

Seismic Cone Penetration Test: The Future of Geotechnical Site Characterization Under Seismic Loads

1. Introduction

The Seismic Cone Penetration Test (SCPT or SCPTu) is an advanced hybrid ground investigation technique that integrates the conventional CPT with in-situ measurement of seismic wave velocities in the soil. This approach enables the collection of data that would traditionally require two separate tests, making it both faster and more economical.

By enhancing the data output from a CPT-led investigation, SCPT provides valuable insight into soil stiffness and dynamic behavior. In particular, it allows for reliable determination of small-strain soil parameters such as the small-strain shear modulus (G_0) and facilitates evaluation of seismic performance indicators like the Liquefaction Potential Index (LPI). These parameters are critical for projects involving seismic safety, dynamic loading, and long-term performance of foundations.

A typical schematic of the SCPT is illustrated in Figure 1.

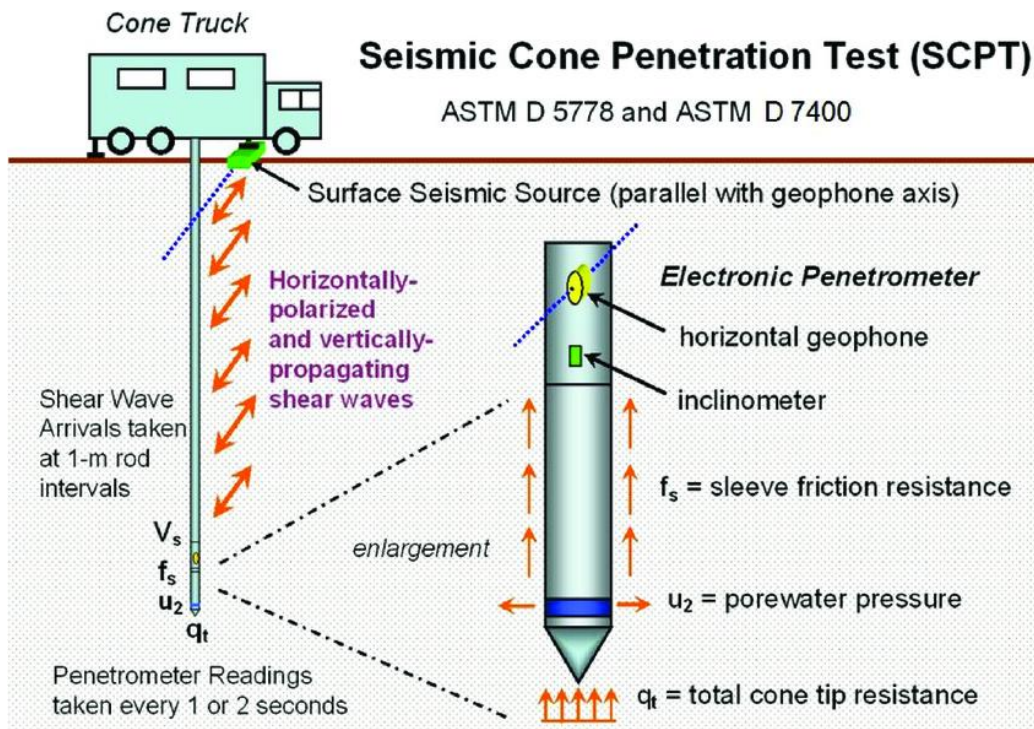


Figure 1. Schematic of seismic cone penetration test.

2. Why do we need SCPT?

- **Seismic Site Classification:** Building codes such as *IS 1893 (Part 1)* require site classification based on shear wave velocity profiles. Accurate V_s measurements from seismic tests form the foundation for seismic hazard assessment and earthquake-resistant design.
- **Liquefaction Evaluation:** Shear wave velocity is a widely accepted parameter for evaluating liquefaction potential. SCPT data supports the estimation of factor of safety against liquefaction, and calculation of liquefaction-induced ground deformations.

- **Dynamic Analysis of Foundations:** Analysis of machine foundations and dynamically loaded structures require the input of accurate dynamic soil properties. Seismic testing provides small-strain parameters such as dynamic shear modulus (G_0), dynamic Young's modulus (E_0), and Poisson's ratio (ν), which are critical inputs for dynamic modeling and design.
- **Static Analysis of Foundations:** Settlement analyses of shallow foundations often rely on the static Young's modulus (E), which can be estimated from the dynamic Young's modulus (E_0) reduced by a modulus degradation factor. This enables more realistic estimates of foundation settlement compared to the use of purely empirical correlations.
- **Identification of Unusual Soil Behavior:** Seismic wave measurements can reveal unusual/complex ground conditions such as cemented soils, which may not be detected reliably through conventional CPT or SPT data alone.

