The direct-push crosshole (DPCH) test for in-situ evaluation of near-surface P- and S-wave velocities

Andrew C. Stolte [*1, 2], Brady R. Cox [3], and Liam M. Wotherspoon [1, 4]

[1] QuakeCoRE, [2] University of Canterbury, [3] University of Texas at Austin, [4] University of Auckland

[*]andrew.stolte@canterbury.ac.nz

TEXAS The University of Texas at Austin

QuakeCoRE NZ Centre for Earthquake Resilience Te Hiranga Rū

Background: Invasive Seismic Testing

Near-surface, seismic testing methods are commonly used to evaluate in-situ soil and rock stiffness for engineering analyses and designs. Of particular interest are the small-strain moduli defined through measurement of the propagation of compression (P) and shear (S) waves. Testing methods aimed at measuring P-wave velocity (V_P) and S-wave velocity (V_S) include invasive seismic testing methods, which involve the placement of the seismic sources and/or receivers below the ground surface. This instrumentation may be lowered into boreholes or directly advanced into the ground.

- **Invasive Methods:** Borehole-based invasive methods were initially developed for petroleum exploration and later adapted for near-surface engineering purposes. Seismic instrumentation is lowered into one or more prepared and (typically) cased boreholes. Direct-push methods were developed subsequent to this, where conical probes are directly advanced into the ground, eliminating the need for boreholes.
  - **Downhole Testing:** A seismic source is excited at the ground surface. Waves are propagated into the ground and measured at a receiver lowered into a single borehole or at a receiver in a conventional cone penetration test probe (termed seismic cone penetration test SCPT). Disadvantages of this method include decreasing signal-to-noise ratio as the measurement depth increases and difficulties in the evaluation of the direct travel path at the near-surface due to refracted ray paths.
  - **Crosshole Testing:** The seismic source and one or more receivers are lowered into individual boreholes. At each testing depth, seismic waves are propagated horizontally between the boreholes. This allows measurement of the soil/rock stiffness directly between the boreholes along a relatively short, consistent travel path depth-to depth. However, this method is expensive and time consuming, requiring the preparation of two or more boreholes.

