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Resolving Bedrock Topography Beneath River Crossings Using Seismic Refraction: Theory, Resolution Limits, and HDD-Oriented Acquisition Design

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Summary

Imaging competent bedrock beneath river crossings represents a significant technical challenge for horizontal directional drilling (HDD) projects. Although seismic refraction is a standard tool for mapping the overburden–bedrock interface, acquisition gaps across wide channels can introduce uncertainty in depth interpretation. This study evaluates three potential refraction scenarios for a 200 m wide river crossing with anticipated bedrock depths of 20–40 m. Using a delay-time theoretical framework, we observe that standard Bank-to-Bank geometries (Case 1) are often mathematically underdetermined, which may result in depth uncertainties near 10 m. The deployment of riverbed receivers (Case 2) can improve coverage but may remain constrained by velocity-depth ambiguity. As an alternative, we propose that the combination of autonomous nodal recording and in-river airgun sourcing (Case 3) could provide the first-order delay-time constraints needed to reduce uncertainty to an estimated 1–3 m. This proposed hardware configuration, utilizing 10 Hz marsh geophones, would also allow for the simultaneous collection of passive MASW data. This approach aims to provide a dual-parameter (V_p and V_s) model to better characterize rock mass quality without requiring additional field logistics. These results suggest practical acquisition parameters that could serve as a framework for mitigating engineering risk in complex HDD river-crossing designs.

Introduction

The characterization of bedrock topography beneath major river crossings is a high-stakes requirement for Horizontal Directional Drilling (HDD) design. Historically, seismic refraction has been the primary tool for mapping the overburden-bedrock interface; however, the logistical difficulty of crossing wide channels (~200 m) often results in suboptimal acquisition geometries.

The industry frequently relies on "undershooting"—placing sources and receivers on opposing banks—assuming that the resulting tomographic model accurately reflects mid-channel conditions. This paper challenges that assumption. By applying the Delay Time Method and Fresnel Zone theory, we quantify the illumination gaps inherent in standard geometries and demonstrate why in-river sourcing is a mathematical necessity for defensible engineering design.

This paper demonstrates that the uncertainty associated with river-crossing refraction surveys is fundamentally controlled by geometric determinacy in the delay-time formulation, and that only acquisition geometries generating critical refractions beneath the river provide first-order constraints suitable for HDD design.

Theory: The Delay Time Approach

To quantify the resolution limits of seismic refraction beneath river crossings, this study adopts the classical delay-time framework developed by Hagedoorn (1959) and extended through reciprocal methods by Palmer (1981). These approaches provide a physically rigorous means of evaluating whether a given acquisition geometry yields a determinable bedrock depth or merely an averaged interpolation across an acquisition gap.

Prior to evaluating the three acquisition geometries, the theoretical framework and physical parameters used in the delay-time analysis are defined following classical seismic refraction theory (Hagedoorn, 1959; Palmer, 1981). The subsurface is represented by a two-layer model comprising a saturated alluvial overburden overlying competent bedrock, a configuration typical of large river crossings encountered in HDD projects. The P-wave velocity of the overburden (V_1) is assumed to lie between 1500 and 1800 m/s, consistent with water-saturated silts, sands, and gravels, while the bedrock velocity (V_2) is taken as 3500–5500 m/s, representative of drillable sedimentary or crystalline rock. Bedrock depth is assumed to range from 20 to 40 m below ground surface, with uncertainty estimates evaluated at a nominal depth of 30 m. For in-river airgun acquisition, the dominant frequency of the refracted arrival is assumed to be 80–120 Hz, corresponding to wavelengths (λ) of approximately 15–20 m in the saturated overburden. These parameters define the critical refraction angle, delay-time magnitude, and lateral resolution limits, and are held constant across all three cases so that differences in bedrock constraint arise solely from acquisition geometry rather than subsurface variability.

Under these assumptions, three acquisition geometries commonly employed for river crossings can be evaluated in terms of their mathematical determinacy and resulting bedrock depth uncertainty.

To quantify the resolution limits of river crossings, we utilize the Delay Time Method. For a horizontally layered model with constant overburden velocity V_1, the depth z beneath any given station is a function of the delay time δt, which represents the additional time required for a ray to travel through the overburden compared to a ray traveling along the refractor surface at velocity V_2:

$$\delta t = \frac{z \cos\theta_c}{V_1}$$

Where z is the vertical depth to the refractor and θ_c is the critical angle defined by $sin\theta_c = \frac{V_1}{V_2}$. This expression assumes a laterally homogenous overburden and a planar refractor; deviations from these assumptions introduced second-order errors addressed through reciprocal analysis.

