimuth (Table 2),
2. Generate dispersion curves, and
3. Invert for 2-D Vs profile

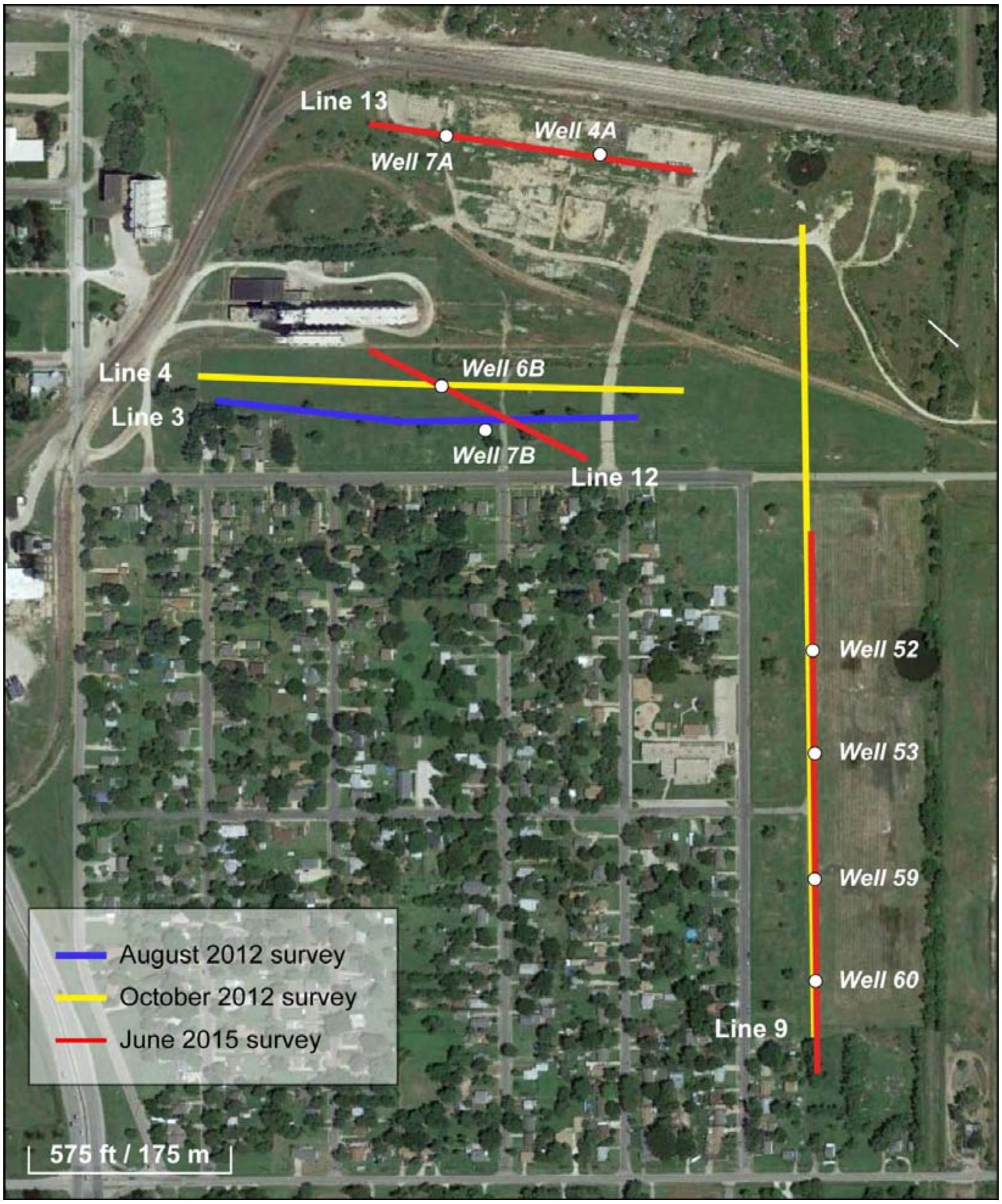

Figure 11. Aerial photo with GPS locations of seismic lines and wells in the study area.

Table 2. Directions of the passive seismic sources and the seismic lines (in degrees counterclockwise from east), the angle of the source with respect to the line (θ), and the percent increase in apparent velocity (Δv) attributable to oblique source orientations.

	source orientation	line orientation	θ	Δv
line 9	270°	290°	20°	6 %
line 12	159°	152°	7°	< 1%
line 13	180°	174°	6°	< 1%

Line 9 is oriented north-south along William Street. Top of bedrock is at a depth of approximately 10-15m (Figure 12a). Velocities observed in the June 2015 2-D Vs profile (Figure 12a) are as a whole ~20% lower than observed in October 2012 (Figure 12b) and the October 2012 results have a smoother appearance. Characteristics of the passive seismic sources are, by nature, variable and uncontrollable. The optimal source for one survey may have different characteristics than another survey. Therefore, each survey was processed using parameters that generate optimal dispersion patterns, which vary from survey to survey.

To improve the signal-to-noise ratio and coherency of dispersion curves in October 2012, multiple time windows were stacked to attenuate passive noise from azimuths that were not aligned with the seismic line. The tradeoff is some degree of smearing of dispersion patterns, which may result in a small systematic increase in apparent shear velocity. The ~20% greater velocities observed in October 2012 is likely, at least in part, a result of stacking time windows to improve signal-to-noise ratio. Additionally, due to the higher signal-to-noise ratio in June 2015, these data were processed with a shorter spread length, which, combined with denser spatial sampling, improved horizontal resolution.