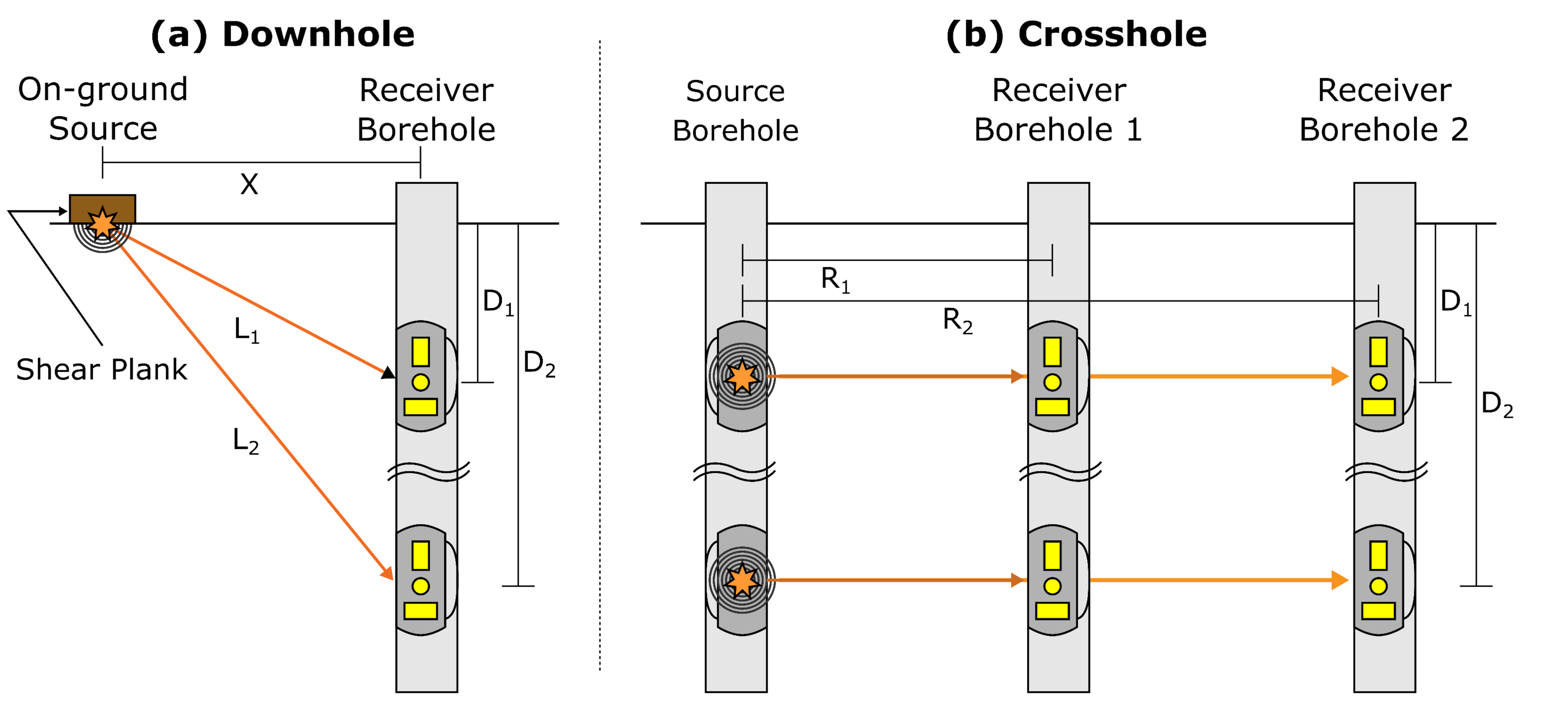

Figure 1: Simplified schematics of (a) downhole and (b) crosshole seismic tests

A New Methodology: The Direct-push Crosshole Test

A new, invasive, seismic testing method has been developed which combines the technical benefits of crosshole testing with the ease and speed of direct-push methods (e.g., SCPT).

The direct-push crosshole (DPCH) testing method has been well documented in Cox et al. (2018) and is conducted by advancing a pair of instrumented seismic cones (Figure 2), directly into the ground to common measurement depths, using CPT rigs (Figure 3). At each measurement depth, P- and S-waves are propagated from one cone (the source) to the other (the receiver) along a horizontal travel path of approximately 1.5 – 2.5 meters in length. Measurements are typically taken every 20 cm, resulting in subsurface profiles of V_P and V_S at high spatial resolution. At each measurement depth, the seismic waves are excited by tapping the source cone push rod with a hammer. A simplified schematic of a DPCH test is shown in Figure 4.

The direct advancement of the cones into the ground provides excellent coupling between the cones and the surrounding soil and eliminates the need for expensive cased boreholes. The relatively short, horizontal direct wave travel path results in a consistent, high signal-to-noise ratio across all testing depths.

