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Seismic Shear-Wave Characterization of Sand and Gravel Groundwater Aquifers in Northern Illinois

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ABSTRACT

Groundwater is a nearly exclusive water resource, specifically for the communities which are part of the Chicago metropolitan area. However, water shortage is predicted for many communities in this region, and demand for locating and delineating groundwater is increasing to fulfill the water supply. Shallow sand and gravel aquifers within the glacial deposits of the area specifically are high volume aquifer and less stressed compare to deeper bedrock aquifer. Yet, these aquifers are poorly understood in terms of their extent and lateral variability. This study applied the shear-wave seismic reflection method to delineate the thickness, lateral extent, and internal variability of these aquifers. We acquired horizontally polarized shear-wave (SH-waves) reflection data along five profiles of a total length of 11 km using the land streamer technology in McHenry County in northern Illinois to delineate sand and gravel aquifers. As shear waves propagate through the rock matrix and less sensitive to the presence of water, information from nearby borings and water wells aided the interpretation of the acquired SH-wave seismic profiles. We delineated multiple sand and gravel units of potential aquifers of different thicknesses and lateral extent along with the seismic profiles. The relatively higher vertical and lateral resolution of the shear-waves reflection method and its insensitivity to water saturation or chemistry made it an ideal method to resolve sand and gravel units of potential aquifers within the complex geological environment if aided by water-well information.

Introduction

McHenry County is located in the northwest of Chicago Illinois. The population of McHenry County is growing very rapidly (Seipel et al., 2016; McKinney, 2011) and is expected to increase two-fold by 2050 (Northeastern Illinois Planning Commission, 2007). This rapid increase in population leads to a rise in the demand for water supply, which is a major concern for local planners. McHenry County exclusively depends on groundwater as its sole source of water supply (Carlock et al., 2016; Meyer et al., 2013). Shallow sand and gravel aquifers supply nearly 75% of the public water demand within the region (Lau et al., 2016; Meyer et al., 2013, Berg et al., 1999), whereas deep bedrock groundwater aquifers below glacial deposits provide the rest of the water supply (Berg et al., 1999). Sand and gravel aquifers within McHenry County have been mapped at a regional scale by Curry et al. (1997) and Thomason and Keefer (2013) and are the most productive aquifers in the study area (Meyer et al., 2013).

Detecting and delineating sand and gravel aquifers are traditionally accomplished by interpreting historic drilling records and sometimes drilling several new exploratory boreholes into the potential aquifers. Drilling boreholes provides high-quality data, but it is costly, and the data are spatially limited. Geophysical imaging has emerged as a more efficient alternative when constrained with boreholes information, which can better detect and delineate sand and gravel aquifers (Thomason et al., 2018). Among the most commonly used geophysical methods for sand and gravel aquifer exploration is electrical resistivity (ER), electromagnetic (EM), ground penetrating radar (GPR), and seismic reflection and refraction methods (Hanafy, 2013; Falgàs et al., 2011).

ER methods provide an indirect indication of groundwater presence in hard rock, coarse-grained and clay-free sediments (Muchingami et al., 2012; Ariyo and Banjo, 2008). However, using the method

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for delineating groundwater becomes very limited within clay-rich and fine-grained glacial deposits. The high moisture content of clay-rich glacial deposits attenuates the EM waves (Beres and Haeni, 1991) and limits the use of EM and GPR methods for groundwater investigation. Seismic methods have been used as an alternative to delineate potential groundwater aquifers (Ahokangas et al., 2020; Maries et al., 2017; Almholt et al., 2013) and image the subsurface with fine-grained deposits within the glacial sediments (Pugin et al., 2009; Guistiniani, 2008; Haines and Ellefson, 2006).