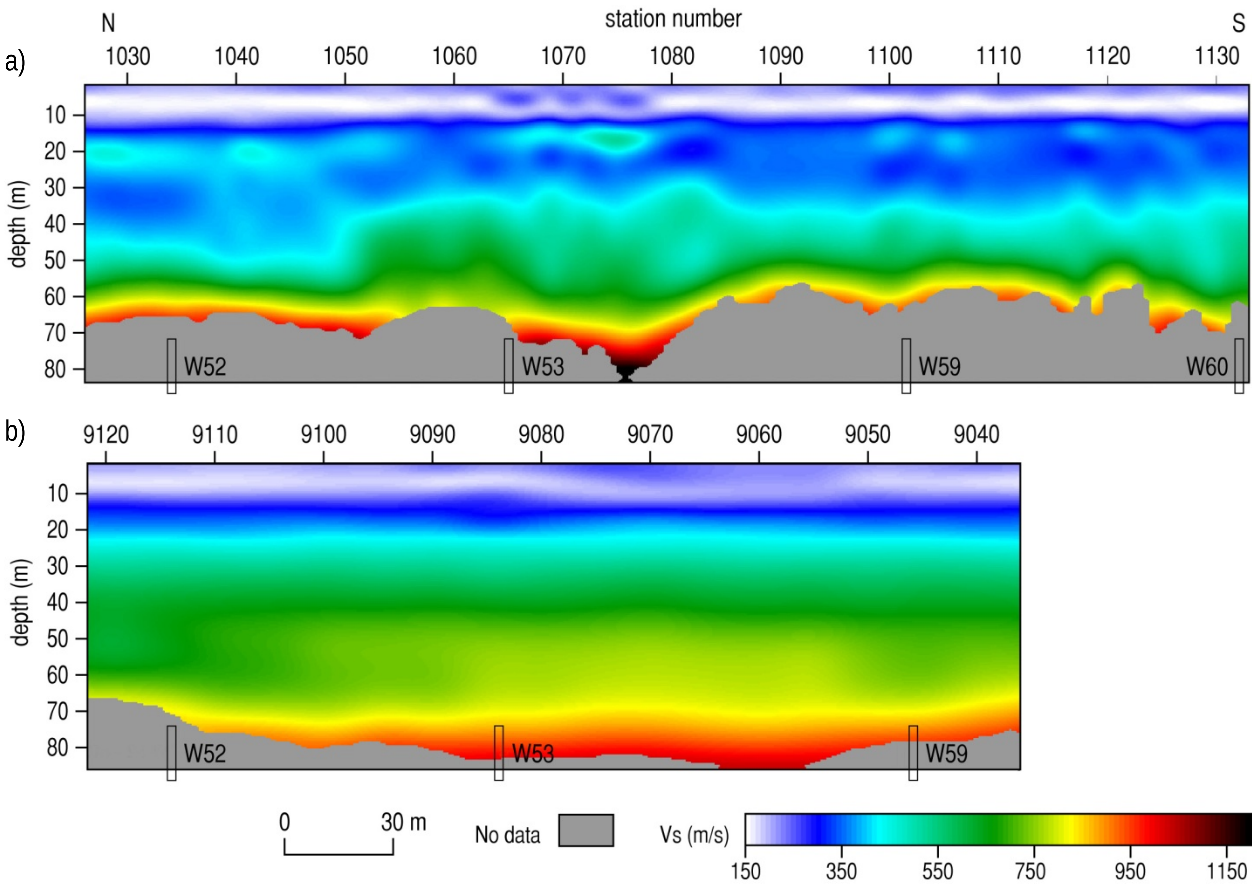

Figure 12. Shear-wave velocity profile of line 9 from (a) June 2015 and (b) October 2012. Approximate well locations are indicated at the bottom of the profiles.

The shear velocity profiles from line 9 of the current survey and the October 2012 study are generally consistent. Reduced bedrock velocity is observed at well 52 and elevated velocity is observed at well 53. Bedrock velocity around wells 59 and 60 represent natural geologic variation. For a more direct time-lapse comparison, dispersion patterns from October 2012 were regenerated using the same processing parameters used to generate the June 2015 dispersion patterns. Dispersion curves from June 2015 are superimposed on dispersion patterns from October 2012 to make relative comparisons at select locations on line 9.

Due to relatively poor resolution of the fundamental mode Rayleigh wave in October 2012 (Figure 13b), it is difficult to interpret the dispersion curve at well 52 with high confidence. However, the dominant signal from 4-7 Hz has a faster Rayleigh wave phase velocity than the fundamental mode dispersion curve observed at this location in 2015 (Figure 13). This suggests a real decrease in shear velocity at well 52 at depths of approximately 28 m and greater. The 2-D Vs profile from June 2015 indicates that the reduced velocity zone may extend as far as station 1051 (Figure 12a), 50 m south of well 52. Dispersion patterns at this location do suggest a slight reduction in velocity in the 2.5 years between surveys (Figure 14). At and near well 53, the dispersion patterns observed in June 2015 are consistent with the dispersion patterns from October 2012 (Figure 15), suggesting no significant changes in the subsurface at this well.