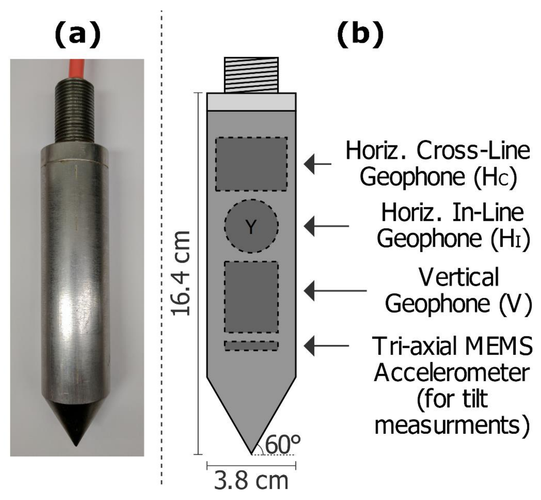

Figure 2: (a) Photograph and (b) schematic of a DPCH instrumented cone

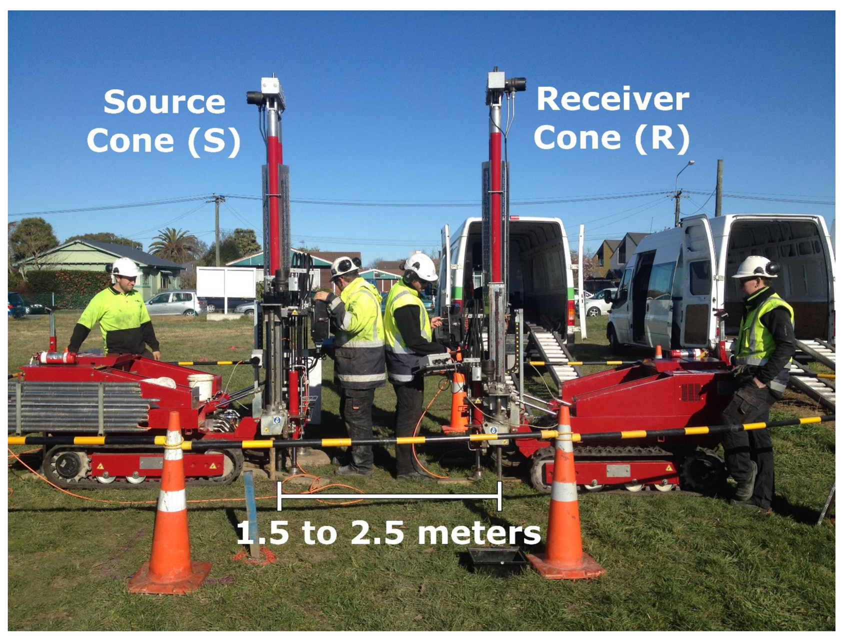

Figure 3: Photograph of two track-mounted CPT rigs advancing two DPCH cones for testing. The CPT rigs are positioned such that the DPCH cones are 1.5 to 2.5 metres apart.

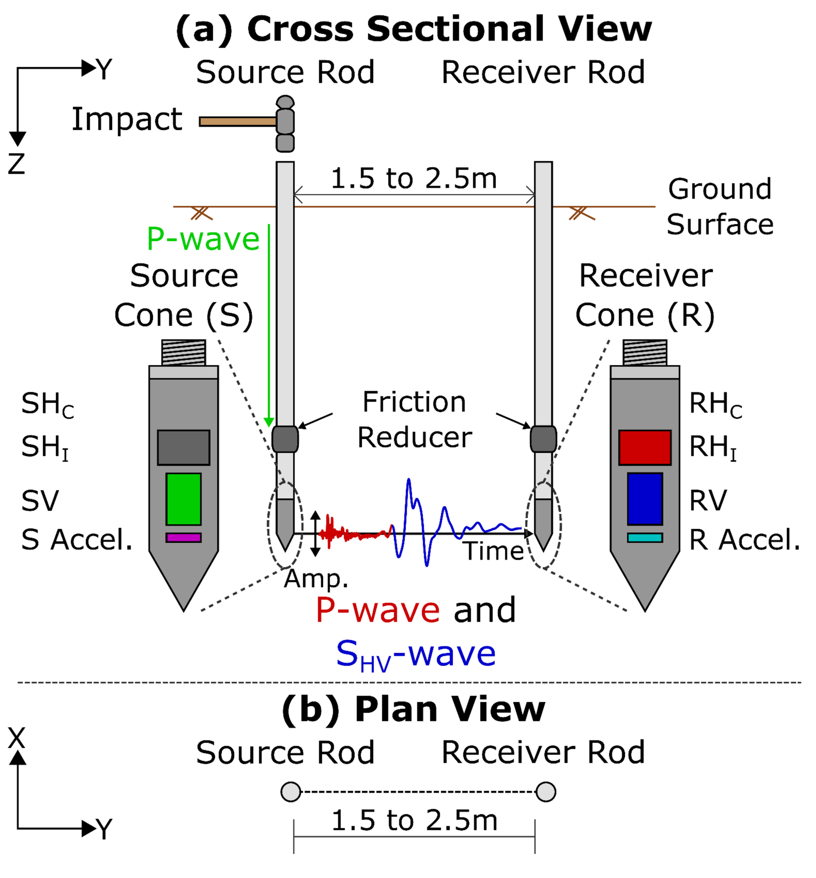

Figure 4: Schematic of the DPCH test

Data Analysis: Development of V_P and V_S Profiles

The raw data collected during DPCH testing consists of velocity and acceleration time histories from the source and receiver cone sensors. The final processed data are profiles of V_P and V_S as a function of depth, which are evaluated using the associated P- and S-wave travel times and the length of the direct travel path between the source and receiver.