3. Test Equipment and Procedure

The core enhancement to the conventional CPT involves attaching a **seismic add-on module** immediately behind the CPT cone. This module houses an array of receivers—typically accelerometers or geophones—arranged in either a uniaxial or triaxial configuration.

As shown in Figure 2, the seismic module typically consists of an instrumented rod with a top sensor (geophone) and a bottom sensor (geophone) spaced vertically by a distance of about 0.5 m. In general, the test consists of generating a shear wave with a shear beam that is pressed vertically against the soil to provide good coupling and with a hammer that hits the shear beam horizontally to generate the shear wave. The generated shear wave then travels down to the top sensor and the bottom sensor. The electronic board inside the instrumented rod will amplify and digitize the signal at depth, send it to the ground surface through a cable, and then display the seismogram shown at the bottom right corner of the figure below.

The shear wave velocity V_s is the ratio of the difference in travel distances ($\Delta S = S_2 - S_1$) from the center of the shear beam to the upper and lower geophone receivers and the difference in arrival times ($\Delta t = t_2 - t_1$) of the shear waves to each geophone receiver.

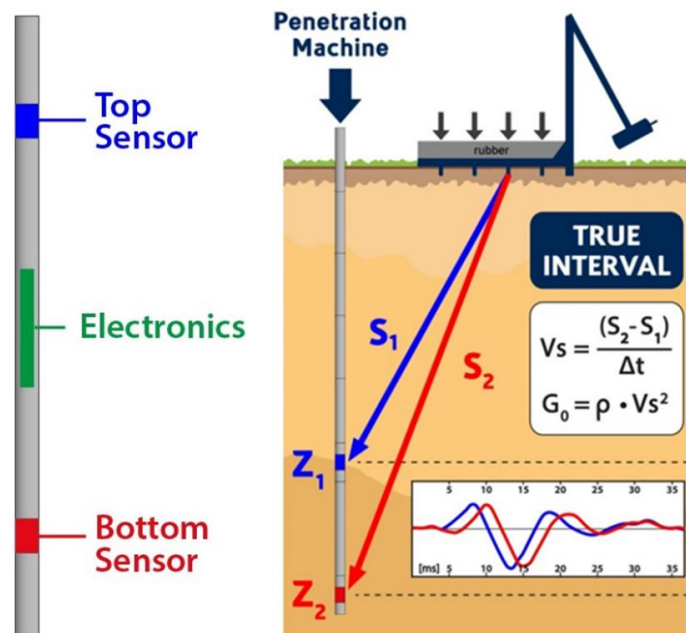


Figure 2. SCPT test layout.

At the surface, a **signal conditioning unit** is used to separate the seismic signals from the standard CPT data. In analogue systems, specialized seismic cables with additional pins are used to transmit the seismic records.

A **waveform generator** is used to create seismic waves for downhole detection:

- **Onshore investigations** typically employ a striking plate/beam and hammer—ranging from manual setups to fully automated hammers.
- **Nearshore and offshore investigations** require submersible sources, most commonly hydraulic pistons that strike an end plate.

While basic sources are designed to generate **shear waves (S-waves)**, more advanced systems are capable of producing both **S-waves and compression waves (P-waves)**, allowing a broader range of soil stiffness parameters to be evaluated. The S-wave is generated by a horizontal blow of a hammer striking the end of a long wooden plank or shear beam placed on and pressed vertically down against the ground for good contact. The longitudinal axis of the shear beam is aligned parallel to the axis of the sensors to maximize sensitivity to the generated shear wave.

Regardless of the equipment configuration, the **testing procedure** follows a consistent approach. The sounding begins in the same manner as a standard CPT. At specified depth intervals—typically every 0.5 m to 1.0 m—the cone penetration is paused, and a seismic waveform is generated. The data acquisition system automatically records the precise time of wave initiation, which serves as the reference point for determining wave travel times and velocities.

