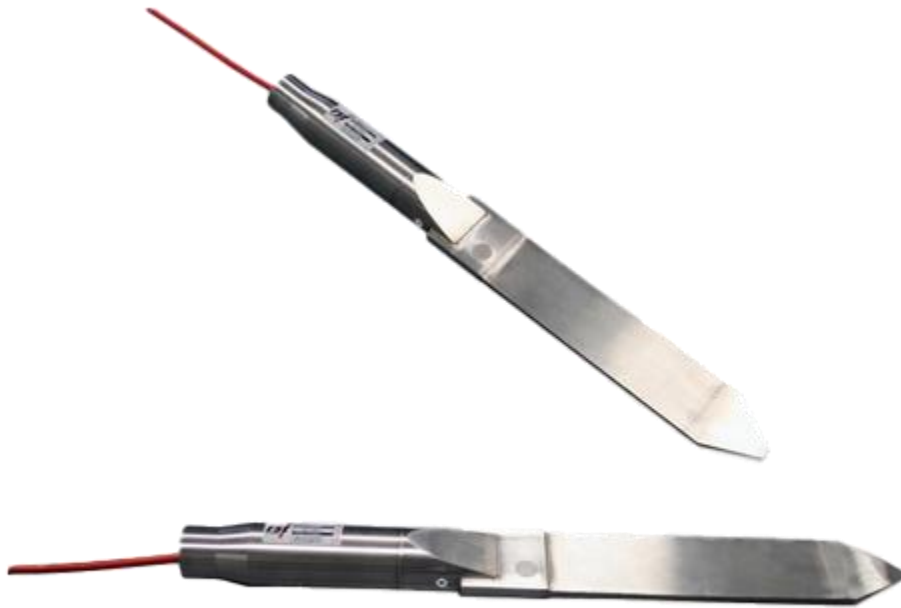




Vibrating Wire Push-In Pressure Cell Installation and User Manual

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REVISION HISTORY

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A	Initial release.	2019-Sep-17	MP	AP
B	Manual re-write. Calibration equations and sample records updated. Ordering information updated.	21 February 2025	SM	QR, SP, JP, WV

1 INTENDED AUDIENCE

This guide is for the personnel responsible for installing or using RST's Vibrating Wire Push-In Pressure Cell. This manual provides steps for installing the Vibrating Wire Push-In Pressure Cell, how to take readings, and interpret them.

2 ICONS AND CONVENTIONS USED IN THIS GUIDE

This guide uses the following icons to call attention to important information.



WARNING: This icon appears when an operating procedure or practice, if not correctly followed, could result in personal injury or loss of life.



CAUTION: This icon appears when an operating procedure or practice, if not strictly observed, could result in damage to or destruction of equipment.



NOTE: This icon appears to highlight specific non-safety related information.

3 SAFETY



WARNING: Always follow safety precautions and use proper personal protective equipment (PPE) including safety glasses and high-visibility clothing when working in the field with this equipment.

4 ABBREVIATIONS AND ACRONYMS

This section lists abbreviations and acronyms used in the document.

Abbreviation or acronym	Definition
VW	Vibrating Wire
CF	Calibration Factor
kPa	Kilopascal
MPa	Megapascal

5 OVERVIEW

5.1 THEORY OF OPERATION

RST's Vibrating Wire Push-In Pressure Cell, also called a Spade Cell, is designed to be pushed into a soil area to measure total earth pressure. An in-built piezometer within the unit allows for the measurement of pore water pressure and hence the calculation of effective soil pressure.

It can be used as a site investigation tool to determine vertical and horizontal in-situ stress state, depending on the direction of installation. Additionally, it can be used to monitor the change in active and passive pressure around structures such as diaphragm walls, in tunnelling, and other earthworks.

While the Vibrating Wire (VW) Push-In Pressure Cell can be used to measure total earth pressure in all soil types, it is typically installed in fine grained cohesive soils, including very soft to stiff clays.

The cell is constructed from two longitudinal stainless-steel plates welded together, leaving a gap between them that is filled with the hydraulic fluid – deaired glycol.

The soil pressure pushes the plates together, causing a build-up of pressure in the fluid contained between them. The fluid pressure is then converted to a signal via the VW pressure transducers, which can be remotely read on a variety of portable readout units or data loggers. The integrated piezometer measures pore water pressure, allowing for the calculation of effective soil pressure using Terzaghi's principle of effective stress.



NOTE: Effective soil pressure obtained using Terzaghi's principle of effective stress:

$$\sigma' = \sigma - \mu$$

Where:

σ' = soil pressure

σ = total pressure

μ = pore water pressure



NOTE: Depending upon the application and project requirements, VW Pressure Cells can be used singly, or multiple cells can be installed near each other.

RST recommends using sufficient cell locations to obtain soil pressure readings that are representative of the area being surveyed.

There is inherent variability in soil properties across an area of soil, causing varying soil pressures at different places in the soil. The use of limited cell locations will hence not provide a good sample of the mean pressure.

5.1.1 Vibrating Wire Pressure Transducer Operating Principle

The vibrating wire pressure transducer operates by measuring total earth pressure through the detection of changes in both the tension and the resonant frequency of a high tensile steel wire that is securely clamped at both ends. When this wire is excited via electromagnetic coil/magnets embedded into the insert housing, it vibrates at a natural resonant frequency determined by its density and elastic modulus. Any applied pressure modifies the wire's tension, which in turn alters its resonant frequency: an increase in tension raises the frequency, whereas a decrease lowers it. The change in frequency is directly proportional to the square root of the applied tension and is quantified into pressure readings using calibration units.

