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Seismic characterization of glacial sediments in central Illinois

Ahmed Ismail [a,*], Andrew Stumpf [b], Robert Bauer [b]

[a] National Research Institute of Astronomy and Geophysics, Helwan, Cairo, Egypt
[b] Illinois State Geological Survey, Prairie Research Institute, University of Illinois Urbana–Champaign, 615 East Peabody Drive, Champaign, IL 61820, USA

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ABSTRACT

The vertical distribution of compressional wave velocity (V_p) and shear wave velocity (V_s) acquired from fifteen boreholes in central Illinois using the standard surface-source downhole-receiver method was studied. The velocity logs were compared with lithologic logs and gamma-ray logs acquired from the same boreholes to: 1) better understand the V_p and V_s ranges and variations within glacial sediments, 2) determine whether characteristic seismic velocities could be resolved to distinguish among the three major Pleistocene glaciations of Wisconsin (WI), Illinois (IL), and pre-Illinois (PIL), and 3) examine velocity variations corresponding to heterogeneities in the sediments composing these three major units. Results showed that deposits composing these units had highly variable V_p and V_s values. Only the contact between deposits of the WI and IL episodes could be delineated by a corresponding slight decrease in V_p. Other than that, neither V_p nor V_s logs showed significant contrasts at the contacts between these units. Some individual sediment packages, or intraunits, exhibited distinctive velocity patterns in the study area and were identified more clearly from V_s than from V_p logs. These intraunits are Wisconsin tills (T), Vandalia till (GV) and Mahomet sand (BM).

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1. Introduction

The unconsolidated sediments mapped in central Illinois were deposited by continental glaciers that flowed southward from northern Canada into Illinois during at least three major glacial episodes (Wisconsin (WI), Illinois (IL), pre-Illinois (PIL)). The advance and retreat of these glaciers left behind sediments that can be assigned to separate geologic mapping units on the basis of their relative age, descriptive physical properties such as color, texture, or density (Hansel and McKay, 2010) and other properties, such as seismic velocity.

Variations in seismic velocity and density within the sediments included in the different geologic mapping units are the key parameters for characterizing these sediments using high-resolution seismic reflection techniques (e.g., Bradford et al., 1998; Gruber, 2007; Ismail et al., 2012; Jørgensen and Sandersen, 2008; Kilner et al., 2005; Musil et al., 2002). Strong geophysical reflections are generated at interfaces between sedimentary units having significant contrasts in seismic velocity and density. Variations in seismic velocity can be measured directly using the refraction and surface wave seismic methods, and this data have been used to characterize glacial sediment (e.g. Francese et al., 2007; Hoffmann and Schrott, 2002; Ismail and Sargent, 2006).

Despite the rapidly growing application of surface seismic methods for characterizing glacial sediment, the ability of these methods to discriminate changes in lithology or sedimentology, and discern and trace their spatial distribution in the subsurface has sometimes been limited (Ismail et al., 2012; Miller et al., 1998). This is mainly due to the heterogeneity of these sediments, which to some degree is a product of their formation within complex depositional environments (Boyce and Eyles, 2000). Successful characterization of these sediments by surface seismic methods has only been possible by obtaining accurate velocity information measured in boreholes (e.g., Carr and Hajnal, 1999). Seismic velocity data, portrayed on downhole velocity logs, are necessary for calibrating seismic depth images and interpreting seismic amplitudes (Al-Chalabi, 1997; Reilly, 1993). The downhole velocity logs are the best data source for calibrating the measurements from surface seismic surveys because they are acquired using similar sources and frequency ranges (Hunter et al., 1998).

The principles and applications of the downhole seismic method have been described in detail by Hardage (1983) and Crice (2002). Specifically for this method, a triaxial geophone is lowered into the borehole to record the energy generated by a surface source. Because the energy from the source travels in a nearly vertical path toward the geophone in the borehole, the method does not encounter the problems experienced by the seismic refraction method (e.g., multiple refractions and overlooking low-velocity layers [LVL] and thin layers). Moreover, this method measures the velocity along an almost vertical path, rather than averaging velocities in the vertical and horizontal directions as in the seismic surface wave method (Park et al., 1999). Therefore, the downhole seismic method is considered a more reliable technique for determining seismic velocities because far more direct measurements can be made compared with the surface seismic methods (Liu et al., 2000; Louie, 2001).

Unfortunately, downhole velocity logs are seldom available along surface seismic survey lines because drilling boreholes may not be

* Corresponding author. Tel.: +20 217 722 8998.
E-mail addresses: aismail19@slb.com (A. Ismail), astumpf@illinois.edu (A. Stumpf), rbauer@illinois.edu (R. Bauer).

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allowed at many locations along the lines. Even when permissible, the cost of drilling is quite high. However, the purpose of this investigation is to evaluate the utility of downhole velocity logs in the absence of densely-spaced boreholes, to develop a more accurate, seismic velocity model for part of the region. The conceptual seismic velocity model can be used to guide and constrain surface seismic surveys in areas where the subsurface data is limited. This preliminary model can then be further revised and validated as new subsurface information is acquired.