4. Data Acquisition

Once the generated seismic wave is detected by the downhole receivers, the corresponding waveform (seismogram) is displayed on the data acquisition system. At this stage, the signal can be reviewed in real time and assessed for quality before proceeding with further cone penetration. Typically, the recorded waveforms exhibit a prominent initial peak of higher amplitude—referred to as the **first arrival**—followed by progressively smaller peaks as the seismic energy attenuates with time and distance.

The waveforms (seismogram plots) should clearly distinguish the following segments, as shown below:

- **Initial silence:** A low-amplitude zone preceding the arrival of the main S-wave.
- **Main S-wave arrival:** A distinct high-amplitude signal representing the primary shear wave.
- **Coda or tail:** A medium- to low-amplitude zone consisting of reflections and refractions that follow the main S-wave arrival.

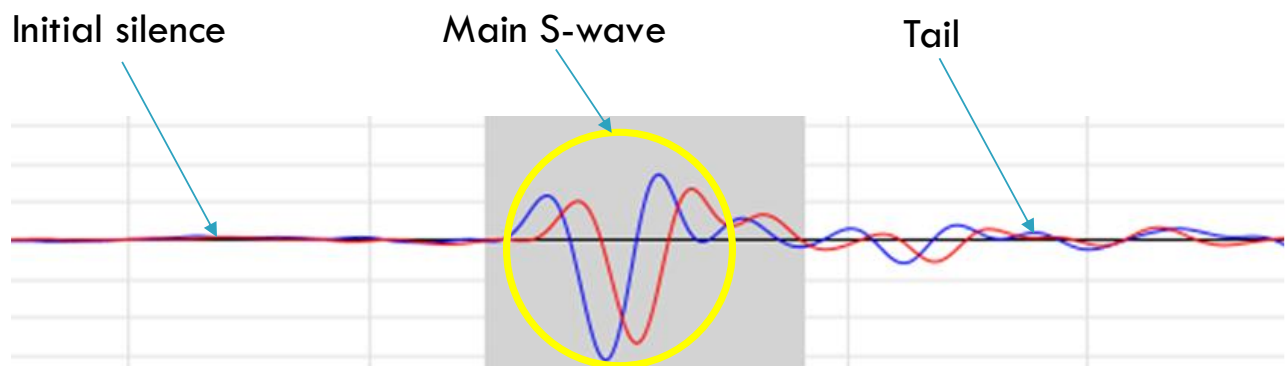


Figure 3. Typical features of a seismogram: initial silence, main S-wave, and tail.

The repeatability of seismic measurements can be evaluated based on the coefficient of variation (COV), as summarized in Table 1.

Table 1. Acceptance criteria for quality of seismic measurements.

COV (%)	≤ 1.0	≤ 3.0	≤ 5.0	≤ 10	> 10
Repeatability	Excellent	Very good	Good	Acceptable	Poor

5. Data Processing and Analysis

The primary objective of seismic data analysis is to determine the time difference in wave arrivals between successive test depths. This time interval forms the basis for calculating seismic wave velocity.

For a given depth below the ground surface, the original raw signals are first filtered to remove background noise and produce the smooth, filtered signals (Figure 4). The filtered signals are then rephased (superimposed) to evaluate the time delay between the blue (top sensor) and red (bottom sensor) waves using a built-in cross-correlation algorithm in the data analysis software. The cross-correlation method involves comparing a pair of waveforms and calculating the time shift required to achieve the closest match between them (Figure 5).