5.2 FEATURES

- Integrated piezometer allows for deduction of effective pressure.
- Rapid response to low volume pressure changes.
- VW frequency output is immune from cable effects, including length (up to several kms), splicing, resistance, noise pickup, and moisture.
- Fitted with thermistor for monitoring temperature.
- High accuracy and sensitivity.
- Long-term stability.
- Constant monitoring capability.
- Ease of data logging.
- Stainless-steel construction.

5.3 APPLICATIONS

- Estimation of in situ horizontal stress.
- Measurement of vertical and horizontal stresses to monitor clay cliffs degradation.
- Measurement of stress change adjacent to retaining walls.
- Monitoring stress redistribution around tunnels in soils.
- Measurement of lateral total earth pressure due to vibro stone columns and strip foundation loading.
- Risk assessment of hydraulic fracture of clay cores or cut-off trenches in dams.
- Measurement of earth pressure changes during and after blasting compaction.

5.4 VW PUSH-IN PRESSURE CELL DESIGN

These pressure cells are hydraulic type; two longitudinal stainless-steel plates are welded together around their periphery and the annular gap between the plates is filled with the hydraulic fluid, deaired glycol. A port and filter for pore water pressure measurement are located on one of the flat sides of the support plate, behind the pressure sensitive section of the cell. The pressure cell and the port for the pore water pressure are connected via stainless steel tubes to two vibrating wire pressure transducers present in the cell, one for the measurement of total earth pressure and one for the measurement of pore water pressure.

A thermistor for temperature measurement is also incorporated in the cell.

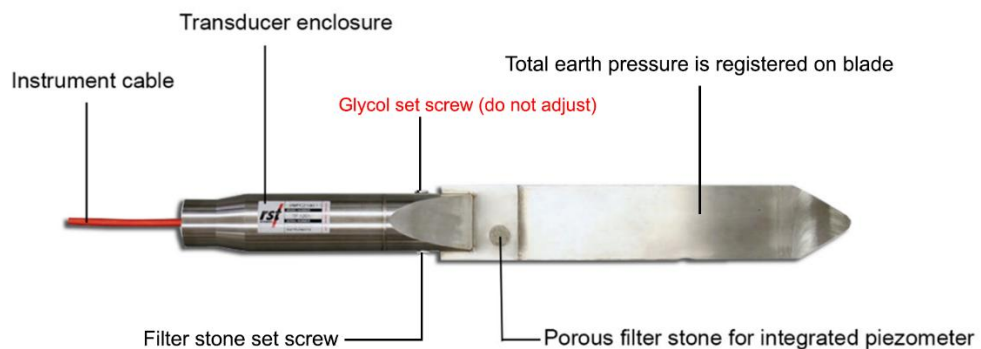


Figure 1: VW Push-In Pressure Cell with Components



CAUTION: Please ensure that the glycol set screw is not tampered with, as this will cause damage to the Push-In Pressure Cell.

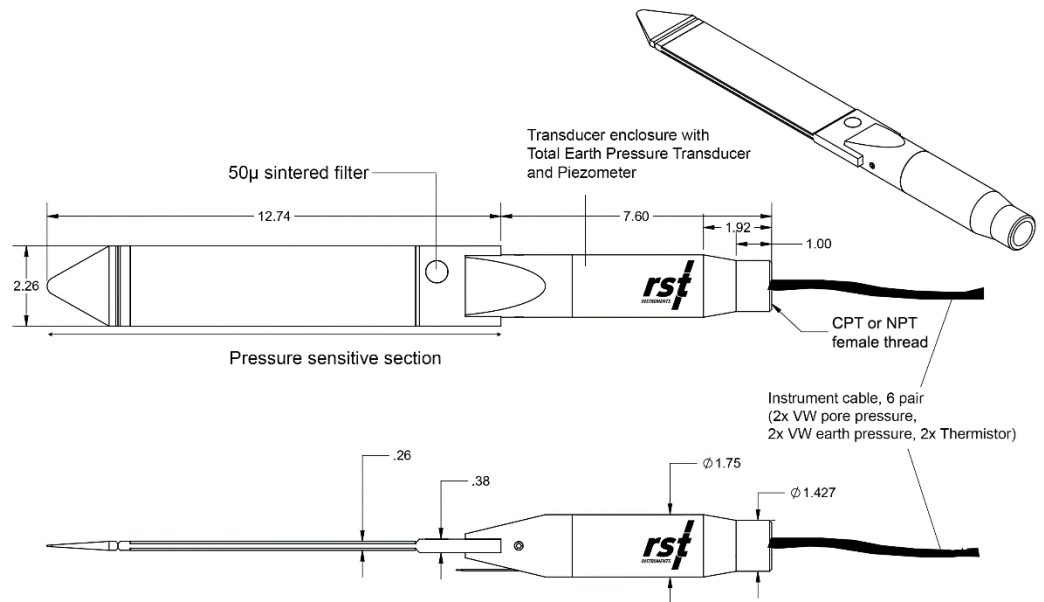


Figure 2: VW Push-In Pressure Cell Dimensions

6 INSTALLATION

6.1 PRELIMINARY TESTING

A full inspection of all received vibrating wire instrumentation equipment is required immediately upon receipt at site to ensure that the instruments have not been damaged in any way during shipment and are fully functional/ready for use.

→ **NOTE:** Contact RST Instruments in case any damage to the instrument is found.

Test readings should be taken and compared to the reading information provided on the Calibration Record sheet. Any discrepancies should be fully investigated and satisfactorily resolved before the instrument is released for field installation and service. The individual performing the inspection and initial test readings must be familiar with the vibrating wire instrument's operation and the contents of this manual.

6.1.1 Functionality Check

1. Connect the cell's electrical leads to a readout device.

→ **NOTE:** If using RST's VW2106 Readout, refer to the wiring chart in [Table 1](#).