For a depth calculation to be deterministic, the total travel time t_{ab}between source A and receiver B must be decomposed into its constituent delay times at the source (δt_a) and receiver δt_b):

$$t_{ab} = \frac{x}{V_2} + \delta t_a + \delta t_b$$

In a 200m river crossing, this decomposition leads to three distinct levels of certainty:

- Case 1 (Bank-to- Bank): Because shots and receivers are limited to the banks, the central 150m of the river lacks discrete δt measurements. The travel time t_{ab} provides only a single "average" depth for the entire gap. This results in an underdetermined model where a single deep paleochannel or a sharp pinnacle could exist without significantly altering the total travel time. Uncertainty: ±10 m.
- Case 2 (One-Way In-River): Placing receivers on the riverbed allows for the measurement of δt_b (receiver delay) beneath the water. However, while riverbed receivers allow partial estimation of receiver-side delay times, the absence of reciprocal shots prevents unique separation δt_b from the source delay δt_a and the lateral velocity variations in V_1. This velocity-depth ambiguity keeps the model weakly constrained. Uncertainty: ±4–8 m.
- Case 3 (Full-Reciprocal In-River): By deploying both sources and receivers within the river, we achieve full reciprocal coverage. Using the Plus-Minus Method, we can algebraically isolate the delay time at any point g:

$$\delta t_g = \frac{1}{2}(t_{ag} + t_{bg} - t_{ab})$$

This calculation is independent of the source depths and provides a first-order constraint on the bedrock surface. Uncertainty: ±1–3 m.

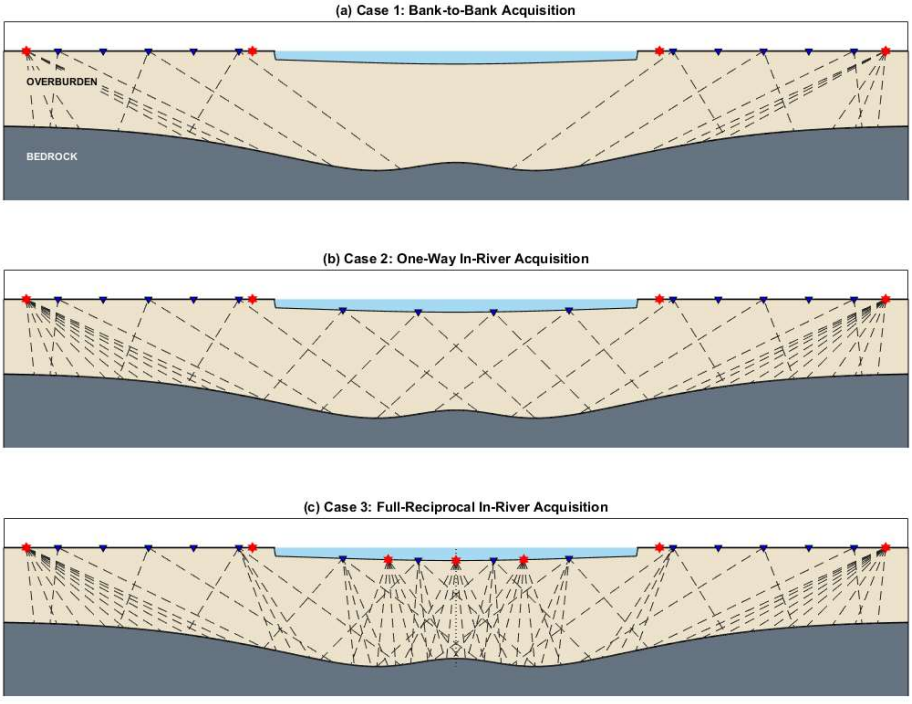


Figure 1: Comparison of ray-path illumination for three seismic refraction acquisition frameworks. (a) Case 1 (Bank-to-Bank): Demonstrates significant "illumination gaps" at the mid-channel bedrock interface. (b) Case 2 (One-Way In-River): Improved interface sampling, but lacks the angular diversity required for stable inversion. (c) Case 3 (Full-Reciprocal In-River): The proposed framework; mid-river sources provide the data redundancy and reciprocity necessary to resolve bedrock topography and reduce structural ambiguity beneath the channel.