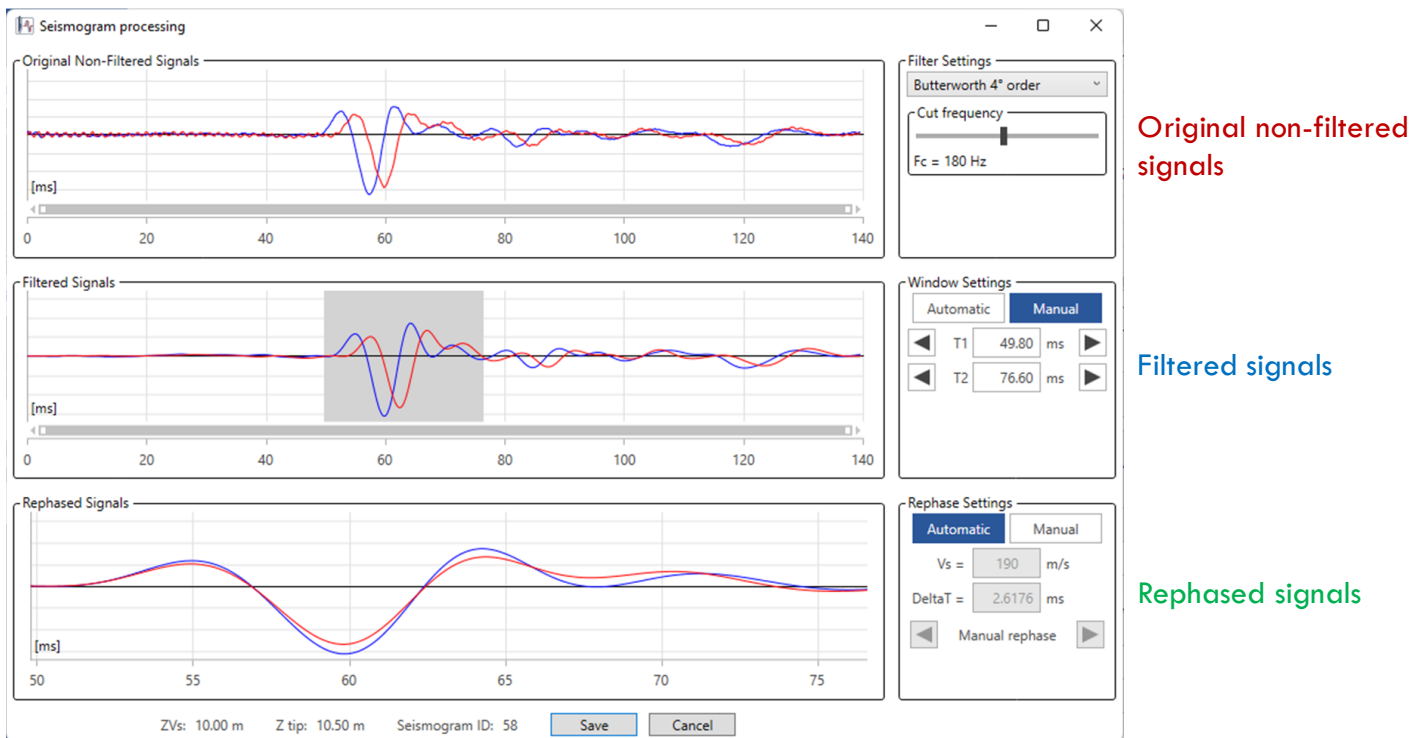


Figure 4. Seismogram processing: original non-filtered signal, filtered signal, and rephased signal.

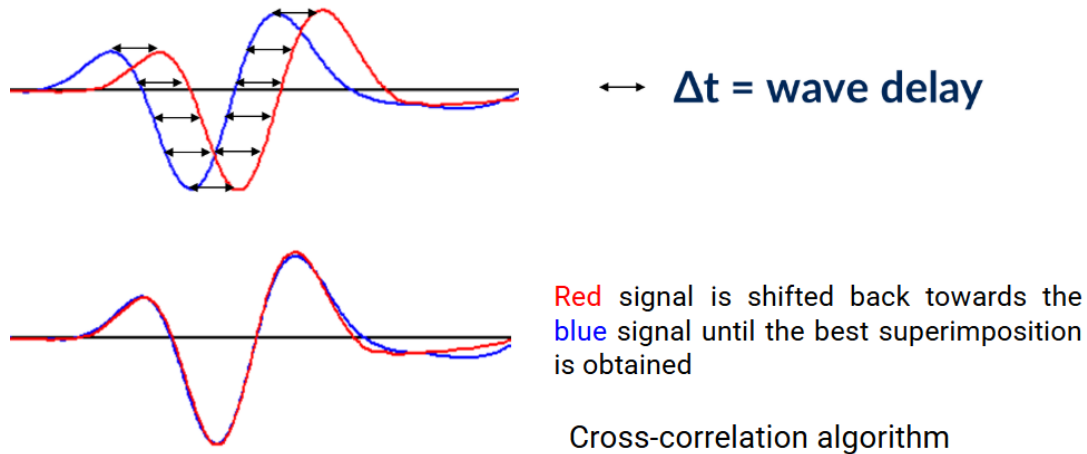


Figure 5. Cross-correlation method for estimation of time delay between waveforms.

6. Interpretation and Use of Seismic Data

Once wave velocity is determined, it can be used to derive several fundamental soil parameters.