2. Gently press on the blade of the cell, causing changes to the readout digits, corresponding to pressure changes in the Total Earth Pressure transducer (red and black wires). Ensure that as pressure is increased or decreased, the reading decreases or increases respectively.

6.1.2 Insulation Check

An Ohmmeter can be used to carry out insulation checks.

For proper insulation, the resistance between any conductor and the shield must be greater than 50 MΩ.

6.1.3 Thermistor Check

An Ohmmeter can be used to carry out thermistor checks.

→ **NOTE:** The integrated thermistor is a Negative Temperature Coefficient (NTC) thermistor, i.e. its resistance decreases as the temperature it is exposed to is increased.

1. Confirm the thermistor's rated value (3 kΩ).

2. Without applying any heat to the thermistor, check the resistance value between the green and white wires. It should be very close to the rated value.

Refer to [Appendix B](#) for a table of expected resistances versus temperature values.



NOTE: At an ambient temperature of 25 °C the resistance value is around 3 kΩ.

3. Next, apply heat to the thermistor using a heating device such as a heater or dry blower. If the thermistor is functioning properly, the resistance should start steadily declining within seconds once heat is applied.

6.2 INSTALLATION PRE-REQUISITE: FILTER SATURATION

The porous filter stone for the integrated piezometer protects the delicate diaphragm area of the pressure transducer while allowing transmission of pore water pressures. It **MUST** be saturated before installation to allow the accurate transmission of hydraulic pressures to the vibrating wire diaphragm.

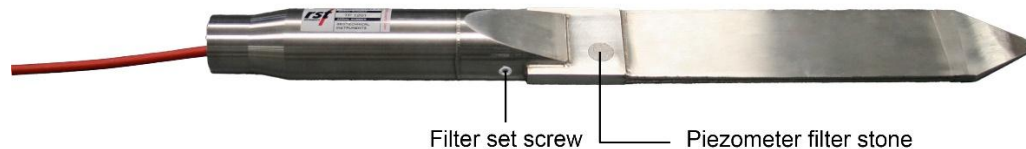


CAUTION: If your Push-In Pressure Cell does not have an integrated piezometer, do not perform filter saturation, and proceed from [Section 6.3](#) onwards.

Do not allow the piezometer to freeze once the filter stone has been saturated.

Perform the following steps to saturate the filter:

1. Ensure the piezometric filter stone is clean and free from any debris or contaminants.
2. Remove the filter set screw, i.e., the set screw closest to the filter stone.



CAUTION: Take care to remove **ONLY** the filter set screw. Removing the glycol set screw on the opposite side of the cell will cause damage to the Push-In Pressure Cell.

3. Submerge the Push-In Pressure Cell vertically, with the pointed end facing upwards in a bucket of flat water to allow for air bubbles to escape. Ensure the entire space between the piezometer diaphragm and the filter stone is filled with water.



NOTE: Flat water is water that has been sitting still for 24 hours.

4. Allow the pressure cell to sit in the water until the filter is completely saturated (for at least 24 hours). During the saturation process, periodically check the water level to ensure it covers the filter stone completely. If required, add more water to maintain the desired saturation level.
5. Keeping the pressure cell submerged, slowly screw the filter set screw back on.
6. Keep the pressure cell submerged to maintain filter saturation until installation.

6.3 ZERO READING

Calibration values for both the Total Earth Pressure and Pore Water Pressure Sensors are present in the calibration report supplied with the pressure cell. See sample calibration reports in Appendix A.



NOTE: The initial (zero) reading of the Total Pressure measurement is obtained from the fluid pressure in the glycol.

Please note that the base reading may be affected by ambient temperature and the barometric pressure.



CAUTION: Prior to installation, the initial (zero) reading must be recorded.

6.3.1 For Total Pressure Measurement

1. Connect the cell's electrical leads to a readout device per [Table 1](#).
2. Each cell is provided with a no-load zero reading. Compare current zero reading with the "Shipped Zero Readings" on the provided calibration report.
3. For a successful test, the two readings must not differ by more than 1% FS after accounting for temperature, barometric pressure, height above sea level and cell position (vertical, horizontal or at an angle).

6.3.2 For Pore Pressure Measurement

Vibrating wire piezometers differ from other types of pressure sensors as the core of the vibrating wire sensor is manufactured with an initial tension. The piezometers have a positive B-Unit reading without any external pressure being applied. Vibrating wire piezometers are acutely sensitive to pressure changes at zero point as there is no zero-point hysteresis to overcome. The determination of vibrating wire instrument initial readings at the “zero point” is extremely important for the accuracy of the subsequent readings.

Before installing the vibrating wire piezometer, it is necessary to take the initial zero reading with no applied load. The initial zero reading can be taken either with the filter stone removed, or with the stone completely saturated and installed. If the filter stone is saturated, initial zero readings should be taken with the piezometer exposed to the open air.



CAUTION: Do NOT submerge the instrument in water to take the initial readings. Only atmospheric pressure should be applied to the piezometer at this time. Failure to do so may impact the accuracy of the subsequent readings.

The temperature reading from the internal thermistor must also be recorded. The barometric pressure for piezometers with a total range lower than 2 MPa must also be recorded. These values are needed to apply the correct correction factors for changes in temperature and/or barometric pressure, which will impact the reading accuracy of the vibrating wire piezometers through their intended range.

Initial zero readings are generally obtained immediately prior to installation with no external pressure and a constant ambient temperature and barometric pressure.



NOTE: Thermistor and barometric pressure readings must be recorded when the initial (zero) readings are taken.

The following checks are required to obtain accurate initial zero readings:

- Has the temperature of the vibrating wire piezometer body reached full thermal equilibrium?

