Add-on Sensors for Cone Penetration Testing

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ABSTRACT: The widely used cone penetration test (CPT) allows in-situ measurements and interpretation of soil behaviour during continuous penetration. The traditional sensors incorporated in a cone penetrometer are for measuring cone resistance, sleeve friction, pore pressure and inclination. Many supplementary sensors have been studied and tried in research settings and in practice. Examples are sensors for natural gamma radiation, electrical resistivity and acoustic emission activity. None have yet made it to routine practice. This paper presents a review of CPT add-on sensors that (1) allow continuous penetration at 20 mm/s, (2) are robust, i.e. have no external moving parts, and (3) offer the potential for broad geotechnical value, not limited to special applications only. This review considers recent advances in electronics, sensor technology and data processing systems. A commentary is presented that provides direction for future research with the aim of enhancing CPT data towards more complex, wider applications.

Keywords: cone penetration test; add-on sensor; in-situ testing; soil investigation; geotechnical engineering

1. Introduction

The Cone Penetration Test (CPT) is one of the most commonly used tools for in-situ testing with a long history of application in geotechnical engineering. The classic CPT [1] results in measurements of cone resistance (q_c), sleeve friction (f_s), pore pressure (u) and inclination (i) with depth. These measurements are commonly used for deriving soil parameter values for general site characterisation and for geotechnical design.

General advances in electronics, sensor technology and data processing systems triggered research and development of CPT add-on sensors, i.e. additional sensors that can fit within a CPT cone. Many supplementary sensors have been studied and tried in research settings and in practice (Fig. 1). Examples are sensors for natural gamma radiation, electrical resistivity and acoustic emission activity. None have made it to routine practice; why not? Barriers to industry acceptance probably include:

- Cone penetration test data are low cost, which means investments in new technology must lead to a significantly improved product which has clear customer demand.
- Fees for special CPTs (e.g. with add-on sensors) are substantially higher than traditional CPTs. Convincing arguments about added value for a particular project can be difficult.
- Validation and wide acceptance of sensors (and demand for their use) takes a long time. Development of a comprehensive data base of special CPT profiles will be required, supplemented by companion (paired) data acquired by other in-situ and laboratory test methods. In most cases, acceptance cannot be achieved by theoretical modelling and laboratory experiments only.
- Correlations tend to focus on utilising standard measurements, to facilitate widespread use.

Opportunities for initial acceptance of add-on sensors may be available for high-end projects, for which (1) added confidence about in-situ conditions offers high value in a broad sense (e.g. ISO 2019 [1]) and (2) schedule reduction can be achieved by reducing the scope of laboratory testing.

Integration of data from a single add-on sensor along with classical CPT data can provide added value. Data acquired from multiple add-on sensors offer further opportunities for added value.

This paper provides a review of CPT add-on sensors, including their advantages and disadvantages, and their state of development. Many tools that resemble penetrometers have been developed, but this review only includes sensors that are added to a standard CPT; this means: (1) data are acquired during continuous penetration at 20 mm/s, (2) they are robust, i.e. have no external moving parts, and (3) they provide broad geotechnical value, i.e. not limited to special applications only.

This review excludes systems requiring internal/external mechanical hardware, such as the cone pressuremeter test, vibratory CPT, seismic cone penetration test, permeability CPT requiring fluid injection, etc. Any sensors with tools having nuclear sources are excluded from this review for safety and environmental concerns. Sensors with a purely geo-environmental application such as pH sensor, redox potential and laser induced fluorescence sensors are also not included.

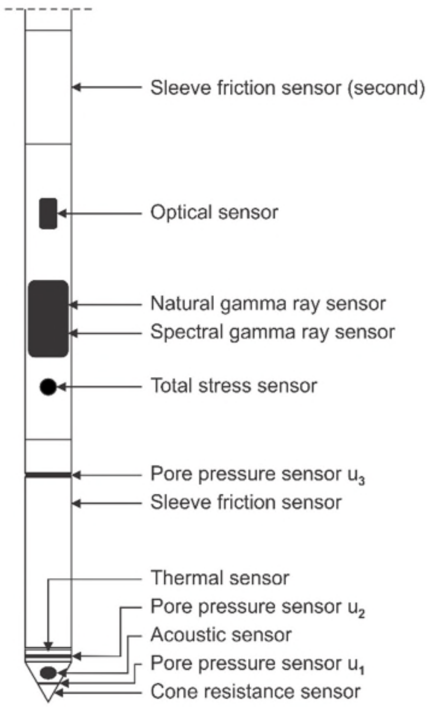

Figure 1. Conceptual cone penetrometer with example add-on sensors.