Seismic refraction is widely used to delineate free water table interface and model aquifer geometries within alluvium and glacial deposits (Gabr et al., 2012). However, this method is less effective when the subsurface is comprised of, for example, alternating low and high seismic-velocity layers as the best results with this method requires increasing seismic velocity with depth (Sjogren, 2013; Abd El-Aal and Mohamed, 2010; Pullan and Hunter, 1990). This low-velocity zone and hidden layer problem is a very common situation within glacial sediments (Ismail et al., 2014). Additionally, the seismic refraction method typically lacks the necessary vertical resolution to discern thin aquifers at the scale of meters (Bowling et al., 2007). In contrast, seismic reflection methods, including both primary (P) and shear (S) wave reflection methods, do not require seismic velocity to increase with depth and provide greater vertical resolution compared to the refraction method (Williams et al., 2005). Thus, these methods are widely used in detecting and delineating shallow groundwater aquifers (Sharpe et al., 2018; Pugin, 2020; Pugin et al., 2014, 2013, 2009; Haines and Ellefson, 2006).

The P-wave seismic reflection method is widely used for delineating broad, subsurface sediment architecture, but discerning thin saturated unconsolidated sediments using this method is relatively difficult (Harris, 2009). Gregory (1976) showed that P-wave velocity increases dramatically with increasing water saturation. In contrast, the S-wave velocity remains nearly constant; thus, P-wave energy is quickly attenuated in areas with very shallow groundwater tables. However, many studies have shown the value of using S-wave seismic reflection methods to image shallow, unconsolidated sediments (e.g., Thomason et al., 2018; Pugin et al., 2015; Cox et al., 2006; Woolery et al., 1999), indicating that S-wave reflection method may be more effective for increased seismic resolution compared to P-wave reflection method (e.g., Harris, 2009). We use high-resolution S-wave reflection methods to detect and delineate thin and shallow sand and gravel units that may comprise potential aquifers in McHenry County. The study includes extensive reprocessing of five horizontally polarized shear-wave (SH-waves) profiles and 12 boreholes and water wells (Fig. 1) to delineate potential groundwater aquifers. These profiles were previously processed and used along with other geophysical data to build a regional 3D geological model of McHenry County (Thomason and Keefer, 2013; Thomason et al., 2018).

Figure 1: A map of the study area in northern Illinois shows the acquired five seismic profiles and nearby boreholes and water wells.
Geological Setting

The shallow, unconsolidated sediments (up to 100 meters thick) within the study area are dominated by interstratified glacial sediments. Multiple glacial events deposited these sediments during the Quaternary Period throughout North America (Fig. 2). Older glacial sediments were often incrementally buried by younger sediments, which resulted in complex glacial sequences that often include alternating beds of clay-rich till, lake sediments, and glacial outwash.

**Figure 2: Schematic Cross-section (E-W) of Lithostratigraphic Unit of the study area (Thomason and Keefer, 2013; modified from Curry et al., 1997).**

A rigorous lithostratigraphic framework for the Quaternary deposits has been developed throughout the study area (Hansel and Johnson, 1996). The framework generally includes deposits that were classified into three sedimentary environments: subglacial (till), proglacial fluvial (outwash), and proglacial lacustrine (lake sediments). Lithostratigraphic till units define the relative chronology and distribution of multiple glacial advances in the area. These till units are often bounded vertically and laterally by outwash and lacustrine deposits, and they are typically the bounding aquitard units in aquifer systems. The outwash deposits in the study area are generally either exposed at the land surface or buried beneath till and lacustrine deposits at depths of up to 100 meters. The outwash deposits are generally less than 10 meters thick, but locally, their thicknesses can be up to 30 meters thick. These outwash deposits are the major sand and gravel aquifer units in the study area, and they are the target of our investigation.