- **Travel Time:** The travel time of a seismic wave between the DPCH cones is the difference between the arrival time of the wave at the receiver cone and the departure time of the same wave from the source cone. To determine the travel times of the direct P- and S-waves at a given measurement depth, three points in time must be picked from the recorded waveforms (as shown in **Figure 5**) as follows:
  - **Trigger:** The initiation of energy/arrival time at the source cone, which does not necessarily correspond to time zero on the digitizer.
  - **P-wave:** The arrival time of the *direct* P-wave at the receiver cone. This arrival is best observed on the in-line horizontal geophone and is picked at the first departure from the noise floor, as shown in Figure 6.
  - **S-wave:** The arrival time of the *direct* S-wave at the receiver cone. This arrival is best observed on the vertical geophone. A general guideline is to pick the arrival of S-waves as *the first major amplitude departure*, occurring after the P-wave arrival, *that has the correct polarity*, in this case downward. However, as shown in Figure 7, picking early arrivals due to waves refracting off of stiff layer boundaries should be avoided.

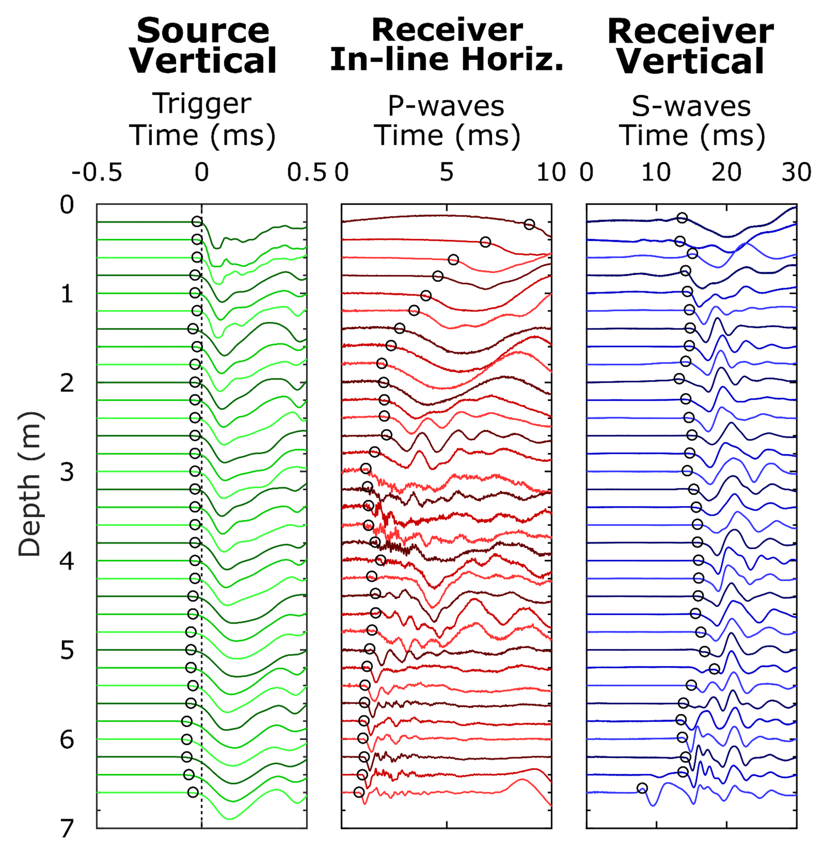

Figure 5: Waterfall plots for the trigger, P-wave, and S-wave DPCH waveforms, with first arrival picks indicated by hollow circles