The horizontal resolution of the refraction method is not infinite; it is limited by the physical footprint of the seismic wave. The lateral resolution (Δx) is governed by the target depth (z) and the dominant P-wave wavelength (λ) in the overburden of the seismic signal:

$$\Delta x \approx \sqrt{z\lambda}$$

where $\lambda = V_1/f_d$ and f_d is the dominant frequency of the refracted arrival.

For a target depth of 30 m, the calculated lateral resolution is approximately 20–25 m. This assumes a dominant frequency of 100 Hz, which is the characteristic spectral peak for small-volume (10–20 in^3) airguns in saturated, unconsolidated sediments (Caldwell and Dragoset, 2000; Mosher and Simpkin, 1999; BOEM, 2017, Table 3.3-2). A 100 Hz dominant frequency was selected as it provides a practical compromise between the penetration and resolution requirements at this depth. This "smoothing" effect means that any bedrock features smaller than the lateral resolution Δx - such as localized rock pinnacles or narrow scour channels—may be averaged out in the final model. This physical limit provides the basis for the dense 10–15 m receiver spacing proposed in this study; such spatial over-sampling is necessary to mitigate the risk of missing critical HDD hazards that fall below the theoretical resolution limit.

Technical Implementation

While Bank-to-Bank and One-Way In-River geometries remain the most common industry practices due to their lower logistical complexity, they inherently suffer from non-uniqueness; without reciprocal ray paths, the inversion remains poorly constrained at the channel margins. This paper focuses on the Full-Reciprocal In-River geometry, as it requires a specialized explanation of the sourcing logistics and wavefield physics necessary to achieve engineering-grade precision. To achieve this framework, we propose a transition from traditional cabled arrays to a nodal seismic system. This approach eliminates the logistical 'drag' associated with analog cables in high-flow environments and provides the flexibility required to occupy the mid-river source and receiver positions that the Full-Reciprocal method demands.

The recording array will utilize autonomous nodes paired with high-output marsh geophones (10 Hz or 14 Hz). Unlike standard land geophones, marsh geophones feature:

- Environmental Resilience: Integrated waterproof seals designed for total immersion and high-pressure saturated environments.
- Coupling Fidelity: High-mass, spiked, or weighted casings that ensure the sensor remains coupled to the riverbed despite flow-induced vibrations or "cable-shake" noise.
- Stable vertical-component coupling: Their rugged design ensures the vertical component of the P-wave is captured accurately, which is essential for the travel time picks used in the Plus-Minus calculation.

To resolve bedrock at 20–40 m depth, the energy source must balance penetration power with a frequency spectrum that satisfies our lateral resolution constraints.

- Small-Volume Airgun (Proposed): A 10–20 in^3 airgun is the preferred source. Small-volume airguns generate low-frequency energy capable of penetrating tens of meters of unconsolidated sediment, producing repeatable pulses suitable for first-arrival picking.

High-pressure shots (~2000 psi) produce a spectral peak that provides the “low-frequency punch” necessary to penetrate silty overburden while generating robust head waves (Mosher & Simpkin, 1999; Caldwell & Dragoset, 2000). Based on BOEM (2017, Table 3.3-2), small airgun arrays concentrate most energy in the 10–600 Hz range. Selecting a nominal 100 Hz as the dominant frequency is consistent with this energy band and maintains the 20–25 m lateral resolution limit assumed in this framework, providing an effective balance between penetration depth and lateral resolution.

- Sparker Systems: Sparker sources utilize a high-voltage electrical discharge to generate seismic energy with a broader frequency spectrum than airguns, typically spanning ~50–4,000 Hz (BOEM, 2017). While higher frequencies improve vertical resolution, they are rapidly attenuated in thick, silty river overburden, resulting in reduced signal-to-noise ratio at the bedrock interface and making first-arrival picking difficult (Mosher & Simpkin, 1999).
- Chirp Systems: As noted by Mosher and Simpkin (1999), these frequency-modulated (FM) systems operate across a wide bandwidth, typically ranging from 400 Hz to 20 kHz. While the lower end of this sweep provides better penetration than traditional high-frequency profilers, these systems lack the acoustic power of an impulsive airgun to penetrate unconsolidated river sediments. Their use is generally limited to mapping shallow stratigraphy within the upper 5–10 m of the riverbed.