Local Correlation of Test Borings

An example correlation between local test borings helps better understand the variability of lithostratigraphy in the study area and ultimately improve interpretations of the seismic profiles. We have correlated the lithologic and geophysical logs of two test borings in the area, which included continuous core samples to bedrock and continuous natural gamma-ray geophysical logs (Fig. 3). The correlation of test holes (HEBR-08-01 and HEBR-08-02, Fig. 3) shows typical local geologic variability that is often interpreted within the glacial sediments in the study area (Thomason and Keefer, 2013; Curry et al., 1997). In general, the regional lithostratigraphic units (e.g., Mason Group, Lemont Formation, and Tiskilwa Formation) are consistent, identifiable, and mappable. These geologic units are often stratigraphically and lithologically distinctive at any given location. However, given the complexity and glacial depositional systems, geologic units may often be locally absent or spatially variable on the spatial order of kilometers. For example, at site HEBR-08-01, the lithostratigraphy is distinctively marked by a thick succession of Tiskilwa Formation (20 meters thick) bounded by Henry Formation (Beverly and Ashmore Members).
Knowledge of the regional geologic framework helped interpret underlying sediments as Illinois Episode Pearl Formation (Thomason and Keefer, 2013). The general stratigraphy of HEBR-08-02 is similar, but the thicknesses of geologic units and the elevation of the bedrock surface are different. For example, the Lemont Formation is present in HEBR-08-02, but it is absent in HEBR-08-01. This is likely a function of local depositional/erosional processes during glaciation and the interpretation that the glacialation that deposited the Lemont Formation did not extend to the location of HEBR-08-01. Nonetheless, the regional geologic stratigraphic framework and expected variability are sufficiently consistent to confidently interpret our seismic profiles.

Figure 3: A correlation between Well HEBR-08-01 and HEBR-08-02 (Fig. 3(a)) with their locations shown in (Fig. 3(b)).

Method and Data Analysis

We utilized SH-wave reflection methods exclusively in this study because they provide higher resolution due to shorter wavelengths compared to the same frequency of P-wave (Dobecki, 1988), and the ability to image small-scale subsurface structures facilitates (Omnes, 1978). Also, the SH-wave component has minimum noise of other seismic modes as it does not convert into shear-wave vertical components (SV-wave) or P-wave at layers interfaces (Schuyler-Rossie, 1987). This study used SH-wave seismic-reflection data acquired along five profiles totaling 11 km length using the SH-wave land streamer system (Fig. 4).

The seismic receivers of this system include 24 horizontally polarized geophones of 14-Hz central frequency mounted on metal sleds and spaced at 0.75 m intervals. Two SH-wave geophones with opposite horizontal polarity were used at each station. Subtracting the outputs of the two-geophones at each station cancels out the unwanted P-wave arrivals and enhances the SH-wave arrivals (Haines & Ellefsen, 2006; Dobecki, 1988; Schuyler-Rossie, 1987). Impact source (i.e., sledgehammer) and horizontal geophones axis oriented perpendicular to the seismic line was used to generate SH-wave. The seismic source is a 2-kg sledgehammer that strikes the horizontal axel of a rolling metal cylinder that is in direct contact with the ground surface (Pugin, et. al., 2004). The source and receivers are moved simultaneously at 1.5 m intervals along the full length of each profile. Each shot was collected at a 0.5 ms sampling rate and 1.0 s of total recording length using the Geode engineering seismograph. Three seismic shot-gathers were acquired at each source station and vertically stacked to improve the seismic signal to noise ratio (SNR) in the recorded data. The data were acquired along asphalt roads for better coupling between the geophones and ground surface and to avoid near-surface energy absorption.
The SH-wave data were processed using Landmark ProMax Software. We assigned the geometry to the headers of acquired seismic data considering the locations of the source and receivers (Fig. 5a) and applied a true-amplitude recovery gain function to the shot gathers in order to compensate for the loss of signals’ amplitudes with depth caused by attenuation and wavefront spreading. This function uses a time raised to a power correction scheme \( g(t) = t^{\text{POWER}} \), where ‘t’ is the time, and ‘\text{POWER}’ is the time power constant) for amplitude adjustment to preserve the relative true amplitude of the signals (Fig. 5b).