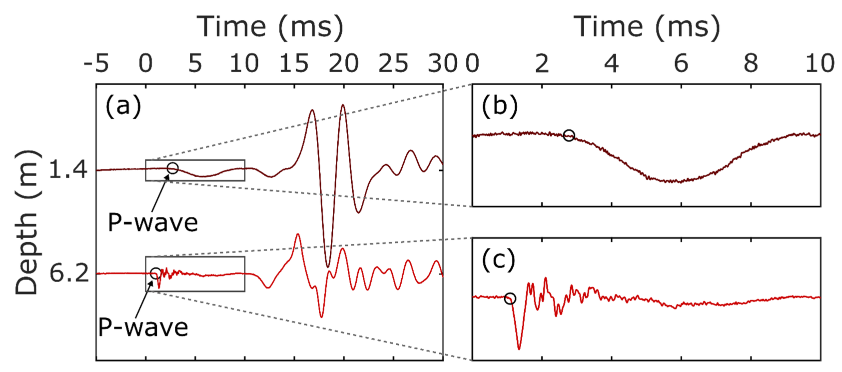

Figure 6: Example P-wave arrival picks

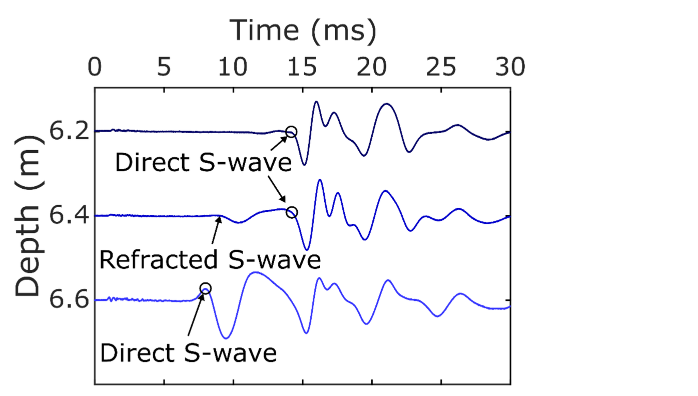

Figure 7: Example S-wave arrival picks

- **Length of the Travel Path:** The position of each cone is tracked from the surface down to the final measurement depth by using the tilt angles observed at each depth in conjunction with the known push increments (Figure 8). The vertical downward acceleration due to Earth's gravity provides a reference from which to track tilting of the cone using the MEMS accelerometer.

  Once the cone positions are known, the length of the direct travel path evaluated based on the distance between the cones.

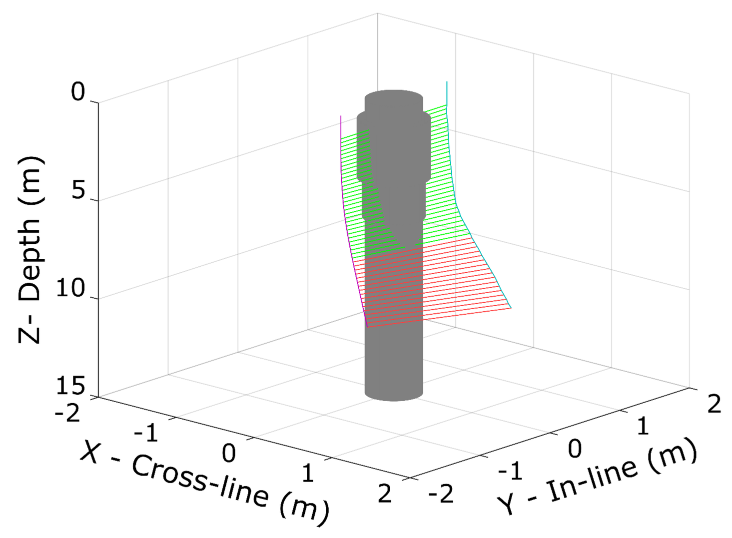

Figure 8: DPCH cone positions below ground surface from a test conducted across a ground improvement element

- **Velocity:** V_P and V_S are the length of the direct wave travel path divided by the associated wave travel time. Example DPCH V_P and V_S profiles are shown in Figure 9 with CPT data from a nearby sounding. Note the similar trends in shear stiffness between V_S and the cone tip resistance.