To generate a seismic velocity model of glacial sediments in central Illinois, we acquired seismic velocity logs in fifteen boreholes (Fig. 1) using the standard downhole seismic method. In each borehole, a downhole compressional wave velocity (V_p) log and a shear wave velocity (V_s) log were acquired. The logs of seismic velocity were compared with the geologic logs in the same borehole. The geologic logs contained information on the physical properties of sediments, including lithology, color, grain size, compaction, and in-field estimate of moisture content. Logs of natural gamma ray were also acquired in the boreholes. The gamma-ray logs were important for this comparison because continuous core was not collected from all the boreholes. In unconsolidated sediment, a relatively low natural gamma response (measured in counts per second or CPS) is a characteristic of coarse-grained sediment (sand and gravel), whereas a relatively high natural gamma response is typical of clay-rich sediment (till, silt, or clay) as demonstrated by Kearey and Brooks (1991), Telford et al. (1990), and Bleuer (2004). These inferences regarding texture made from the gamma-ray logs assisted us in better resolving the variations in velocity between and within the geologic mapping units.

The correlations made between the V_p and V_s logs in each borehole with the corresponding geology and gamma-ray logs were necessary to identify the ranges and variations of velocity within the different geologic mapping units. More specifically, this correlation was used to determine, (1) whether the sediments deposited during the three major glacial episodes (WI, IL, and PIL) exhibited characteristic velocity ranges; (2) whether an abrupt change in seismic velocity was observed between the three glacial episodes; and (3) whether the geologic mapping unit(s) have a characteristic velocity contrast; information that is important for generating a velocity model for the area. To achieve these objectives, the V_p and V_s logs were evaluated separately.

2. Regional geology

In the fifteen boreholes studied, we encountered complex sequences of glacial sediment (75–120 m thick) overlying the bedrock (Fig. 2). These sequences contained multiple units of glacial diamicton (till) formed during the three glacial episodes, and sand and gravel (glaciofluvial sediment) and silt and clay (glaciolacustrine sediment), deposited in front advancing and retreating ice margins (Kempton et al., 1991; Soller et al., 1999; Stumpf and Dey, in press; Stumpf and Ismail, 2013). The remnants of well-developed soils formed during the intervening interglacial periods were identified in some of the boreholes.

The most notable feature on the bedrock surface is the Mahomet Bedrock Valley (MBV) and its tributary valleys, which are part of an extensive preglacial bedrock drainage system (Teays–Mahomet Valley System; Horberg, 1945; Kempton et al., 1991) that had its headwaters in the Appalachian Mountains to the east. The Teays–Mahomet Valley System extended westward across Ohio and Indiana into central Illinois

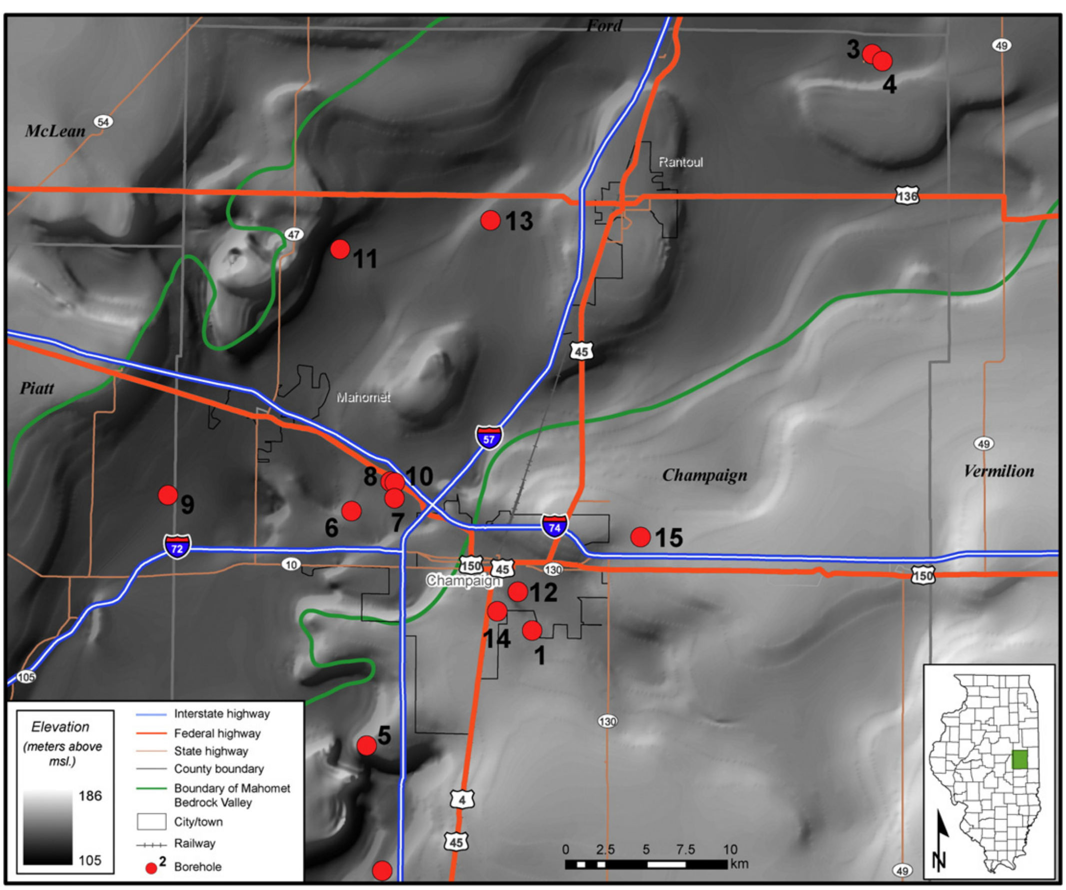

Fig. 1. Location of boreholes where seismic velocity logs were collected. Some boreholes were drilled over the Mahomet Bedrock Valley (MBV). The elevation of the bedrock surface is shown in the background as a hill-shaded relief map.