Variations in temperature across the mass of the piezometer body may result in a temperature reading which is not consistent with the entire vibrating wire instrument. This inconsistency will result in an error in the calculated pressure being read by the vibrating wire sensor. Allow 20 to 30 minutes for the temperature of the vibrating wire piezometer to equilibrate. Sources of temperature fluctuation, such as water flow, may have to be eliminated.

- Is the filter stone saturated?

Surface tension effects within the pore spaces of the filter could affect the zero readings if the filter stone is only partially saturated. This can be a problem particularly at low pressures (less than 350 kPa). Remove the filter stone to allow direct atmospheric connection with the transducer diaphragm if there is any question regarding the adequate saturation of the filter stone.

6.4 OTHER CONSIDERATIONS

It is not recommended that the cells be installed in wells or standpipes where an electrical pump and/or a power supply cable is present or nearby. Electrical interference from these sources can cause unstable readings.

Additional steps must be performed on site to ensure complete isolation and adequate grounding of the instrumentation circuits if installation under these conditions is unavoidable.

The instrument shield wire should be well grounded but isolated from sources of external electrical interference. In situations where pressure cells and packers are used at the same time in standpipes or wells, special care must be taken to avoid damaging or cutting the cable jacket with the packer equipment or tools. Any cuts in the cable jacket will cause water ingress, which can potentially result in damage or failure of the vibrating wire sensor.

6.5 REQUIRED EQUIPMENT

Before installing the VW Push-In Pressure Cell, make sure to have the following equipment:

- Single-channel or multi-channel data acquisition systems and readout terminal stations (depending on site requirements)
- Push Adapter (1 required per cell)
- Push Adapter for rods (1 required per project)

6.6 PRESSURE CELL INSTALLATION



NOTE: RST recommends obtaining pre-installation zero readings in the drill hole at the drill hole temperature. It may take some time for the sensor to reach thermal equilibrium.



CAUTION: Ensure that the drillhole diameter is at least 100 mm. To ensure that the drillhole stays open, casing may be needed to stop the drillhole from collapsing, especially in soft ground.

The following instructions outline the steps required to successfully install a Push-In Pressure Cell:

1. Drill a pilot hole slightly shorter than the planned installation depth.
2. Connect the Push-In Pressure Cell to a readout. Take initial readings for both piezometer and total pressure transducers. Refer to [Table 1](#) for a wiring chart if using RST's VW2106 readout unit.
3. Carefully push the Pressure Cell into the pilot hole. Monitor the readout to ensure that the cell is not over pressurized.



CAUTION: While pushing the cell into the soil, pressures larger than the maximum range of the sensors can be generated, causing the sensor to experience a zero shift or in extreme cases, permanent damage.

To prevent this, take readings continuously as the sensor is being pushed in. When the indicated pressure approaches 150% of the maximum range, pause the pushing action until the sensor output returns to its normal calibrated range.

4. Push the Pressure Cell about 1 meter past the bottom of the pilot hole using standard drill rods or Cone Penetration Test (CPT) rods. The rods may either be left in place or retrieved at a later stage after the measurements are completed.



NOTE: An inverse thread adapter on the cell or push rods together with a push adapter may also be used if the cell is to be left permanently in place.

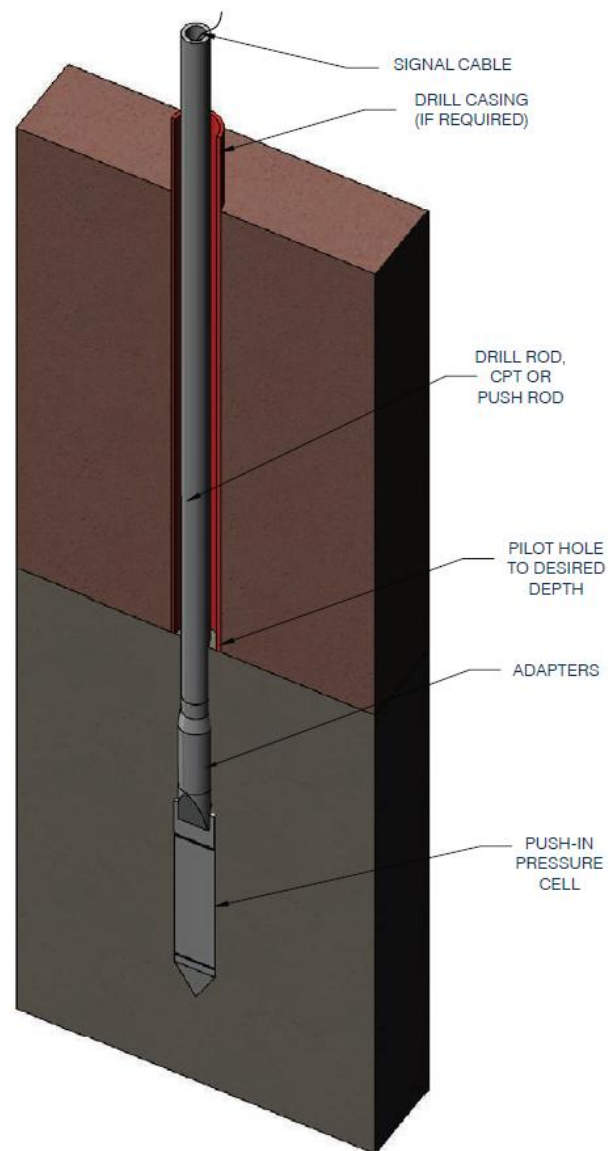


Figure 3: Typical Installation of a Push-In Pressure Cell

6.7 CABLE IDENTIFICATION

The vibrating wire cables are identified with a serial number tag that is attached to the cable jacket at the readout end. If the cable must be cut, this VW serial number tag must be removed and reattached at the new cable end.