Line 12 is oriented approximately northwest-southeast and is located southeast of the Irsik & Doll grain elevator. Top of bedrock is at a depth of 10-15 m (Figure 16a). Similar to line 9, the data acquired in 2012 have slightly higher velocities (Figure 16b). In general, the velocity profile from June 2015 is consistent with the profiles acquired over these wells in 2012 and suggests natural geologic variation.

Line 13 is oriented approximately west-east and is located ~60 m south of the BNSF railroad. Top of bedrock is at a depth of approximately 10 m (Figure 17). Bedrock velocity is 450 m/s on average and in general represents natural geologic variation. Depth of surface-wave penetration is slightly reduced at well 7A with a ~2 m increase in the depth to bedrock. Dispersion patterns from stations 3022-3030 indicate a consistent velocity at 8 Hz (Figure 18), which corresponds to approximately the top of bedrock. Therefore, the apparent variability in the top of bedrock is not real and likely an artifact of inversion, related to a decrease in the surface-wave penetration within this zone. Dispersion patterns suggest that the decrease in depth of penetration may be the result of a localized decrease in velocity at stations 3022-3025.

Interpretation and Discussion

Wells 52 and 53

Due to variability in source characteristics, signal-to-noise ratio, and different processing parameters required for optimal dispersion analysis of line 9 along William Street, the Vs profiles cannot be directly compared. Dispersion patterns computed with the same parameters provide more accurate relative comparisons and insight into time-lapse changes in the shear strength of the subsurface. At well 52, dispersion patterns indicate reduced surface-wave phase velocity in June 2015 relative to October 2012 (Figures 13 and 14). This suggests a change in material properties consistent with continued incremental failure in the bedrock overlying the void at this well. This does not necessarily imply that the roof of the void has physically collapsed, but that some kind of failure may have reduced strength in the overburden and/or redistributed stress within bedrock. Changes in dispersion patterns at and near well 52 suggest that failure was limited to depths greater than 28 m, but may have a lateral extent up to 50 m

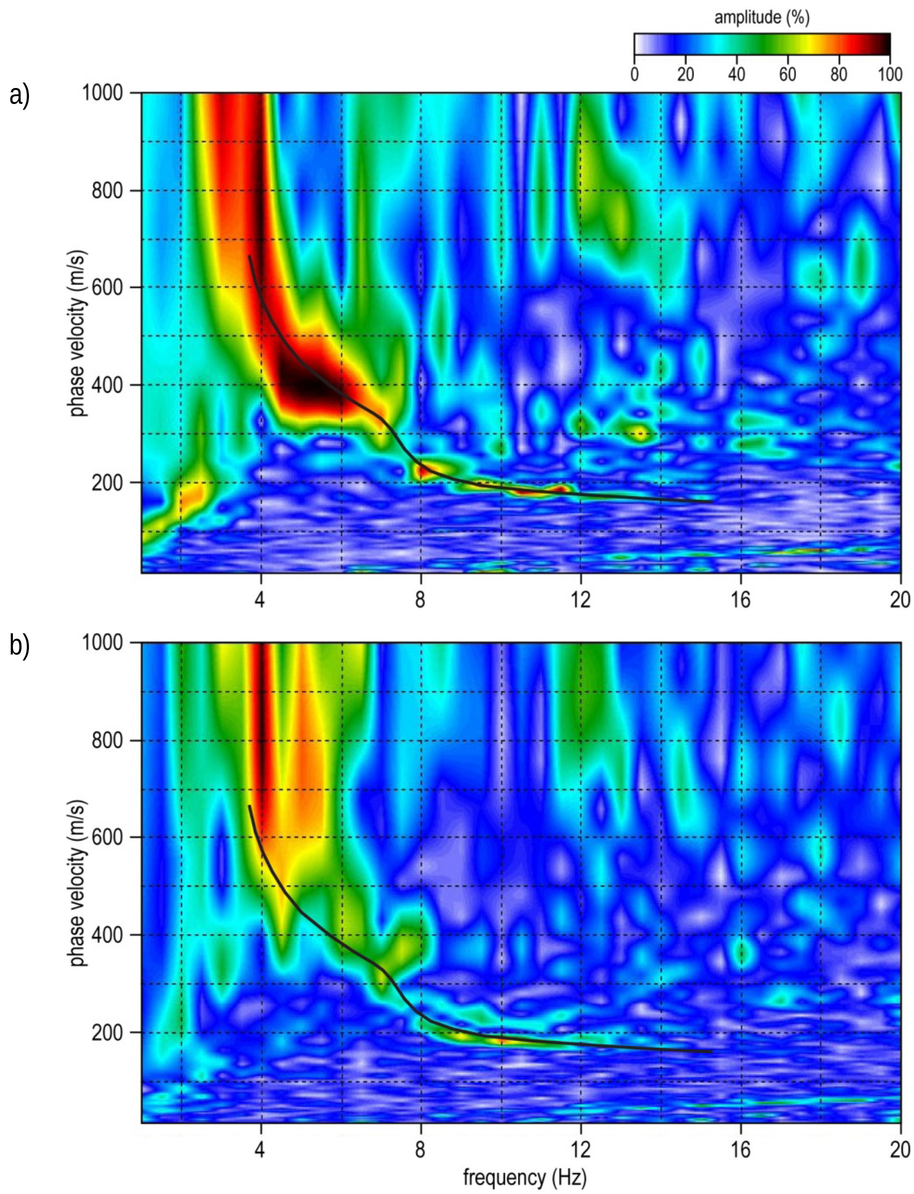

Figure 13. Dispersion patterns at well 52 from (a) June 2015 and (b) October 2012. Black line represents the June 2015 dispersion curve.

