Construction and use of an inexpensive, lightweight free-fall penetrometer: applications to paleolimnological research

Ian S. Spooner^{1,*}, Peter Williams² and Kathleen Martin³

¹Department of Geology, Acadia University, Wolfville, NS, Canada B0P 1X0; ²Department of Physics, Acadia University, Wolfville, NS, Canada B0P 1X0; ³Environmental Science Program, Acadia University, Wolfville, NS, Canada B0P 1X0; *Author for correspondence (e-mail: ian.spooner@acadiau.ca)

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Abstract

This paper describes the construction of an inexpensive, lightweight, free-fall lake sediment penetrometer with application to paleolimnological research. This penetrometer is suitable for use in a variety of fresh water lake settings. Data are collected on a laptop PC, Palm OS handheld, or a Texas Instruments handheld data collection unit and are analysed using commercially available software. The quality of these data are adequate for determining changes in substrate type based on hardness. The unit can also be used to locate sites for optimum penetration of gravity cores and to calibrate sonar records. Addition of up to three optional transducers could expand the capabilities of the unit. Other potential uses include the determination of specific geotechnical properties of the lake sediment including the undrained shear strength.

Introduction

Penetrometers have long been used to measure the physical properties of sediments *in situ* (Dayal et al. 1975; Chari et al. 1979; Akal and Stoll 2002), most commonly the undrained shear strength and relative density of sea floor sediment (Dayal 1981; Akal and Stoll 2002). Penetrometer data support a variety of applications including seabed classification, geotechnical site investigation, dredging surveys, and naval applications. Two main types of penetrometers are used in lakes or shallow marine settings. *In situ* designs are, in general, lowered to the lake bed and use the depth of penetration of modified weighted rods to characterise lake sediment properties (Gaugush 1998). Free-fall designs impact the lake bottom and use acceleration and, in some cases, pressure sensors to monitor the sediment response to penetration (Dayal et al.

1975). Several types of free-fall penetrometers exist. Scott (1967) correlated deceleration of a gravity corer with variations in marine sediment characteristics. Thompson and Colp (1970) used a 3" (76 mm) diameter, 5' (127 mm) long penetrometer for ocean bottom exploration. Penetrometers instrumented with accelerometers have been used to measure acceleration/deceleration and to calculate penetration velocity and depth of penetration by single and double integration of acceleration respectively, with time. These modern penetrometer systems tend to be large and heavy, or as size decreases, expensive. As a result penetrometers have not been used extensively in limnological research and have seen little application in paleolimnology.

The nature and the thickness of post-glacial lacustrine sediments in Atlantic Canada varies widely in lakes located short distances apart

(Spooner 1998; Stea and Mott 1998) and between basins within individual lakes (Martin et al. 2003). We have noted also that the recovery of sediments by gravity coring varies widely within basins (Martin 2003). The development of the penetrometer described below arose out of the need to quantify variance in the physical characteristics of modern sediment within lake basins, resolve discrepancies in core recovery and lake sediment distribution, and to calibrate sonar records.

This paper discusses the construction and use of an inexpensive, lightweight (electronic), free-fall penetrometer well-suited to use in fresh water lakes. This system weighs approximately 3 kg (excluding the weight of a computer) and can operate in depths up to 15 m using either an ice surface or a boat as a stable platform. Greater depths are possible but were not tested in this study. The penetrometer costs about \$540.00 USD to build excluding computer costs.

Equipment and assembly

Our penetrometer incorporates commercial components available from Vernier Software and Technology, a science education company. This includes a 25-g accelerometer, a Labpro™ data collection interface (or optional Go!Link™ single channel interface), and Logger Pro 3™ analytical software. The accelerometer has a range of ± 245 m/s/s and an accuracy of ± 2.45 m/s/s. The Logger Pro 3 software can be run on a standard desktop or laptop PC or with optional software (Data Pro™) on Palm OS handhelds and Texas Instruments (TI) handhelds. Vernier components and software are described at www.vernier.com. All other parts are readily available through local hardware stores, plumbing outlets, and electrical retailing stores. Some minor machining is also required.

The penetrometer housing is made of 2" (5.1 cm) schedule 40 ABS, commonly used for plumbing (Figure 1). The penetrometer head is constructed from barstock aluminium machined to fit the ABS pipe. The radius of the head is 1.18" (30 mm). The accelerometer is mounted directly to the penetrometer head using a custom made 'C' shaped mounting bracket (Figure 2). All openings on the accelerometer are sealed with silicone to prevent moisture entering the unit. Once the head

Figure 1. Penetrometer with data acquisition cable. The penetrometer housing is constructed of ABS, the head is aluminium. The design and proportion of the fins (relative to the housing) are based on previous penetrometer designs.

is installed in the ABS housing lead shot is added to increase the mass of the penetrometer. An acrylic epoxy (Envirotex Lite™) was used to completely seal both the lead shot and the accelerometer and was added to a height of 1 cm above the top of the accelerometer. The sealed penetrometer weighs approximately 2 kg. We use 6 conductor round colour-coded 22 AWG solid telephone wire (15 m length) to carry the accelerometer signal to the Labpro™ unit. Although this wire is inexpensive it is rather stiff and in cold climate conditions a more flexible stranded wire may be desirable.