Following the true amplitude recovery, a bandpass filter of 8-12-80-90 Hz was applied to eliminate unwanted frequency within the data (Fig. 5c). The next processing step focused on eliminating surface waves (Love waves) from the data. Removing the love wave arrivals from the filtered seismic records is essential because Love-waves obscure the SH-wave reflections at the shallow part of the SH-wave records, especially where the near-surface materials are highly compacted. Love waves are the most coherent type of noise for SH-wave methods, and their velocities are closer to the velocities of shear-waves. Therefore, Love waves arrive at nearly the same time as the direct and refracted SH-waves (Haines & Ellefsen, 2006). We used the surface-wave noise attenuation (SWNA) module within the ProMax processing Software to eliminate Love waves (Fig. 5d). SWNA uses a low-frequency array, which transforms data from time to frequency-space domain, performs frequency-dependent mix with the adjacent trace, then transforms the data back to the time-space domain (ProMAX, 1997). The SWNA requires selecting the cut off phase velocity and frequency of the targeted surface waves. Since surface waves in the acquired data attained different phase velocities (180 – 250 m/s) and frequencies (10 – 35 Hz), we applied SWNA multiple times with different velocity and frequency values to eliminate most of the surface wave noise from the data (Fig. 5d). SWNA is applied to the data in common-source domain after splitting it into panels; each panel has a panel size or number of traces, which we selected at seven traces. Traces from adjacent panels are mixed while edge traces are eliminated (ProMAX, 1997). The panels are overlapped and merged after data transformed back from frequency domain to time-domain. Trace scaling was applied before the application of SWNA to better suppress the noise level and enhance...
the SH-wave reflection events. Following the SWNA, a predictive deconvolution operator length was determined and applied to the data to eliminate multiples and increase the temporal resolution. (Sablon et al., 2011) (Fig. 5e). Although the data were acquired along relatively flat asphalt roads, elevation correction was applied as the next step to correct for long-wavelength elevation change.

Figure 5: Shear-wave seismic gather from profile 812 showing applied processing steps. (Fig. 5(a)) Raw shot gathers, (Fig. 5(b)) with true amplitude recovery, (Fig. 5(c)) with a bandpass filter, (Fig. 5(d)) with Surface wave noise attenuation, (Fig. 5(e)) with Predictive deconvolution.

Following the elevation correction, a semblance-based velocity analysis was conducted to estimate optimum-stacking velocity functions. The functions will be used as input to the pre-stack time migration process and then convert the stacked seismic profiles from time to depth. The data were migrated using Kirchhoff pre-stack time migration (PSTM). The application of the PSTM to the high-resolution seismic data has recently become a common processing practice and proved to significantly improve the signal-to-noise ratio of seismic data (Matsushima et al., 2003; Pasasa et al., 1998). In preparation of PSTM, stacking-velocity functions were smoothed along the length of the seismic profiles, and elevation statics were calculated and applied. We applied Kirchhoff PSTM on the data in the CMP domain and the migrated output was stacked to generate final stacking profiles. A post-stack frequency-space (F-X) deconvolution using Wiener Levinson type filter (Giustiniani et al., 2008) was applied to further improve the coherency of the reflections, eliminate remnant random noise, and increase the lateral continuity of the signal.

Estimating the smallest vertical resolution of the seismic profiles is necessary to understand the limits of interpreting thin aquifer units in our study. Widess (1973) and Yilmaz (2001) have estimated the vertical resolution of seismic data to be a quarter of the seismic wavelength (λ). In our study, an estimated peak frequency of 50 Hz was determined along with an average SH-wave seismic velocity (Vs) ranging between 260 and 450 m/s within the sediments. This resulted in an estimated vertical seismic resolution limit ranging between 1.3 to 2.6 m. Thus, relatively thin lithological units, similar to those recorded in the test borings, may be resolvable.