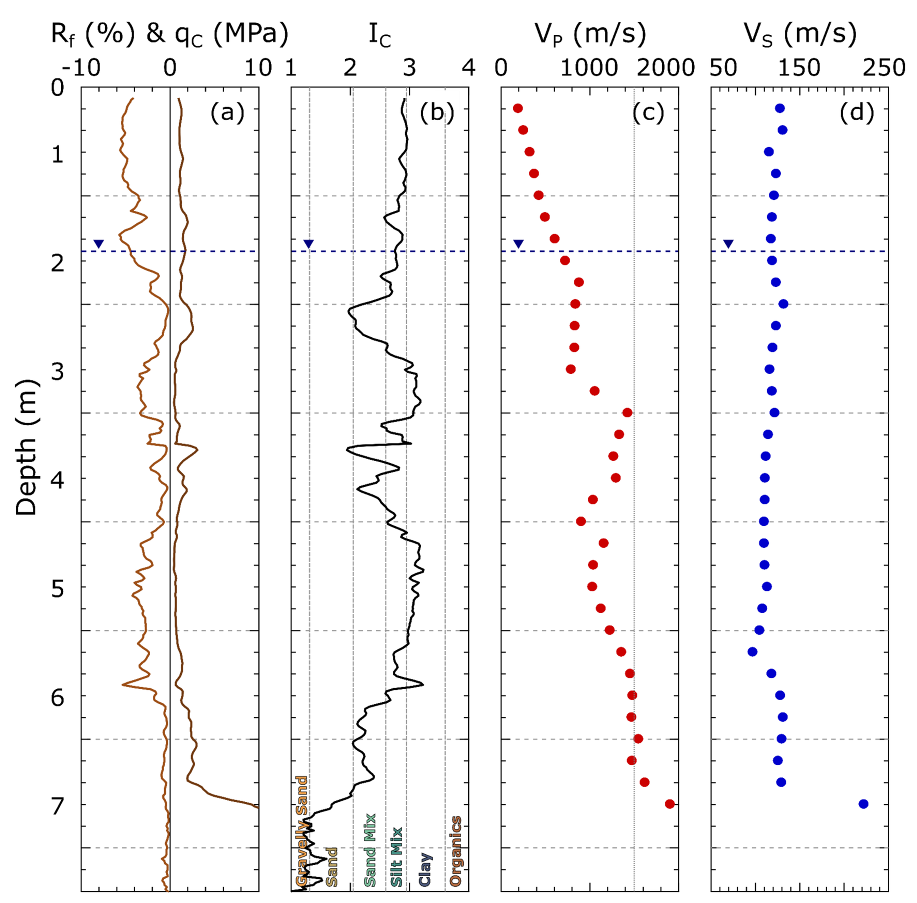

Figure 9: Comparison of (a) friction ratio (R_f) and cone tip resistance (q_C) from CPT testing, (b) normalised soil behaviour type index (I_C) from CPT testing, (c) V_P from DPCH testing, and (d) V_S from DPCH testing.

Applications: High-Spatial Resolution V_P and V_S

- **Ground Improvement Verification:** DPCH testing allows measurement of small-strain shear stiffness across and between ground improvement elements, as shown in Figure 8.
- **Soil Liquefaction:** In-situ degree of saturation may be evaluated using in-situ measurements of V_P from DPCH testing. V_P measurements greater than 1,500 m/s (e.g., the V_P of water) indicate that soil is fully saturated. Furthermore, the DPCH V_S measurements are well suited to use in V_S-based simplified liquefaction triggering relationships (Andrus and Stokoe 2000, Kayen et al. 2013).
- **In-situ Void Ratio:** Based on the theory of linear poroelasticity, relationships have been developed to evaluate void ratio based primarily on V_P and V_S. On-going studies are exploring the use of this relationship and DPCH measurements to evaluate in-situ void ratio.

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References

Cox, B. R., Stolte, A. C., Stokoe, K. H., II, and Wotherspoon, L. M., (2018). "A Direct Push Crosshole (DPCH) Test Method for the In-Situ Evaluation of High-Resolution P- and S-wave Velocities". *ASTM Geotechnical Testing Journal*. In press.