Figure 2. Schematic diagram of penetrometer system. The penetrometer housing is constructed from ABS with a aluminium or brass head and plated steel fins (3). The penetrometer incorporates a 25 g accelerometer. Data from the accelerometer is transferred to a data collection unit where it is processed and sent for visual display to either a Laptop PC or a Palm unit.

The penetrometer is connected to the Labpro™ or Go!Link™ interface which converts the electrical response from the accelerometer to a data stream. We find that a laptop PC is most efficient for displaying and analysing data while in the field. Although Palm OS and TI handheld computers offer a low-weight and low-cost alternative, processing of incoming data was somewhat slower.

Operation

The drop height required for terminal will vary depending on the weight and material used in the construction of the penetrometer and fluid prop-

erties. We found that results were comparable if a consistent drop height was employed even if that height was less than that required for terminal velocity. In practice terminal velocity might be hard to achieve for many settings. In our testing the change in the shape of the acceleration curve produced when the penetrometer contacted the substrate varied considerably with changing substrate composition regardless of the drop height (Figure 3). The data displayed in Figure 3 were generated from a drop height of 2 m.

The method of data analyses and acceleration curve characterisation will vary greatly according to application (Martin 2003). Relative changes in substrate hardness and consistency were quantified by generating a height:width ratio for each accel-

Figure 3. A 50 kHz sonar record from a shallow lake showing representative penetrometer curves for different substrates. Note that each substrate has a characteristic curve shape and height to width ratio. Relative recovery with a Glew gravity corer (Gilbert and Glew 1985) is shown by shaded rectangles, greatest recovery was achieved at site 3.

eration curve which we called the hardness coefficient (C):

$$C = \frac{\text{Height of curve}}{\text{full width at half maximum}}$$

The height of the curve was measured from a line connecting inflection points to the apex of the curve. The width was measured at half the maximum height. This is a standard technique used to characterise Gaussian curves which acceleration curves resemble (Bevington and Robinson 2003). As shown in Figure 3 we noted that higher recovery with a Glew gravity corer was generally

associated with low C values (Gilbert and Glew 1985). Note however that the lowest C value was obtained when the corer was used over a weed bed.

Data consistency is difficult to measure in natural settings due to changes in substrate composition. However, we evaluated the penetrometer at a 5 m deep clay lined water reservoir and at a small, gyttja-dominated organic lake (Canoran Lake; Figure 3) using a drop height of 2.0 m (Figure 4). Thirty tests were conducted at each site; for clarity only maximum and minimum curve height results are shown (Figure 4). For both tests curve shape remained consistent though, as ex-

Figure 4. Two examples of acceleration data generated using the freefall penetrometer and a drop height of 2 m. For site A bottom sediment was lodgement till overlain by 5 cm's of lake clay (LOI 8%). For site B bottom sediment was gyttja (LOI 35%). At both sites note the consistency of the post-impact oscillation which can be used to quantify the elastic properties of the lake sediment.

pected, peak height fluctuated in response to changes in the substrate composition and density (Figure 4). We note that though a range of C values for the clay substrate were obtained ($C = 22,400\text{--}25,600$) these values were more than an order of magnitude greater than those obtained for organic sediment ($C = 50\text{--}70$).

Applications: An example

In our research we have used the penetrometer primarily to determine the relative hardness and consistency of lake-bottom sediment in order to identify optimum coring locations. Sites with very high C values indicate a very hard substrate (till or rock) that may be unsuitable for coring whereas low values indicate sites where greater core recovery is expected. As well, a hard substrate may indicate periods of erosion or non-deposition and the presence of a discontinuous sedimentary record. We have also used the penetrometer to interpret sonar records, especially to characterise the sonar responses to bedrock, inorganic sediment, and organic substrates.

We envisage a number of additional paleolimnological applications. For example, the addition of a pressure transducer would enable the penetrometer to collect simultaneous sounding data. Other sensors (e.g. temperature, dissolved oxygen, conductivity) could also be considered as the Labpro™ interface (Figure 2) can accept up to four

sensors. Finally, a post-impact oscillation is common on acceleration curves for hard substrates (Figure 4). This oscillation is a consequence of the elastic properties of the sediment and, if present can be used to quantify the shear strength of that sediment (cf. Dayal et al. 1975).

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