Given the estimated vertical resolution, the migrated SH-wave reflection profiles were converted from time to depth using the smoothed velocity field input to PSTM within the ProMax time-to-depth conversion module. The migrated and depth-converted SH-wave profiles were interpreted to lithological units within the IHS Kingdom software with the aid of boreholes and waterhainers-well information. The seismic profiles in SEGY format were loaded into the IHS Kingdom software using the coordinates of each seismic trace stored in the seismic file headers. The control wells were also loaded into the software and displayed at their location along the seismic profiles. Horizon picking started at the locations of the

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control wells and were completed manually along each seismic profile. The picked seismic horizons were correlated to the control wells and interpreted as interfaces between lithological units.

**Data Interpretation**

Five seismic profiles were interpreted separately because the geologic framework at each profile location was relatively unique. We selected the locations of the seismic profiles where we thought the regional geology suggested that shallow sand and gravel aquifers were likely present. Accordingly, we acquired seismic profiles to investigate the local geology in those sites. Twelve water wells/test borings located along the seismic profiles improved their interpretation. Test borings were drilled by the ISGS and included detailed descriptions of lithology and continuous gamma-ray and electrical-conductivity logs. Electrical conductivity logs provide information about clay content and water contents in the geologic units (Schulmeister et al., 2003). Gamma-ray logs also provide information that is, generally, a proxy for clay content, where gamma counts are inversely proportional to grain size (Nazeer et al., 2016). Thus gamma-ray logs help interpret lithologic variability between and within geologic formations. The remaining geologic data were residential water wells that contained reasonable descriptions of the lithology.

**Seismic profile 812**

Profile 812 is 2.6 km long and contains 3441 CMP traces (Figure 6a). Five water wells located along the profile have aided the interpretation of this profile (Figure 6b) identifying several distinct seismic units. A strong reflector at a depth of ~18 m marks the interface between the uppermost unit (interpreted as surficial Unit A) and the underlying unit that exhibits sub-horizon layering, interpreted as stratified clay (unit B). This contact is consistently observed in the water-well records (Fig. 6b). A local incised channel was identified at the northeastern part of the profile between 1750 m and 2250 m. The horizontal seismic reflections inside the channel suggest that sediments were deposited as flat strata filling the channel (Fig. 6b).

Seismic unit C underlies the stratified upper layer and exhibits flat-lying and weak reflections along the length of the profile. This unit is interpreted as glacial outwash deposits of sand, silt, and gravel with a thickness of up to 30 m. The low amplitude and less coherent reflections within this unit are most likely due to the high dissipation of shear-wave energy caused by coarse-grained and gravel deposits as indicated by the lithological interpretation of Thomason and Keefer (2013). A moderate to weak, discontinuous reflector exists within the sand and gravel aquifer at an average depth of ~30 m from the surface (marked by a dotted line), which may correspond to a change in the grain size or compaction of the sand and gravel deposits at this depth. Such change is not indicated by the available borings. The bedrock surface is recognized as a strong, coherent, and continuous reflector at ~40 m depth (unit E) underlyng the interpreted sand and gravel aquifer.

**Figure 6.** The processed seismic profile 812 (Fig. 6(a)) and the interpreted seismic profile (Fig. 6(b)) delineating sand and gravel unit of a relatively thick groundwater aquifer.
Seismic profile 810