6.8 CABLE INSTALLATION AND ROUTING

→ **NOTE:** Specific cable installation instructions will depend upon the VW Push-In Pressure Cell installation, on a case-by-case basis.

Contact RST for support and additional information.

In general, all installations must adhere to the following guidelines:

- Protect the cable from damage by sharp surrounding material
- Protect the cable from damage by compaction equipment
- In embankments and backfills, protect the cable from stretching

6.8.1 Transition from Vertical Drillhole to Horizontal Trench

The vibrating wire cable should be routed along a curved path as it goes from a vertical to a horizontal position. At the collar of the borehole, prepare a large radius circular transition path within a cushion of screened sand/5% bentonite mix, hand compacted to the surrounding fill density. Embed the cable along this transition pathway and bury it in place to ensure the cable will not be stretched or kinked by uneven loading.

6.8.2 Horizontal Cable Runs

Two methods are currently used to protect horizontal cable runs from damage. The first method is embedment within selected materials on the surface of the fill. The second method is embedment in an excavated trench in the fill. The second method is the most used because once the trench is backfilled and compacted, the surface can be used for access.

The trench method is discussed below.

→ **NOTE:** The trench dimensions should be 300 mm wider than the width required for the cable layout and a minimum 600 mm deep. A 100 -150 mm bedding layer of 1 mm minus sand is then placed along the trench bottom. Bentonite can be added to the sand to form an impervious section or plug if required.

All surface cable installations require continuous surveillance and protection from traffic and earth moving equipment which must move around on the fill surface.

1. Cover the cable completely with a 150 mm lift of 10 mm minus select material.
-

2. Completely backfill the trench with selected material. Compact it with light hand operated equipment.
3. Avoid traversing transition zones in the fill where large differential settlements could occur and create excessive strain in the cable. If cables must traverse these zones, install them with additional length for cable snaking which will allow slack for settlement to occur, rather than creating excessive cable strain.
4. Avoid cable splices. Only use an RST ELSPLICE13 Electrical Cable Splice Kit for Vibrating Wire Cables if splicing is required. The kit will ensure a strong and waterproof splice.
5. Spend time on the design of the cable layout in the trench. Avoid overlaying or crossing the cable runs on top of each other. If overlaying and crossing cannot be avoided, the cables must be separated by a 50 mm blanket of compacted fine-grained soil.
6. Use horizontal or vertical snaking of the cable within trenches to provide a certain amount of potential slack to avoid overstressing the cables during backfilling and the subsequent fill placement.
 - For most materials, a pitch of 1.8 m with an amplitude of 0.4 m will be suitable.
 - In very wet clays, which could be subject to settlement, increase the amplitude from 0.4 m to between 0.6 m and 1.0 m.
7. During cable routing, taking pressure readings at regular intervals to ensure the continued function of the instrument. This is especially important prior to backfilling any trenches.

6.9 CABLE SPLICING

If the vibrating wire cable is cut and needs to be repaired, or the cable must be lengthened with a cable splice, RST recommends the use of an RST ELSPLICE13 Electrical Cable Splice Kit for Vibrating Wire Cable. Any cable splice that will be exposed to any moisture should be protected in this manner to eliminate the potential of water egress, short circuiting, and conductor corrosion.



CAUTION: If the cables are damaged or not spliced properly, the cell output can be extremely reduced.

6.10 ELECTRICAL INTERFERENCE

If installed near sources of electrical interference (power lines, generators, motors, transformers, arc welders, AC lines, etc.), the instrument cables will intercept frequency noise from them causing issues obtaining a stable reading.

Ensure that instrument cables are installed as far as possible from sources of electrical interference and never buried or run alongside AC power lines.

6.11 LIGHTNING PROTECTION

All RST Vibrating Wire Push-In Pressure Cells include built-in surge/lightning protection, suitable for most uses. However, when connecting multiple instruments into a large network, ensure the entire system is effectively isolated. This helps protect against potential damage from transient or induced currents affecting sensors and data acquisition equipment.

In cases where there may be additional risks of surge damage to the network and/or data loss, the following are suggestions for additional surge protection:

- If a pressure cell is connected to a terminal box or multiplexer on surface, components such as plasma surge arrestors (spark gaps) could be installed in the terminal box/multiplexer to provide an increased measure of transient protection.



NOTE: Terminal boxes and multiplexers available from RST provide built-in locations for the installation of these surge protection devices

- RST offers lightning arrestor boards and enclosures that can be installed where instrument cables exit drill holes or structures. These enclosures are easily accessible for quick servicing or replacement of the Surge 4C protection board if damaged by a surge. They are connected to the ground to divert transients away from the vibrating wire instrument.



NOTE: Additional information on surge protection alternatives is available from RST Instruments.

7 CALIBRATION

→ **NOTE:** RST's VW Push-In Pressure Cells are calibrated as a complete assembly (rather than just the sensor) to capture the calibration of the complete cell for highest quality of data.

All RST Vibrating Wire Push-In Pressure Cells are individually calibrated in the laboratory before shipment. Each pressure cell is calibrated over its full working pressure range. A Linear Calibration Factor (CF) is established by using the calibration data points to perform a linear regression. In addition, the calibration data is also fitted to a polynomial regression which provides slightly more accurate data output over the full reading range. Both formulae are provided on the instrument Calibration Record sheet for use as appropriate.

As part of the calibration procedure, all pressure cells are tested to 150% of the standard working range to prove their function at overpressure.

A Temperature Correction Factor (T_K) is provided for both pressure transducers in the Push-In Pressure Cell, to compensate for temperature dependent change in transducer output over the -20° C to +80° C operating range.

A Calibration Record sheet is provided with each vibrating wire sensor for use in calculating the applied loads on the vibrating wire sensors.