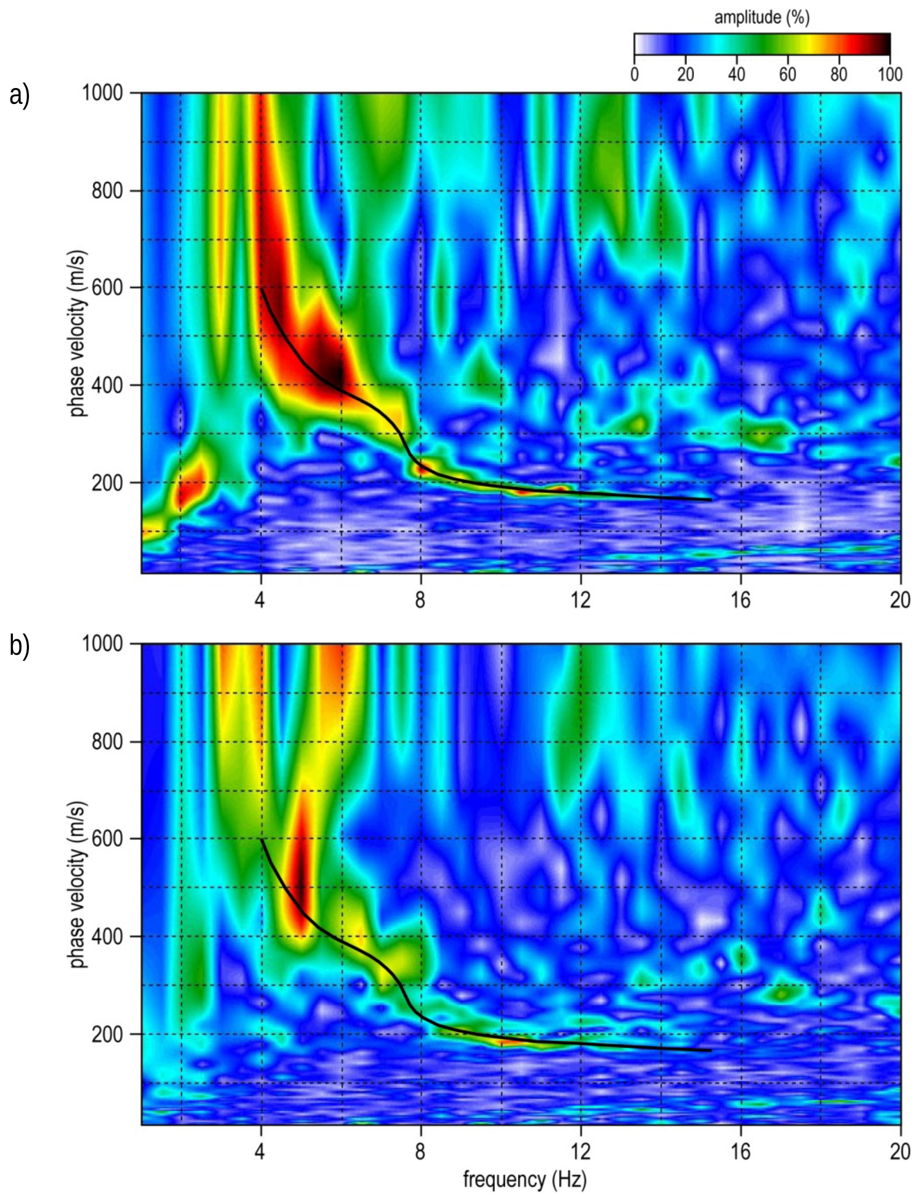

Figure 14. Dispersion patterns 48 m south of well 52 (a) at station 1052 in June 2015 and (b) the equivalent location in October 2012. Black line represents the June 2015 dispersion curve.