Profile 810 extends 1.5 km and contains 1979 CMP traces. Only one water well is located along with this profile. This seismic profile was previously processed and interpreted in Thomason et al., 2018. Our reprocessing and interpretation of the profile shows a flat-lying strong reflector at ~ 5 m depth is identified as the bottom of an uppermost surficial unit ‘A’ characterized by thin sub-horizon reflections (Fig. 7b). This unit attains a varying thickness (5 – 15 m) and is interpreted as surficial material and stratified clay deposits. A strong and coherent reflector appears at ~ 15 m depth at the most western part of profile 810 sloping eastward marking the eastern side of a relatively wide incised channel (Fig. 7b). The western side of the channel was not imaged by the seismic profile 810, which suggests that the channel is likely > 1 km wide. The relatively thick channel fill (60 - 65 m) are characterized as multiple seismic units marks as units B through D with flat-lying and weak seismic reflections. This channel fill exhibits low amplitude and less coherent reflections and is interpreted as flat layering deposition of sand and gravel glacial outwash. A weak to moderate and discontinuous reflector appeared within the unit at an average depth of 30 m, which may be caused by a change in grain size or lithological composition at that depth (Unit C).

A strong, flat-lying, and coherent seismic unit (Unit E) underlying the interpreted sand and gravel unit is recognized at the western part of the profile up to a depth of 40 m. This unit exhibits sub-horizon layering and is interpreted as stratified clay as indicated by the water well (Fig. 7b). The unit has a maximum thickness of 20 m at the west end of profile 810 and thins out towards the interpreted incised channel.

The top of the bedrock (unit G) is identified by a relatively moderate seismic reflector at a depth of 40 m underlying the stratified clay and fine sand units (units E and F) to a weak, discontinuous, and undulated reflector showing at 70 m depth below the sand and gravel channel fill (units B to D). The low amplitude of the bedrock reflector along this line may be due to several aspects of shear-wave energy propagation. The thick and dense glacial till deposits on top of the bedrock (unit E) reflect most of the shear-wave energy and thick sand and gravel deposits attenuate the penetrating shear waves leaving less energy to be reflected off the bedrock surface. Using a lightweight shear wave source in the data acquisition can also limit the shear-wave imaging of the relatively deep bedrock.

Figure 7. Acquired seismic profile 810 (Fig. 7(a)) and the interpreted seismic profile 810 with a water well (Fig. 7(b)) showing thick sand and gravel aquifer.
Seismic profile 808

Profile 808 is 1.1 km long and contains 1450 CMP traces. Test holes and water-well records were unavailable along with this profile, but we relied on the seismic signature of the different glacial sediments interpreted in the other seismic profiles in the study area as well as our understanding of the geological setting of the area to make reliable interpretation of this profile (Curry et al., 1997, Thomason and Keefer, 2013, Thomason et al., 2018). The upper 15-20 m of profile 808 (Fig. 8b) shows a series of strong and nearly horizontal seismic reflectors, interpreted as stratified flat-lying silt and clay layers (units A-C). This layer caps a wide incised channel marked by a strong and coherent seismic reflector that extends along the entire length of the profile and cuts through the glacial deposits down to the bedrock surface between distance marks of 440 and 700 m (Fig. 8b).

The channel fill deposits, which attains a maximum thickness of 40 m at the center of the channel, are characterized as two flat-lying seismic units with relatively weak seismic reflections, interpreted as an unconsolidated sand layer (unit D) overlying coarse-grained sand and gravel deposits filling the base of the channel (unit E). The sand and gravel channel fill deposits have a great potential to be a major groundwater aquifer in this area. The top of the bedrock (unit G) was imaged as a strong seismic reflector only at the base of the channel between distance marks of 440-700 m mainly due to the significant seismic impedance contrast between the bedrock and overlying coarse sand and gravel channel fill deposits. Away from the base of the channel, the bedrock reflections have dramatically faded mainly due to the lack of seismic impedance contrast between bedrock and overlying dense till deposits (Thomason et al., 2018) (unit F), and also because the latter have reflected most of the seismic energy before reaching the bedrock surface.

Figure 8. Acquired seismic profile 808 without interpretation (Fig. 8(a)) and with interpretations superimposed (Fig. 8(b)).