2. Add-on Sensors

2.1. Overall Potential Rating

Table 1 presents add-on sensors meeting the scope and criteria given in the Introduction section. The table also presents sensor parameters, potential application(s), technology readiness level (TRL) according to API 17 N [3], and overall potential rating. The sensor parameters of Table 1 refer to the data that are directly measured by the add-on sensor.

Potential applications of each sensor are assessed in terms of added value for three primary areas: soil stratigraphy, soil composition/classification, and soil behaviour. The assessment considers a single type of add-on sensor, i.e. ignores potential enhancement by combining multiple add-on sensors.

The API technology readiness level (TRL) system considers "concept" (TRL 0 to 3), "prototype" (TRL 3 to 5) and "field qualified" (TRL 6 and 7) phases of any new technology. The TRL system is a type of measurement system for assessing the maturity level of a particular technology. Each technology development can be assessed against defined parameters for each technology. A TRL rating can then be assigned.

The overall potential rating focuses on the applicability of a sensor to be incorporated in a cone penetrometer used in routine industry practice. The rating system considers (1) added value with respect to application(s), (2) operational robustness, (3) challenges anticipated during integration of the sensor with the classic cone penetrometer, considering current TRL and (4) add-on cost. A rating of H indicates high potential for sensor integration with wide application, added value to existing data, and minor challenges to overcome. A rating of M indicates a medium potential with limited application, and/or multiple challenges to overcome (e.g. design, cost, efficiency etc.). A rating of L indicates a low potential for integration due to low application and/or a lack of efficiency (cost and/or time).

The following sub-sections provide more detailed information. The sensors are grouped according to the rating assigned, starting with the high potential sensors and moving to the lower rated sensors. The discussion typically includes a brief introduction of each sensor and its measuring concept along with comments to justify the rating. The test procedure is covered in cases where deemed necessary.

Table 1. Summary of add-on sensors

Add-on Sensor (alphabetically	Parameter(s)	Potential applications	TRL	Overall Potential Rating
Acoustic sensor	Acoustic emission activity [kHz]	stratigraphy, relative density	3	H
Electrical resistivity sensor	Soil/water electrical resistivity [ohm-m]	ground water level, stratigraphy	7	L
Total stress sensor	Total stress [kPa]	horizontal stress, soil stiffness	5	L
Magnetometer	Magnetic flux density [nT]	detecting in-ground structures and ferrous objects (e.g. Unexploded Ordinance, UXO)	7	L
Multi pore pressure sensors	Pore Pressure [kPa]	liquefaction, strength, strain induced degradation, flow & consolidation characteristics, permeability	7	H
Multi sleeve friction sensors	Axial force [kN]	stratigraphy, friction degradation, strength, strength degradation, interface shear	2	H
Natural gamma ray sensor	Total gamma ray count from Th, U & K [GAPI]	stratigraphy, depth indicator	6	H
Optical sensor	Optical image	stratigraphy, particle size analysis	4	M
Spectral gamma ray sensor	Individual gamma ray count - K, U, Th [GAPI]	stratigraphy, depth indicator, soil type interpretation, clay mineralogy	5	H
Thermal sensor	Temperature [° Celsius]	stratigraphy, soil classification	7	M

2.2. High Potential Sensors (rating = H)

2.2.1. Acoustic sensor

The acoustic sensor is typically microphone placed in the tip of the cone penetrometer for measuring acoustic emission activity generated by particle rearrangement and particle crushing due to cone penetration.

The added-value for an acoustic sensor is mostly for coarse grained soils; clay-dominated soils generate very low levels of acoustic emission when sheared [4]. The sensor shows potential for enhanced interpretation of stratigraphy at sites with varying fines content [5], due to the amplitude of the acoustic signal increasing with increase in particle size [6].

Acoustic emission is influenced by factors such as particle size, soil density, structure and aging and is largely independent of in-situ stress levels. These factors offer potential for improvement of estimation of relative density and/or state parameter. Neural networks have been used to automate the process of identifying soil characteristics from acoustic emission data [5].

An obvious limitation is influence from background noise such as generated by the CPT push rods, the thrust machine, nearby traffic and (breaking) waves in case of nearshore/ offshore CPTs.

The acoustic add-on sensor is assessed to be highly favourable in terms of robustness and limited costs to include the sensor. It is considered to have medium favourability for the resolution of the data and for level of the difficulty in interpreting the results.

2.2.2. Multi pore pressure sensors

Cone penetrometers with multiple pore pressure sensors have been available for more than a quarter of a century. However, they are rarely used in practice.

A minimum system would comprise pore pressure filters at the u_1 and u_2 positions [1], i.e. within the conical part of the cone tip and within the cylindrical part of the cone tip, respectively. A simple system for u_1+u_2 measurements can be by using by duplicate (immediately adjacent) CPTs, using one piezocone penetrometer with a u_1 filter position and one piezocone penetrometer with a u_2 filter position. Some cone penetrometers cover u_1+u_2+u_3, i.e. also include a pore pressure filter immediately above the friction sleeve.