One of the most important applications is the calculation of the small-strain shear modulus (G_0), using the simple relationship:

$$G_0 = \frac{\gamma}{g} V_s^2$$

where γ is the bulk unit weight of the soil, g is the acceleration due to gravity, and V_s is the shear wave velocity.

Because G_0 governs soil stiffness at very small strains, it is relevant to both static and dynamic soil behavior, and applies under both drained and undrained conditions. This makes it one of the most useful parameters in geotechnical engineering.

In addition to G_0 , SCPT data can be used to estimate the small-strain Young's modulus (E_0):

$$E_0 = 2G_0(1 + \nu)$$

where ν is Poisson's ratio. Calculation of ν requires both P-wave and S-wave velocities:

$$\nu = \frac{V_p^2 - 2V_s^2}{2(V_p^2 - V_s^2)}$$

where V_p is the compression wave velocity. However, P-wave measurements are more difficult to obtain in saturated soils, since their propagation is strongly influenced by pore water. This makes accurate P-wave testing below the groundwater table particularly challenging.

Accurate determination of soil density ρ is also important, as it directly influences the calculated values of G_0 and E_0 . Therefore, the most robust site characterization program typically combines:

- **Limited borehole drilling, sampling, and laboratory testing** to establish soil descriptions and densities, with
- **Widespread SCPT soundings** to develop detailed shear wave velocity profiles across the site.

This integrated approach yields a more reliable and comprehensive ground model. Beyond stiffness characterization, shear wave velocity (V_s) plays a central role in evaluating soil performance under dynamic conditions, such as:

- **Cyclic loading** (e.g., under wind turbines, machine foundations, and transport corridors).
- **Seismic hazard assessment**, including evaluation of liquefaction potential in both natural deposits and man-made fills (e.g., tailings dams).
- **Liquefaction analysis** through determination of cyclic resistance ratio (CRR), where reliable V_s values are used to assess the likelihood of liquefaction under a given cyclic stress.

7. Sample Results

Sample SCPT results from the geotechnical investigation conducted by Cengrs for a proposed solar power plant project in Kachchh, Gujarat, are presented in Figure 6. The interpreted shear wave velocity [based on the Robertson and Cabal (2022) correlation] is in good agreement with the measured shear wave velocity from the seismic cone penetration test conducted at the site.