The seismic profile 811

Figure 9a shows a 2 km long seismic profile extending west-east and contains 2700 CMP traces. The two water wells located along the profile were used to aid the interpretation of this seismic profile. A moderate and coherent flat-lying seismic reflector appears at ~ 8 m depth marks the bottom of the uppermost unit (unit A), interpreted as the surficial unit with clay deposits as indicated by the nearest water well (Fig. 9b). A strong, coherent, and undulated seismic reflector appears at ~ 15 m depth marks the bottom of three undulated incised features (Unit B1 to B3), interpreted as stratified hard clay and dense glacial deposits. These incised features B1 to B3 show varying fill thickness of 20 m, 15 m, and 10 m, respectively at the western part of the profile and thin out gradually towards the east. An incised

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channel (B4) is identified in the eastern part of the profile between distance marks of 1150 m and 1450 m. The seismic signature of the channel fill indicates flat layered deposits, interpreted as a sequence of very soft soil, probably lake sediments, as it caused significant seismic energy attenuation.

A low amplitude seismic unit (C) has been identified underlying the stratified hard clay unit. This unit is interpreted as the glacial outwash deposits of sand, silt, and gravel with a maximum thickness of ~ 20 m. The low amplitude reflections within this unit could be due to the hard glacial clay deposits overlying the unit causing higher energy reflection to the surface and lower energy penetration further deeper. A moderate to weak undulated reflector at a depth of ~ 25 m marks the top of another low amplitude seismic unit (Unit D), interpreted as the coarse-grained sand and gravel unit with a thickness of ~ 10 m along with the profile. Available borehole data supports the sand gravel unit interpretation and identified water table in the wells indicates both sand and gravel units (units C and D) could be interpreted as potential groundwater aquifer. A strong, coherent, and continuous reflector identified at a depth of ~ 35 m indicates the presence of bedrock unit (Unit E) underlying below the sand and gravel aquifer unit.

**Figure 9.** Acquired seismic profile 811 without interpretation (Fig. 9(a)) and the interpreted seismic profile (Fig. 9(b)) showing sand and gravel fill deposits.

The seismic profile 809

Figure 10a shows a 3.1 km long west-east seismic profile 809 containing 4000 CMP traces. Four water wells located along the profile have aided the interpretation to resolve potential aquifers (Fig. 10b). A strong, flat-lying seismic reflector at ~ 10 m depth marks the bottom of the uppermost thin surficial unit (A) interpreted as thin clay deposits as observed in the boreholes along with the profile. A relatively thick (30-35 m) seismic unit (B) underlies the upper clay unit and shows low amplitude reflections along the profile. Unit (B) is interpreted as glacial outwash sand and gravel deposits as indicated in the boreholes. The low amplitude reflection of unit (B) could most likely cause by higher energy dissipation from the loosely consolidated, coarse-grained sand and gravel of this unit. Available water table information in all the wells located along the profile falls within this seismically interpreted unit which led us to interpret it as an aquifer within the area. A strong and coherent seismic reflector marks the interface between the bottom of this sand and gravel aquifer unit and an underlying clayey till unit (C) as observed in the boreholes. No seismic reflectors were identified within or below the clayey till deposits unit (C), thus unlike other profiles, the bedrock surface could not be identified confidently in this profile.

**Figure 10.** Seismic profile 809 (a) and the interpreted seismic profile (b) showing water well locations along the profile.
Discussion and conclusions

Several studies have used single or multiple geophysical methods to delineate sand and gravel aquifers in glacial deposits, some of them were successful, and either has met significant challenges. Pugin et al., 2015 used integrated surveys, including P-wave and SH-wave reflection methods, and observed that the P-wave method permits overall seismic facies delineation, but a lesser detailed seismic section compares to SH-wave. However, SH-wave faced difficulties to penetrate deeper and showed higher energy attenuation where thick till deposits were present. Thomason et al., 2018 integrated Electrical Resistivity besides the Seismic Shear-wave reflection method to characterize glacial sediments. However, the Electrical resistivity method was largely ineffective to comprehend the channel morphology and vaguely resolved the internal subsurface features interpreted by the Seismic SH-wave method.