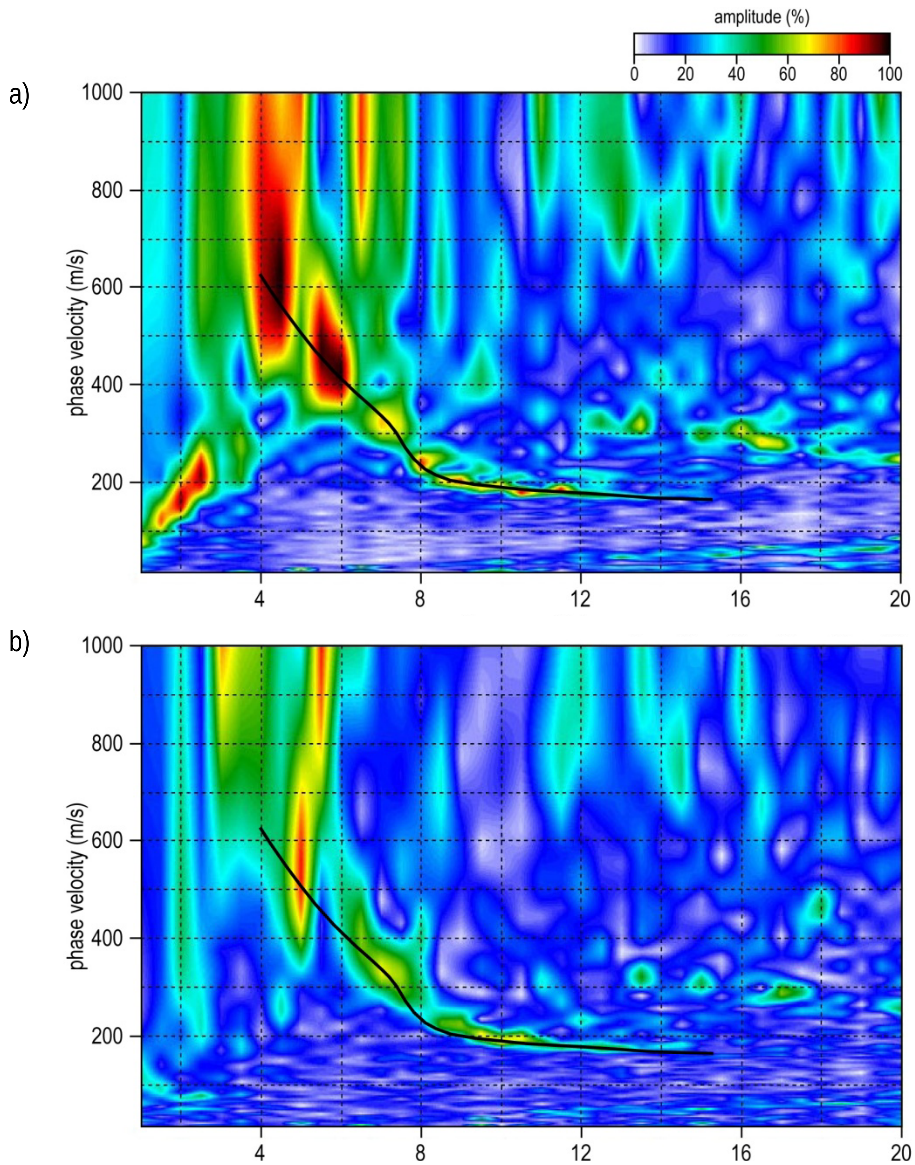

Figure 15. Dispersion patterns at well 53 from (a) June 2015 and (b) October 2012. Black line represents the June 2015 dispersion curve.

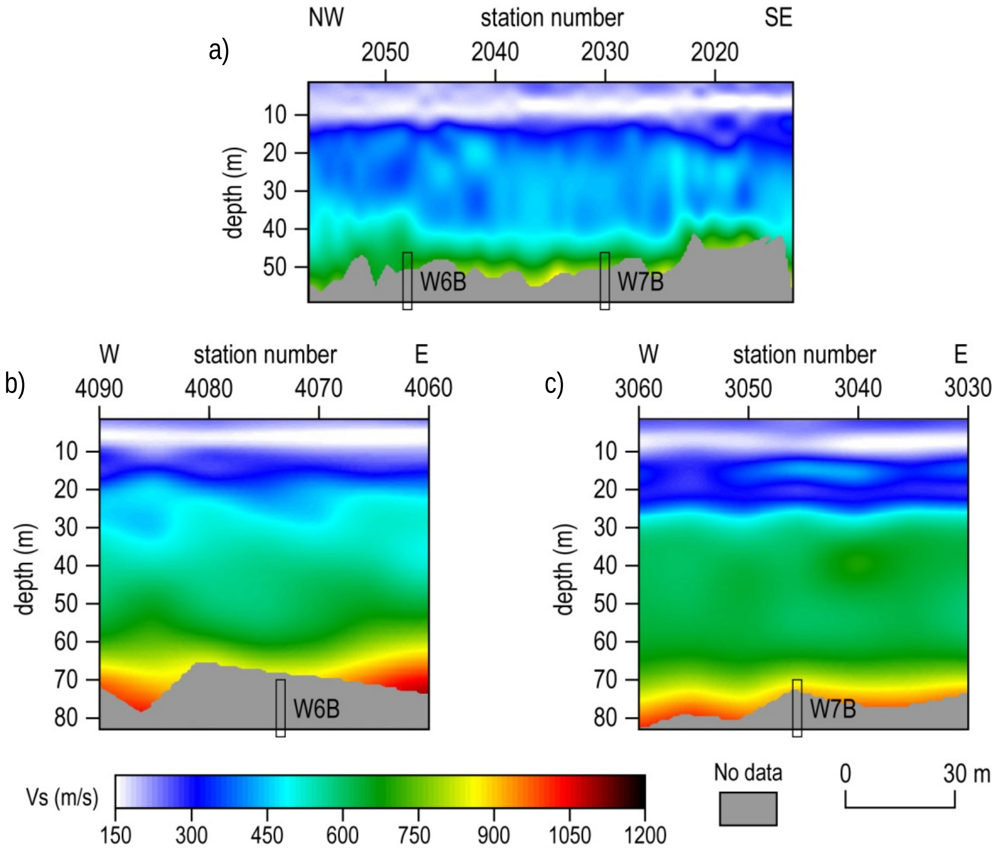

Figure 16. Shear-wave velocity profile of (a) line 12 from June 2015, (b) well 6B extracted from line 4 acquired in October 2012, and (c) well 7B extracted from line 3 acquired in August 2012. Approximate well locations are indicated at the bottom of the profiles.