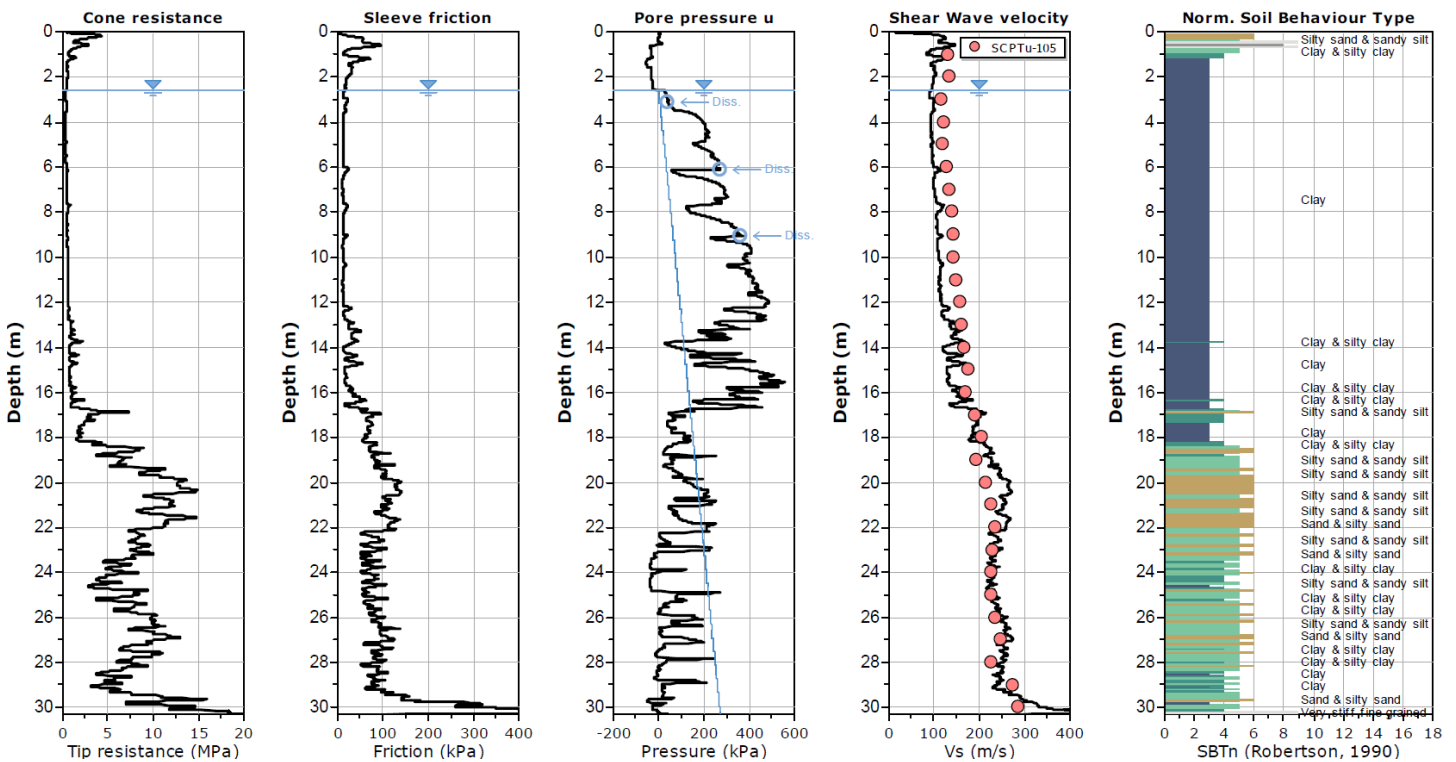
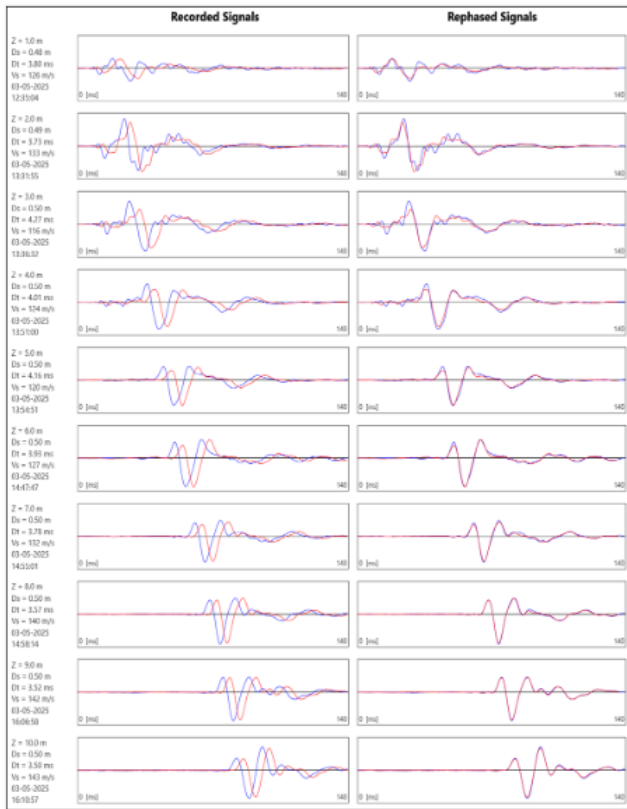
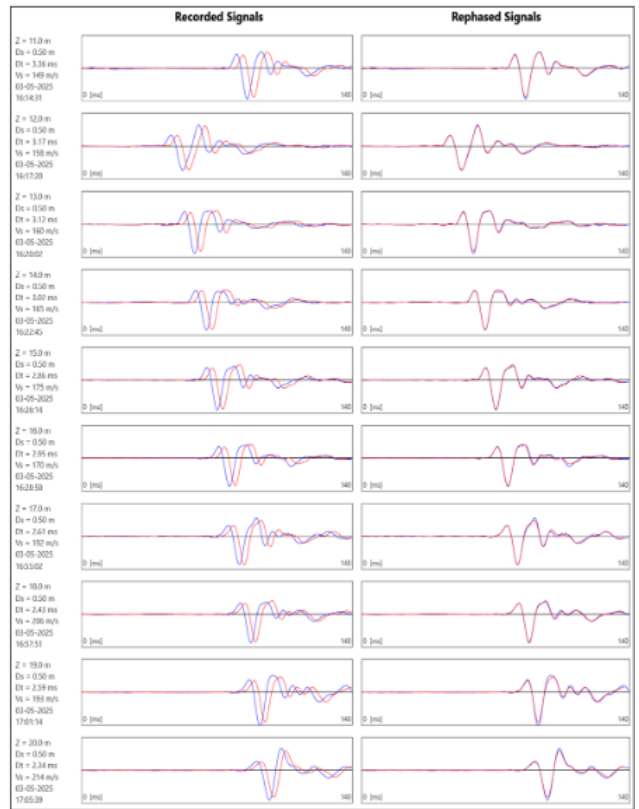