The benefits of classic piezocone penetration testing (one pore pressure sensor) are well understood [7]. Published research on the added value of multiple pore pressure sensors is found to be limited.

Theoretical and experimental interpretation models exist [8, 9, 10] for obtaining valuable information on soil behaviour (e.g. soil strength, stiffness, permeability, shear induced pore pressure, liquefaction potential) from the differential pressure between the sensor locations, some of which are hard to obtain from the classic CPT. However, many of the interpretation models appear to be empirical and can require soil-specific calibration.

Interpretation of multiple pore pressure data is challenging for transitional and layered soils, as also for classic CPT data. Multiple pore pressure data probably offer insignificant added value for the specific cases of uniform, normally consolidated clays and clean sands with minimal or no change in the differential pressure.

Multi pore pressure sensors are evaluated to be highly favourable in terms of equipment robustness and resolution of data. The sensor system does however require additional research and developing a database for a large range of soils in order to be implemented in industry.

2.2.3. Multiple sleeve friction sensors

Cone penetrometers with multiple friction sleeves are largely experimental, i.e. TRL of 2. A minimum system would comprise a cone penetrometer with two friction sleeves, each with a geometry resembling classic CPTs, but one immediately above the other. Results from sleeve friction sensors are sensitive to wear and tear on the friction sleeve [11].

The primary add-on value for multiple sleeve friction sensors relates to soil friction degradation effects, i.e. how the friction changes with large (shear) strains. Such effects can be important, for example, for axial design of long, flexible piles.

DeJong [12] presented results for multiple textured friction sleeves, each with different roughness characteristics. The varying degree of shearing allows for estimation of differences in soil-structure interface [13, 14, 15].

Multiple sleeve friction sensors will generate added value for most soil types, including sandy, silty, clayey mixture soils.

The addition of one or more friction sleeves is evaluated to be highly favourable with respect to data resolution and relatively low add-on cost. A medium favourability is assigned with respect to equipment robustness. The addition of one or more friction sleeves makes the penetrometer longer, with weaker intermediate points compared to a classic cone penetrometer. This will limit maximum thrust that can be applied to the penetrometer.

2.2.4. Spectral gamma ray sensor

A spectral gamma ray sensor includes a Bismuth Germanate (BGO) crystal that records gamma ray counts from naturally occurring radioactive elements Thorium (Th), Uranium (U) and Potassium (K) present in soil.

To the knowledge of the authors, no spectral gamma ray sensor has been used as CPT add-on sensor to date. However, the spectral gamma ray sensor is commonly used in borehole geophysical logging and its dimensions would fit inside cone penetrometers with a cross sectional area of 1500 mm^2.

The primary application in site characterisation is that of a stratum–depth indicator, making it highly useful for correlating data between intrusive investigation locations for development of (spatial) ground models. Furthermore, understanding of the depositional environment, in particular clay minerology, can be enhanced [16].

The logging speed (rate of penetration) affects the resolution of data acquired. Borehole geophysical data suggest optimal logging speeds between about 15 mm/s and 65 mm/s [17], i.e. comparable to the standard CPT penetration rate of 20 mm/s. The sensor is robust with well-established principles and technology. The sensor provides gamma ray count in GAPI units (gamma ray API units), for which specific calibration is required [18, 19]. It is anticipated that incorporating a spectral gamma ray sensor in a cone penetrometer will imply some investment of cost and time to address any design or integration challenges that arise.

The spectral gamma ray sensor is assessed to have high favourability with respect to robustness and resolution of data, and medium favourability with respect to the technical integration challenges and add-on costs anticipated.

2.2.5. Natural gamma ray sensor

The natural gamma ray sensor is a sodium iodide (NaI) crystal that records total gamma ray count from naturally occurring radioactive elements Thorium (Th), Uranium (U) and Potassium (K) present in soil. The natural gamma ray sensor is often seen as a qualitative sensor (i.e. does not separate the gamma ray count between U, K, Th sources) where the spectral gamma ray sensor is seen as a quantitative sensor.

The natural gamma ray sensor has been incorporated in cone penetrometers with a cross sectional area of 1500 mm^2. Fugro has used this add-on sensor for a limited number of industry projects (TRL of 6).

Favourability for use are generally similar to those provided for the spectral gamma ray sensor.

2.3. Medium Potential Sensors (rating = M)

2.3.1. Optical sensor

Cone penetrometers with an optical add-on sensor are typically called video cone penetrometers. A video cone penetrometer allows a high resolution view of the soil passing along the sapphire window during continuous penetration. Systems typically include miniature cameras (with multiple magnification), an embedded lighting system, micro-optic components, and a durable scratch-resistant sapphire window installed in a camera housing unit placed above the friction sleeve.