The following general information is contained in the Calibration Record sheet:

- Model, Serial, and Manufacturing Numbers
- Pressure Range
- Sales Order Number
- Cable Information (Length, Meter Markings, Color Code, and Type)
- Thermistor Type
- Linear Calibration Factor (CF)
- Temperature Correction Factor (T_K)
- Polynomial Gauge Factors (A, B, and C)
- Calibration Data Table
- Linear and Polynomial Formulas
- Zero Reading, Temperature, and Barometric Pressure at time of Shipment
- Calibration Certification

→ **NOTE:** Please refer to [Appendix A](#) for sample calibration record sheets.

8 READOUT PROCEDURES



NOTE: The readout procedures detailed here are specific to the RST VW2106 Readout Unit.

However, the pressure cell can be used with a wide variety of readout units or data loggers, such as RSTAR Affinity, RST VW2106 and DT2011.

For information on operating a specific data logger, refer to the logger's instruction manual.



CAUTION: Consulting the [RST VW2106 Readout Unit manual](#) is highly recommended prior to proceeding with readout procedures. Failure to become familiar with the function and operation of the VW2106 Readout could potentially result in damage to the VW2106 Readout unit and/or the vibrating wire sensors that are connected to it.

RST's VW2106 Readout Unit generates plucking voltages to the coil/magnet in a spectrum of frequencies, spanning the natural frequency of the vibrating wire. This plucking allows the vibrating wire to find its current natural frequency related to the pressure it is currently experiencing. In turn, the oscillation of the vibrating wire generates AC voltage in the coil. This output signal is amplified by the VW2106 Readout Unit, which also discriminates against harmonic frequencies, to determine the resonant frequency of the wire.

The VW2106 Readout Unit measures 100 cycles of vibration with a precise quartz oscillator and displays a value proportional to the frequency squared, which is called B-Units ($\text{Frequency}^2 \times 10^{-3}$). The B-units can then be converted to applied pressure via calibration factors.



NOTE: Please ensure that the "B" sweep setting (1200 – 3550 Hz) is applied for the Total Earth and Pore Water pressure vibrating wire sensors. For more information on sweep settings, navigate to the [RST VW2106 Readout Unit](#) product page and refer to the provided installation and user manual under the Downloads tab.

Referring to the following wiring chart, make the appropriate connections to the readout unit:

Table 1: RST VW2106 Wiring Chart for VW Push-In Pressure Cell

	Sensor Wiring		Thermistor Wiring
	Total Earth Pressure	Pore Water Pressure	
+ Input	Red	Orange	Green
- Output	Black	Blue	White

8.1 INITIAL READINGS



CAUTION: At the time of installation, initial readings at the zero point must be recorded along with barometric pressure and temperature. This ensures the accuracy of subsequent readings.

Record the initial no-load zero readings while the cell is in position, just prior to it being covered by fill or pouring of concrete.

Refer to Section 6.3 for more information.



CAUTION: Do not submerge the instrument in water to take the initial readings. Only atmospheric pressure should be applied to the piezometer at this time. Failure to do so may impact the accuracy of subsequent readings.

8.2 TEMPERATURE MEASUREMENT

RST VW Push-In Pressure Cells are supplied with an integrated thermistor for temperature measurements. The thermistor outputs varying resistances to a digital ohmmeter as the temperature changes.

Refer to [Table 1](#) for wiring diagrams.

To convert the measured resistance into a temperature reading, follow one of the following two procedures:

1. Refer to [Table 3: Thermistor Resistance Varying with Temperature](#) to convert the measured resistance into a temperature reading.
2. Use Equation 1 in Appendix B to convert the measured resistance into a temperature reading.

→ **NOTE:** When using long cables, the cable resistance may need to be accounted for. Standard 22 AWG stranded copper led cable is approximately 48.5Ω/km, multiplied by two for both directions.

8.3 SUBSEQUENT READINGS AND FREQUENCY OF MONITORING

Several readings should be taken on day 1 of installation, followed by a reading every day for the next 3 to 5 days. Sufficient readings taken during the first 10 days after installation will ensure the pressure cell is functioning properly in the short term.

Long-term monitoring frequency depends upon the individual project requirements.

For example, if an on-site soil stress profile is required, the following reading frequency would be sufficient:

- Several readings taken on day 1
- 1 reading every day for the next 10 days
- Weekly readings for the next month

→ **NOTE:** After a profile is obtained, the cell can be removed and installed in another location. Check that the initial (zero) reading when the cell is being removed is the same as the initial (zero) reading at the time of the installation.

If pressure cells have been installed permanently, for example, to continuously monitor earth pressure changes, the monitoring frequency will depend upon the operations.

8.4 OTHER NOTES

Excessive pressures are generated around the cells when first pushed into the ground, providing a higher value than the actual pressure.

RST recommends up to 10 days after installation to obtain a constant equilibrium pressure value.

Pore water pressures from the piezometer can take up to 7 days to completely stabilize before measurements can be confidently used.

9 DATA REDUCTION

→ **NOTE:** The VW2106 Readout Unit displays vibrating wire readings in frequency units called B-Units, which equal $\text{Frequency}^2 \times 10^{-3}$, where frequency is in Hertz. The B-Unit values represent absolute pressure and must be corrected for changes in temperature and barometric pressure.

→ **NOTE:** RST's dataloggers are set up to use either formula to calculate the pressure cell output in engineering units.

9.1 PRESSURE CALCULATION

Pressure is calculated with the following equations, which can also be found on the sample calibration sheets in Appendix A.

→ **NOTE:** [Appendix A](#) contains example calibration sheets for both Total Earth Pressure Sensor and Pore Water Pressure Sensor.

Please ensure to refer to the correct sheet for each calculation.