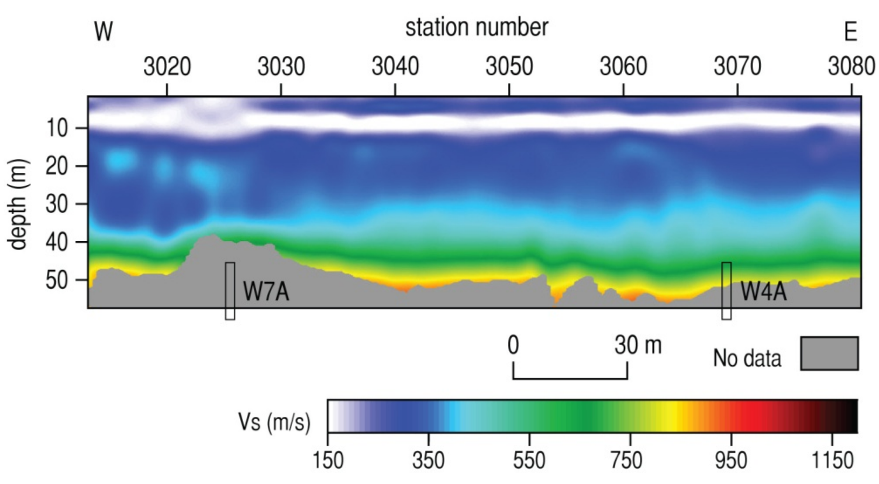

Figure 17. Shear-wave velocity profile from line 13 of the June 2015 survey. Approximate well locations are indicated at the bottom of the profiles.

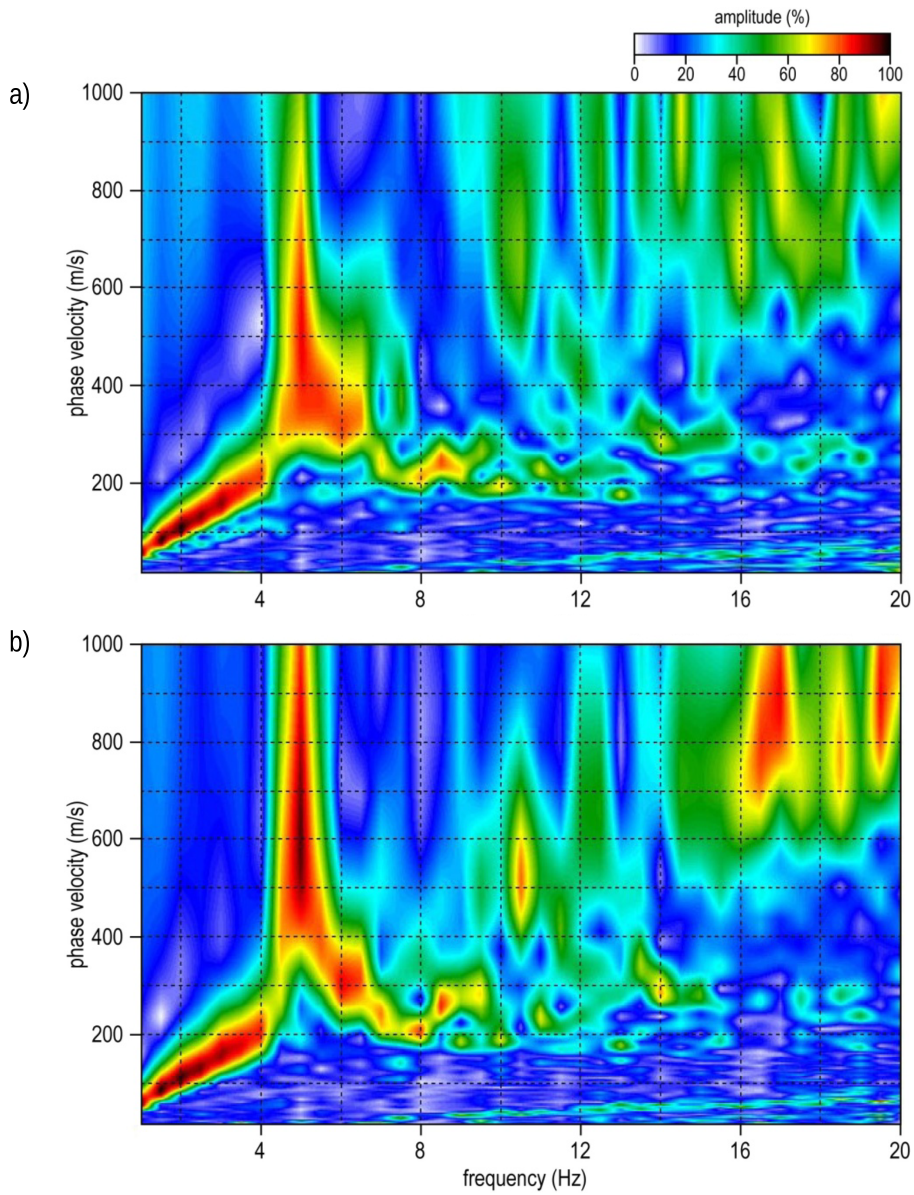

Figure 18. Dispersion pattern from line 13 at (a) well 7A and (b) station 3035.

from the well. However, the spread size used to generate optimal dispersion patterns was 150 m. This large spread size results in horizontal averaging; thus, the lateral extent of the reduced velocity zone is uncertain and may be smaller.