Shear-waves propagation is less sensitive to the presence of water, water saturation, or water chemistry compared to p-waves (Haines and Ellefsen, 2010; Dobecki, 1988), which made the method far from being applied in hydrogeological exploration. However, some groundwater aquifers are present in very complex subsurface settings with relatively variable lateral and vertical distribution, which makes their delineation with surface geophysical methods is a great challenge. For example, delineating the relatively thin and shallow sand and gravel aquifers within the glacial deposits using the electrical and electromagnetic methods is a great challenge (Hanafy, 2013). The P-wave surveys may produce a strong reflection of the saturated zones that mask further deeper events (Steeples et al., 1997). P-wave propagation is largely influenced by water saturation (Gregory, 1976), has a lower vertical resolution, and may not provide a better image of much shallower subsurface as well as the image of bedrock interface compare to SH-wave. On the contrary, shear-waves are characterized by shorter wavelengths and high resolution, which provide better understandings of the lithology and the pore-fluid distribution, especially for the near-surface area compare to P-wave data alone (Carr et al., 1998).

Applying the shear-waves reflection method in this study enabled to delineate deposits of potential sand and gravel aquifers in shallow depth with their extent, thickness, and lateral lithological variability within the glacial deposits. For instance, the incised features identified in the seismic profile 811 (Fig. 9) at less than 35 m depth represent the ability of the SH-wave reflection method to provide detailed information of the architecture and stratigraphy of the overlying sediments on top of the bedrock even at very shallow depth.

Most of the seismic profiles presented in this study showed distinct valley or channel cut features in shallow depth including seismic profiles 812, 810, 808, and 811 (Figs. 6, 7, 8, and 9, respectively). The distribution and depositional pattern of the filling of these delineated cut-and-fill valleys or channels features in this study seemed to be nearly identical as the base of the valley was filled by coarse-grained
sand and gravel units underlying a thin clay/tell layer. The valley fill is capped by surficial topsoil deposits (e.g., profile 810, Figure 7; and profile 808, Figure 8). The resolved channel morphology and stratigraphic boundaries by the Seismic SH-wave reflection method are consistent with interpretations of other studies of complex glacial deposits (Thomason et al., 2018; Lao et al., 2016; Pugin et al., 2015, 2009).

The results of this study demonstrate that shear-wave reflection surveys can help delineate potential sand and gravel aquifers within complex Quaternary and glacial deposits. Water well information along seismic profile 809 (Fig. 10) showed distinct clay and sand layers below the shallow sand and gravel aquifer unit at 30 m depth. However, the seismic profiles could not identify deeper layers along with this profile due to the severe attenuation of the seismic energy below this depth. One possible explanation could be due to a strong reflection event between the aquifer unit and the underlying clay unit so that most of the energy has been reflected off to the surface. Also, the lightweight source (sledgehammer) we implemented during data acquisition in this study has resulted in a limited depth of penetration.

Despite these limitations, the SH-wave reflection method seemed to be a promising method to delineate shallow aquifers within complex glacial deposits. Along with available geological and geophysical data including water well, this method clearly depicts the near-surface variations and the architecture of the sand and gravel aquifers with their spatial extent and depth along with the seismic profiles. Based on the nature and thicknesses of the seismically delineated aquifers, locations for drilling potentially high-producing and water wells can be suggested along each of the presented seismic profiles. The central parts of profiles 808 and 812; at distance marks of 800 m, 750 m, and 1100 m along with profiles 809, 810, and 811, respectively are all good drilling locations where shallow and thick sand and gravel units were detected. Delineating the potential aquifers by this study contributed to the overall understanding of the groundwater resources in the Northern Illinois as the demand for locating freshwater aquifers has increased dramatically due to the rapidly growing population of Illinois.

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## Allen VeriFig Report

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