9.1.1 Total Earth Pressure Calculation (Glycol Sensor)

9.1.1.1 Linear equation

$$P \text{ (kPa)} = CF (L_o - L) + (S_o - S)$$

Where:

P	=	Pressure in kPa
CF	=	Calibration factor in kPa/B-unit (see calibration sheet)
L _o , L	=	Initial & Current B-unit reading ($\text{Frequency}^2 \times 10^{-3}$)
S _o , S	=	Initial & Current barometric pressure readings in kPa

9.1.1.2 Polynomial equation

$$P \text{ (kPa)} = A(L^2) + B(L) + C + (S_0 - S)$$

Where:

P	=	Pressure in kPa
A, B, C	=	Polynomial gauge factors (see calibration sheet)
L	=	Current B-unit reading (Frequency ² x 10 ⁻³)
S ₀ , S	=	Initial & Current barometric pressure readings in kPa

9.1.2 Pore Water Pressure Calculation (Water Sensor)

9.1.2.1 Linear equation

$$P \text{ (kPa)} = CF (L_0 - L) - T_K(T_0 - T) + (S_0 - S)$$

Where:

P	=	Pressure in kPa
CF	=	Calibration factor (see calibration sheet)
L ₀ , L	=	Initial & Current B-unit reading (Frequency ² x 10 ⁻³)
T _K	=	Temperature Correction Factor (see calibration sheet)
T ₀ , T	=	Initial & Current Temperature Readings in °C
S ₀ , S	=	Initial & Current Barometric Pressure Readings (kPa)

9.1.2.2 Polynomial equation

$$P \text{ (kPa)} = A(L^2) + B(L) + C - T_K(T_0 - T) + (S_0 - S)$$

P	=	Pressure in kPa
A, B, C	=	Polynomial gauge factors (see calibration sheet)
L	=	Current B-unit reading (Frequency ² x 10 ⁻³)
T _K	=	Temperature Correction Factor (see calibration sheet)
T ₀ , T	=	Initial & Current Temperature Readings in °C
S ₀ , S	=	Initial & Current Barometric Pressure Readings (kPa)

To convert the output to other engineering units, multiply the calibration factor by the conversion multiplier listed in the following table:

Table 2: Conversion Table for Engineering Units

From → To ↓	psi	"H ₂ O	'H ₂ O	mm H ₂ O	m H ₂ O	"HG	mm HG	atm	mbar	bar	kPa	MPa
psi	1	.036127	.43275	.0014223	1.4223	.49116	.019337	14.696	.014503	14.5039	.14503	145.03
"H ₂ O	27.730	1	12	.039372	39.372	13.596	.53525	406.78	.40147	401.47	4.0147	4016.1
'H ₂ O	2.3108	.08333	1	.003281	3.281	1.133	.044604	33.8983	.033456	33.4558	.3346	334.6
mm H ₂ O	704.32	25.399	304.788	1	1000	345.32	13.595	10332	10.197	10197	101.97	101970
m H ₂ O	.70432	.025399	.304788	.001	1	.34532	.013595	10.332	.010197	10.197	.10197	101.97
"HG	2.036	.073552	.882624	.0028959	2.8959	1	.03937	29.920	.029529	29.529	.2953	295.3
mm HG	51.706	1.8683	22.4196	.073558	73.558	25.4	1	760	.75008	750.08	7.5008	7500.8
atm	.06805	.0024583	.0294996	.0000968	.0968	.03342	.0013158	1	.0009869	.98692	.009869	9.869
mbar	68.947	2.4908	29.8896	.098068	98.068	33.863	1.3332	1013.2	1	1000	10	10000
bar	.068947	.0024908	.0298896	.0000981	.098068	.033863	.001333	1.0132	.001	1	.01	10
kPa	6.8947	.24908	2.98896	.0098068	9.8068	3.3863	.13332	101.320	.1	100	1	1000
MPa	.006895	.000249	.002988	.00000981	.009807	.003386	.000133	.101320	.0001	.1	.001	1

10 TROUBLESHOOTING



NOTE: This section details commonly encountered scenarios and steps for troubleshooting them.

Contact RST for additional support and troubleshooting help.

10.1 UNSTABLE PRESSURE READINGS

10.1.1 Nearby Sources of Electrical Interference

Shield the cables from nearby interference sources (motors, generators, transformers, arc welders, antennas, etc.) or move them.

10.1.2 Incorrect Drain Wire Connection

Ensure the drain wire is properly connected to the readout unit.

10.1.3 Low-battery or Malfunctioning Readout Unit

1. Check the readout unit's battery.
2. Check if the readout unit works with another pressure cell. If not, it may have a low battery or be functioning improperly. Refer to the appropriate readout manual for charging or troubleshooting instructions.
3. Shield the readout unit from the ground by placing it on a section of laminate or another insulating material.

10.1.4 Incorrect Readout Unit Settings

The incorrect excitation sweep frequency is being used which will not produce a stable reading.

1. Check the VW Calibration Record sheet for the installed VW sensor to determine the recommended sweep frequency for the sensor.
2. Change the sweep frequency settings in the VW2106 Readout and re-take the reading.

10.1.5 Sensor Outside of Range

The sensor may have been over-ranged or physically damaged. Inspect the pressure cell and housing for any obvious damage. Contact RST Instruments if necessary.

10.1.6 Sensor Body Shorted to Drain Wire

Check the resistance between the drain wire and the sensor housing.

10.1.7 Damage to Sensor

The sensor may have been damaged by electrical shocks or due to water ingress. The complete cell will need replacement.

10.1.8 Cable Compromised

Confirm the cable integrity.



NOTE: If the cable is severely damaged, refer to Section 8: Ordering Information for replacing the cable.