Elevated bedrock velocity at well 53 was observed in both October 2012 and June 2015 (Figure 12). Surface waves recorded at this well during the two surveys have very similar dispersion patterns (Figure 15), indicating that little if any change has occurred in the overall stress regime at this well at the time of the surveys. It is possible that periodic episodes of incremental failure and buildup of stress have occurred in the interim. Lack of significant observable change suggests that, although the bedrock above this void continues to exhibit elevated velocity, the void is likely relatively stable with low immediate risk of vertical migration.

Well 7A

A decrease in surface-wave penetration depth is observed near well 7A. Dispersion patterns suggest that the decrease in depth of penetration may be the result of a localized decrease in velocity at stations 3022-3025 (Figure 18a). However, the resolution of the fundamental mode dispersion pattern is lower at these locations relative to the rest of line 13 (e.g., Figure 18b); the true phase velocity may be higher and consistent with adjacent stations. Although variability in surface-wave penetration depth is not necessarily anomalous in and of itself, its coincidental location with well 7A suggests the possibility of reduced bedrock strength at a depth of 45 m. However, confidence in this interpretation is relatively low.

Wells 4A, 6B, 7B, 59, 60

Velocity profiles over these wells are representative of natural geologic variation and a normal stress regime.

Summary and Conclusions

Subtle drops in sub-bedrock velocity over wells 2A and 52 observed during the last couple years suggest some kind of incremental change has occurred above the old dissolution jugs that may have reduced strength and/or redistributed stress very locally in the overburden. This change in strength or stress appears to currently be confined to depths greater than 25 m—approximately 10 m beneath the top of bedrock. Dispersion patterns at well 2A in May 2015 are similar to those observed at this location in November 2014, suggesting that no significant change has occurred during the interim six months and that the observation is real. Reduced bedrock velocities between wells 2A and 4B are likely the result of interference of more than one surface wave mode, possibly an artifact associated with the abrupt transition from the dispersion pattern associated with lower bedrock velocity above well 2A and the dispersion pattern associated with a normal stress regime south of well 4B. Although the amplitude of the lower velocity dispersion pattern was slightly more dominant (suggesting reduced bedrock velocities between wells 2A and 4B), this area should not garner immediate concern, but should be an area of interest during future monitoring to establish whether more conclusive changes at well 4B are observed to improve confidence in our interpretation.

No significant time-lapse changes occurred since 2012 at wells 53, 59, 6B, or 7B. Bedrock velocity at well 53 was elevated in both June 2015 and October 2012. Dispersion patterns indicate no significant change in velocity, suggesting a stable void during the time since the previous survey. Velocity profiles acquired in June 2015 over wells 4A and 60 suggest natural geologic variation and a normal stress regime. A decrease in surface-wave penetration depths coincident with well 7A may be related to a localized zone of reduced velocity at depths of 45 m or greater. This interpretation is relatively low-confidence and reduced surface-wave penetration likely represents natural geologic variation.

Recommended Monitoring Program

Future monitoring of the subsurface around wells 2A and 4B near the Irsik & Doll grain elevator and 52 and 53 along William Street is advisable in lieu of invasive investigations, providing direct measurements and the potential for remediation, if necessary. For seismic monitoring, it is important to retain consistency in method and parameters. To ensure the highest quality data, train data should be recorded at night when cultural and industrial noise is minimal to provide optimum signal-to-noise ratio. Analysis of the previous seismic energy sources captured during passive recording at this site clearly indicated trains from a distance of 3 kilometers (km) or more provided the best broad-spectrum, low-frequency seismic energy (Miller, 2011). Because seismic energy with characteristics best suited for the purpose of this study may arrive when trains are at a distance greater than they can be detected by spotters, seismic records need to be recorded continuously during acquisition to ensure that optimum data are recorded.

Individually, each profile represents a snapshot in time that lacks any measure of the dynamics of void migration or change in time. From a single, static measurement it can be difficult to definitively establish void stability. Comparison of shear-wave velocity profiles collected over time (time lapse) provides insight into void dynamics and overburden stability not otherwise evident from a single survey. Additionally, multiple measurements provide the opportunity to quantitatively assess time lapse variability associated with non-geologic processes—changes in source/train characteristics, receiver coupling and positioning, seasonal conditions, etc. We recommend a repeat survey using a newly established grid of seismic lines to evaluate precision (range of measured values) at a given well location, identify additional wells that exhibit time lapse variability due to void dynamics, and monitor wells with suspected or possible stress/migration identified in the March 2015 survey. The proposed field layout is designed to incorporate all designated wells (not covered by the V&S Railroad monitoring lines) near the Irsik & Doll grain elevator, William Street, and south of the BNSF Railroad using optimal acquisition parameters (i.e., line lengths) determined during previous surveys.