Image processing analysis is typically used for post processing of data, e.g. for identification of soil type.

The primary added value appears to be for characterisation of transitional soils, where classic CPT interpretation struggles. The video feed can also be inspected for geological features that are too small to be detected using interpretation of classic CPT data, such as changes in stratigraphy, location of fine soil layers, and small-scale soil anomalies such as clay veins/fissures, sand lenses etc.

Based on the limited number of field tests carried out to date, the optical sensor is assessed at a TRL of 4 [20].

The optical sensor is rated to have high favourability for resolution of data with a medium favourability for added value, robustness, and add-on cost.

2.3.2. Thermal sensor

An add-on thermal sensor typically consists of a thermocouple located within the cone penetrometer, above the cone tip. A cone penetrometer equipped with a thermal sensor is commonly called a temperature cone penetrometer. As the penetrometer is pushed through the soil, the thermal sensor records temperature variation resulting from ambient (in-situ) temperature and temperature generated by friction between the soil and the cone penetrometer.

Temperature cone penetrometers are used by industry to derive thermal conductivity of soil by performing a temperature dissipation test [21] during an interruption of cone penetration. The authors are not aware of industry use of *continuous* thermal data for geotechnical interpretation. Some research is in progress on interpretation of additional information from a continuous temperature profile. The research is driven by the low-cost simplicity of incorporating and maintaining a thermal sensor in a cone penetrometer.

It can be noted that temperature data offer no added geotechnical value for the specific case of uniform, normally consolidated clays, as frictional heat generation will be negligible. However, one or more thermal sensors can offer benefits for verification of temperature effects on accuracy of CPT results [22].

This sensor is assessed to be highly favourable in aspects of robustness, data resolution and add-on cost; it is assigned low favourability with respect to interpretational challenges to overcome.

2.4. Low Potential Sensors (rating = L)

2.4.1. Electrical resistivity

Cone penetrometers with add-on electrical resistivity sensors typically include these sensors immediately above the friction sleeve. The added value of measurement of soil/water resistivity is mostly used in industry practice for environmental applications (TRL of 7).

Parameters of geotechnical interest, such as porosity and degree of saturation, can be estimated from the resistivity readings [23, 24]. The degree of resolution and accuracy is limited.

Other applications such as subsurface spatial variation (thin layer detection), sand dilatancy characteristics, relative density etc. have been proposed [25]. The added value of the add-on sensor for these applications is assessed to be limited compared to classic CPT data.

2.4.2. Magnetometer sensor

A magnetometer sensor measures the disturbance in a magnetic field induced by a ferromagnetic material. The magnetometer sensor requires a nonmagnetic module that is typically situated above the friction sleeve.

The magnetometer cone penetrometer is well established in industry practice (TRL of 7) with a highly specialised application in magnetic survey, for e.g. detecting mineralisation (with corresponding geologic features), detecting buried ferrous objects such as Unexploded Bomb/Ordnance surveys (UXB/UXO), pile foundation length, sheet pile length, anchor locations, cables and pipeline positions.

It is assessed that the acquired data provide no significant added value to physical and or mechanical properties of soils.

2.4.3. Horizontal Stress sensor

Incorporation of one or more total stress sensors along the perimeter of a cone penetrometer has been studied by multiple researchers [26, 27]. The ultimate ambition for a horizontal stress sensor is to derive in-situ horizontal total stress during cone penetration and during any penetration interruptions.

The low potential assigned to this add-on sensor is linked to "instrumentation details" such as (1) separation of the simultaneous influence of shear stresses and radial stresses acting on the surface of the sensor and (2) significant effects of "microscopic" geometry variations on acquired data.

3. Discussion and concluding remarks

Enhancement of the capability of the site investigation industry can lead to improved sustainability, including lower risk for developers of facilities. One potential route for improvement is integration of add-on sensors with existing in-situ tests, such as the cone penetration test.

Sensors have become physically smaller, more robust, cheaper and more precise at measuring, yet many sensors have not made it to CPT practice, primarily due to a lack of research, long lead times and high costs anticipated. It can be inferred that no short-term, easy wins are foreseen for industry practice.

The presented overview of available and possible CPT add-on sensors attempts reconsideration of status quo, particularly by means of an overall potential rating applicable to a single sensor added to classical CPT data acquisition. The rating provides a basis for further investigation of opportunities for (1) incorporating two or more different add-on sensors in a cone penetrometer and (2) application of data sciences (machine learning) for analysis and interpretation of the multiple data sets.

Enhanced CPT data also offer opportunities for more complex, wider application to multiple types of methods for site characterization. Examples include improved correlation of the enhanced CPT data with, for example, laboratory test results, borehole geophysical logging and 2D/ 3D ultra-high resolution seismic reflection data.

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