Figure 6. Depth profiles of cone resistance q_c , sleeve friction f_s , pore pressure u_2 , shear wave velocity V_s , and normalized soil behavior type (SBTn) from an SCPTu test conducted at Kachchh, Gujarat.

Figure 7 shows typical recorded and rephased signals for 0-10 m and 11-20 m depth in 1-m depth intervals, while Figure 8 shows the depth profiles of V_s and G_0 for the site in Kachchh, Gujarat.



0-10 m depth (1-m intervals)



11-20 m depth (1-m intervals)

Figure 7. Recorded and rephased signals for 0-10 m and 11-20 m depth in 1-m depth intervals for the SCPTu test conducted at Kachchh, Gujarat.

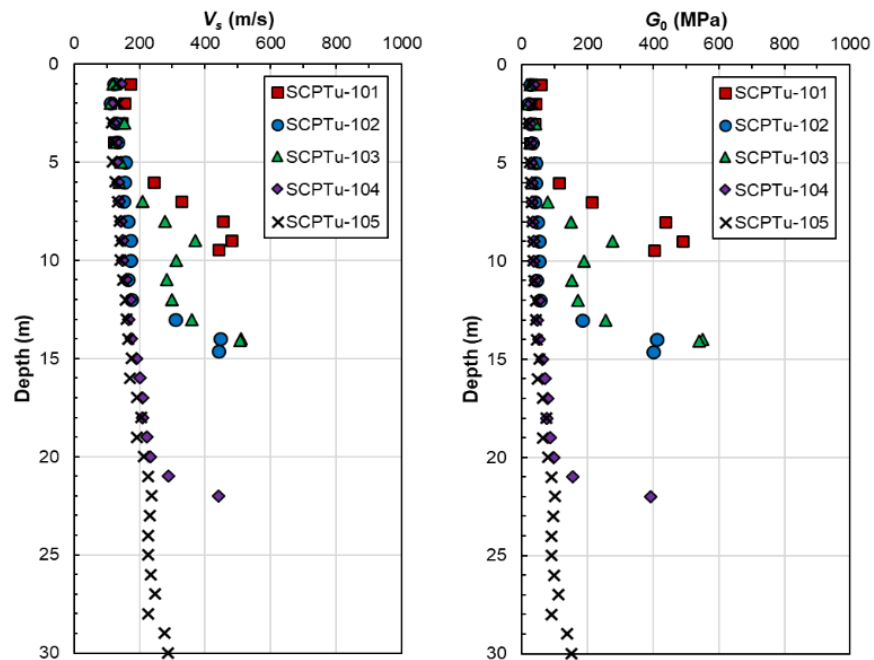


Figure 8. Depth profiles of shear wave velocity V_s and small-strain shear modulus G_0 for five SCPTu tests conducted at the site in Kachchh, Gujarat.

8. Conclusions

The seismic cone penetration test (SCPT) is an effective, hybrid investigation method that combines the stratigraphic and behavioral profiling capabilities of the CPT with direct measurement of seismic wave velocities. This integration enables simultaneous characterization of both soil strength and stiffness parameters, significantly enhancing the value of a ground investigation program.

SCPT is particularly attractive because it can be rapidly deployed and provides reliable measurements of small-strain soil stiffness, including the shear modulus (G_0) and Young's modulus (E_0). These parameters are essential in addressing geotechnical problems involving dynamic and cyclic loading, such as the design of wind turbine foundations, machine foundations, highways, and the evaluation of sensitive or man-made deposits (e.g., tailings dams).

Finally, as with all geotechnical testing methods, SCPT should be performed in accordance with relevant international standards. Adhering to these standards ensures data consistency, reliability, and acceptance in engineering practice.

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IS 4968: Part 4 - Method of subsurface sounding for soils - Electric Cone and Piezocone Penetration test (*draft code under review at BIS, expected to be finalized this year*)