Six seismic lines will be deployed during each monitoring survey directly over key wells, and a 2-D grid of receivers will be deployed nearby to monitor passive seismic energy (Figure 19). Four lines will be located directly over wells adjacent to the Irsik & Doll grain elevator (1B, 2A, 3B, 4B, 5B, 6B, and 7B), one line near William Street over wells 52, 53, 59, and 60, and one line south of the BNSF Railroad over wells 4A and 7A. Seismic receivers will likely be single GeoSpace GS11D 4.5 Hz geophones spaced at 3 m intervals. The seismic lines will total nearly 2 km in length. The 2-D monitoring grid will consist of 144 receivers spaced at 5 m intervals and configured to form four concentric expanding squares with 10-, 30-, 50-, and 70-m sides. Data will be recorded during four nights with a 600+-channel 24-bit Geometrics Geode distributed seismic system. Seismic records will be 30 s long with a 2 ms sampling interval. In total, approximately 3,000 seismic records, equivalent to 90 Gb of data, will be recorded.

Considering the changes in shear velocity observed between surveys, it would be advisable to perform repeat MASW surveys on an annual basis. If change is observed and appears to be accelerating or migrating vertically, then shorter lags between surveys would be advisable. In light of the history of the jugs in question and proximity to surface structures near wells 2A and 4B and known or suspected migration into the shale overburden near wells 52 and 53, an annual monitoring program continuing through 2018 should be considered before reevaluating sub-surface conditions. Future evaluations should focus on consistency between annual surveys and relative shear velocity over the jugs compared to native areas around the site.

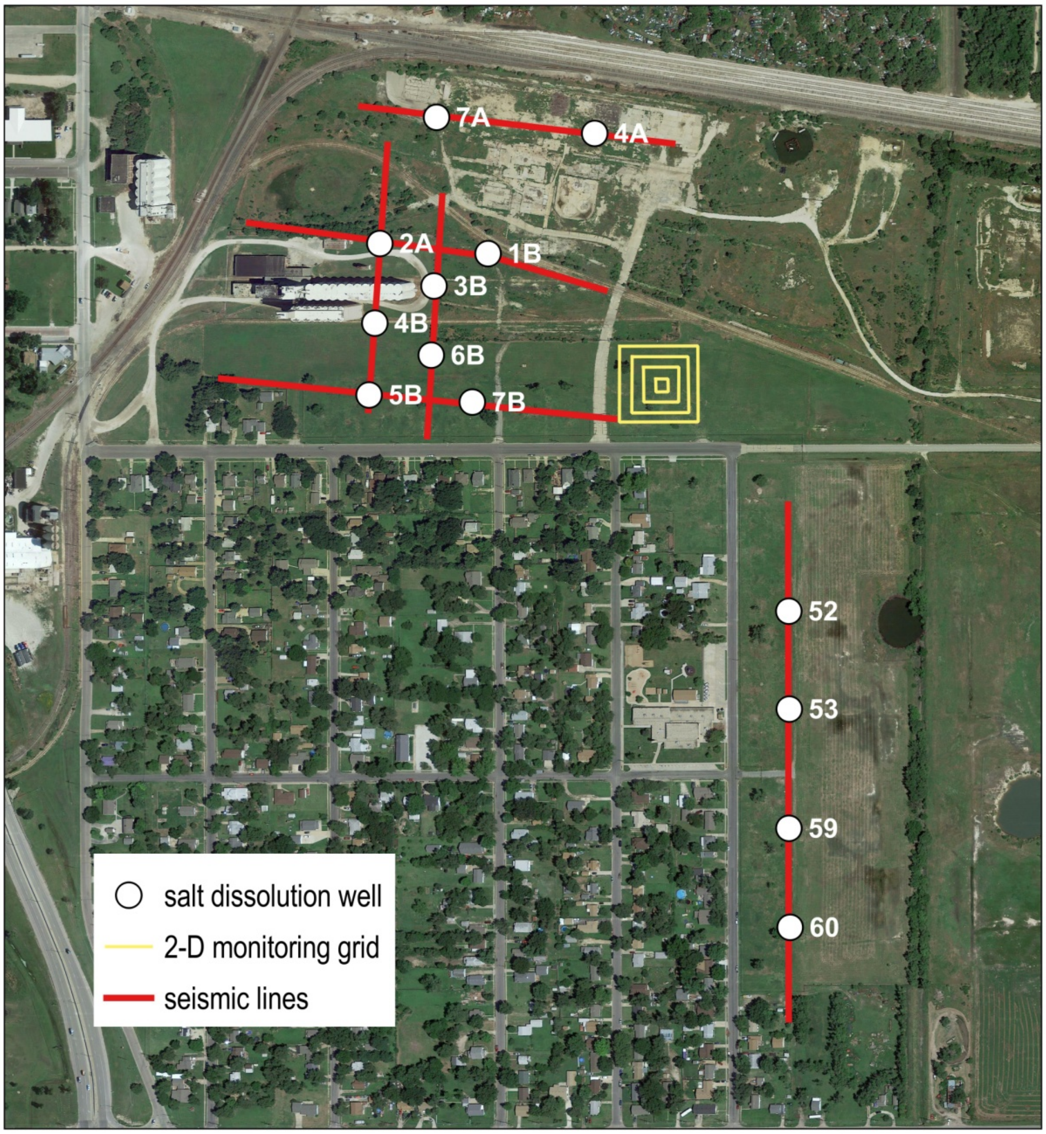

Figure 19. Aerial photo with locations of seismic lines and wells recommended for inclusion in the Irsik & Doll, BNSF Railroad, and William Street monitoring program.

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