Implementing Full-Reciprocal In-River geometry requires solving three primary logistical hurdles:

1. Vessel Positioning: To maintain the precision of the delay time budget, the source boat must utilize Real-Time Kinematic (RTK) GPS. This ensures that every shot is located within centimeters, allowing for accurate offset calculations.
2. Coupling in Currents: High river velocities can create "noise" around the source. We propose a towed-frame deployment to keep the airgun at a constant depth to avoid "bubble pulse" interference and "ghosting" effects.
3. Timing Synchronization: Since the nodes are autonomous, they must be synchronized via a Master GPS Clock before deployment and "drift-corrected" after recovery to ensure that travel times are accurate to the millisecond.

Integration of Passive MASW

While the primary focus of this investigation is seismic refraction, the use of a distributed nodal array facilitates the simultaneous collection of Passive MASW (Multichannel Analysis of Surface Waves) data1. The 10 Hz marsh geophones used in the Full-Reciprocal In-River geometry are particularly well-suited for this dual-purpose acquisition, as they provide the low-frequency sensitivity necessary to capture ambient surface waves (Parker et al., 1999, 2007). Consequently, the refraction deployment inherently serves as a passive MASW array, providing an independent V_S (shear-wave velocity) constraint without additional field logistics.

- The Methodology: Because the autonomous nodes record continuously, they capture the ambient seismic noise field (e.g., river flow turbulence and microseisms). By applying Interferometry or Spatial Autocorrelation (SPAC) methods to this background noise, we can derive an S-wave velocity profile beneath the riverbed.
- The Value Add: S-wave velocity is a more direct indicator of rock mass quality and shear strength than P-wave velocity alone.

- Overcoming Refraction Limits: Passive MASW is significantly less sensitive to "velocity inversions" (where a hard layer overlies a soft layer) than traditional refraction method. In refraction-only models, such inversions can sometimes "hide" the true bedrock depth. MASW provides a vital check on the full-reciprocal depth calculations in areas of complex overburden.

Risk Quantification

The uncertainty in bedrock depth is directly linked to the level of mathematical constraint in the acquisition geometry.

The uncertainty values are calculated based on:

1. Bank-to-Bank(±10m): At a depth of 30m, a 10m error represents ~33% of the total depth. In a 200m Bank-to-Bank gap, a 10% error in the assumed V_1 velocity (very common in river silts) will easily trigger a 10m depth error.
2. One-Way In-River (±4–8m): By placing nodes on the bottom, you eliminate the "water column" variable, which reduces error. However, you are still "estimating" the entry angle. This half the error of Case 1 but does not remove it.
3. Full-Reciprocal In-River (±1–3m): This is the industry standard for high-resolution refraction. With a 10m receiver spacing and reciprocal shots, you are over-sampling the refractor. The error is reduced to the "Fresnel Zone" limit, which is roughly 5–10% of the depth.

Based on the error propagation of the delay time equation, the expected depth uncertainties for a 30 m target are categorized as follows:

	Geometry	**Math Status**	**Primary Limitation**	**Uncertainty**
Case 1	Bank-to-Bank	Underdetermined	Mid-channel shadow zone	± 10 m
Case 2	One-way In-River	Weakly Constrained	Velocity-depth ambiguity	$\pm 4 - 8$ m
Case 3	Full-Reciprocal In-River	First-Order Constrained	Fresnel zone physical limit	$\pm 1 - 3$ m

Passive MASW acts as a secondary validator for the Full-Reciprocal In-River model, reducing the risk of 'blind zones' and providing shear-strength data for HDD steering and tooling selection.

Conclusion

This study suggests that the accuracy of seismic refraction beneath river crossings is fundamentally influenced by geometric determinacy rather than equipment sensitivity alone. In the absence of mid-river sourcing, the resulting bedrock profile may remain an interpolation influenced by software smoothing rather than direct physical measurement.

The application of the delay-time and plus-minus frameworks indicates that a Full-Reciprocal In-River geometry could be an effective approach for resolving localized topography that might otherwise be missed. Furthermore, considerations of lateral resolution limits suggest that dense sampling is likely required to identify specific sub-channel hazards relevant to HDD operations. For high-stakes HDD projects, moving from bank-based estimation toward a river-based measurement framework could represent a significant step in project de-risking. The proposed transition to nodal frameworks and marsh geophone technology aims to address traditional logistical barriers to in-river sourcing, potentially allowing for a more defensible bedrock model. By considering a dual-parameter approach that incorporates both active refraction and passive MASW, it may be possible to generate a subsurface model with higher confidence for HDD clearance and risk mitigation.

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