Minor cable cuts may be spliced in the meantime using RST ELSPLICE13 Electrical Cable Splice Kit to ensure a strong and waterproof splice.

10.2 NO READING DISPLAYED

10.2.1 Readout Unit Dead Battery

1. Check the readout unit's battery.
2. Refer to the appropriate readout manual for charging or troubleshooting instructions.

10.2.2 Incorrect Readout Unit Settings

The incorrect excitation sweep frequency is being used, which will not produce a stable reading.

1. Check the VW Calibration Record sheet for the installed VW sensor to determine the recommended sweep frequency for the sensor.
2. Change the sweep frequency settings in the VW2106 Readout and re-take the reading.

10.2.3 Sensor Outside of Range

The sensor may have been over-ranged or physically damaged. Inspect the housing for any obvious damage. Contact RST Instruments if necessary.

10.2.4 Cable Compromised

Confirm the cable integrity.



NOTE: If the cable is severely damaged, refer to Section 8: Ordering Information for replacing the cable.

Minor cable cuts may be spliced in the meantime using RST ELSPLICE13 Electrical Cable Splice Kit to ensure a strong and waterproof splice.

10.3 No VW PIEZOMETER READING DISPLAYED

10.3.1 Cable Damaged or Gauge Conductors Shorted

Check the resistance of the VW coils by connecting an ohmmeter across the gauge terminals (red and black wires).



NOTE: Nominal resistance is approximately 180Ω ($\pm 5\%$), plus cable resistance at approximately 15Ω per 300 m of 22 AWG wire.

Ensure to account for the two lengths of 22 AWG wire (i.e. red wire and black wire) in this calculation.

If the resistance is extremely high or infinite, the cable is possibly broken or cut.

If the resistance is extremely low, the gauge conductors may be shorted.

10.3.2 Readout Unit Not Working Correctly

Check the VW2106 Readout Unit with another vibrating wire piezometer to confirm that the unit is functioning properly.

10.3.3 VW Piezometer Over-Ranged

Inspect the pressure cell and housing for any obvious damage.

Contact RST Instruments if necessary.

10.4 VW PIEZOMETER READINGS UNSTABLE

10.4.1 Improperly Grounded Sensor

Connect the blue shield drain wire on the vibrating wire readout to the shield wire of the pressure cell. If this does not result in more stable readings, proceed to step 2 below.



NOTE: In the absence of a shield wire on the readout, the blue shield drain wire can be connected to the black or green wires from the vibrating wire instrument.

10.4.2 Malfunctioning Readout Unit

Isolate the readout unit from the ground by placing it on a piece of laminate or similar insulating material.

10.4.3 Sources of Electrical Interference

Check for sources of nearby electrical noise such as motors, generators, antennas, or electrical cables. Move the instrument cables as far as possible away from any sources of electrical noise. Filtering and shielding equipment are likely required if the noise cannot be eliminated.

Contact RST for technical advice.

10.4.4 Sensor Body Shorted to Drain Wire

The vibrating wire piezometer housing may be shorted to the shield. Check the resistance between the shield drain wire and piezometer housing. The resistance should be extremely high.

10.4.5 VW Piezometer Over-Ranged

The vibrating wire piezometer may have been over-ranged or physically damaged. Inspect the pressure cell and housing for any obvious damage.

Contact RST Instruments if necessary.

10.5 THERMISTOR READING IS TOO LOW

1. If the calculated temperature from the thermistor resistance reading is unrealistically low, it is very likely that there is an open circuit or poor connection in the thermistor wiring which is resulting in excessive resistance.
2. Check all connections, terminals, and plugs for any damage or corrosion that could cause excessive in-line resistance.
3. If cable damage or a cut is located, a splice must be performed to return the function of the wire connection to normal.



NOTE: It is recommended that an RST ELSPLICE13 Electrical Cable Splice Kit for Vibrating Wire Cables be used to ensure a strong and waterproof splice.

10.6 THERMISTOR READING IS TOO HIGH

10.6.1 Possible Shorting in Thermistor Wiring

1. If the calculated temperature from the thermistor resistance reading is unrealistically high, it is very likely that there is a short circuit in the thermistor wiring which is resulting in a lower resistance reading.
2. Inspect all connections, terminals, and plugs for any damage or current leakage that could cause a partial short and lead to lower circuit resistance. If a short or partial short is found in the cable, repair it with a splice.



NOTE: It is recommended that an RST ELSPLICE13 Electrical Cable Splice Kit for Vibrating Wire Cables be used to ensure a strong and waterproof splice.

11 PRODUCT SPECIFICATIONS

Item	Specification
Pressure Range	350, 700 kPa 1, 2, 3, 5 MPa
Over Range	150% FS (maximum)
Resolution	0.025% FS (minimum)
Accuracy	± 0.5% FS
Sensor Type (Earth and pore water pressure)	Vibrating Wire
Temperature Range	-20°C to +80°C
Thermistor Type	NTC 3k Ω @ 25°C YSI 44005, Dale 41C3001 B3, Alpha #13A3001 B3
Filter	50-micron sintered filter
Length x Diameter x Thickness (pressure sensitive section)	200 x 57 x 6.3 mm
Total Length	524 mm

12 ORDERING INFORMATION

Item	Part #
VW Push-In Pressure Cell	VWPC2100-XX-CPT (VW Push-In Pressure Cell with CPT Thread)
	VWPC2100-XX-NPT (VW Push-In Pressure Cell with 1" NPT Thread)
	<i>"XX" specifies the rated pressure range of the cell. For example, VWPI2100-0.35-CPT would be a 0.35 MPa instrument with CPT thread</i>
Three twisted pairs cable with polyurethane jacket	EL380006
Push-In female adapter for Push-In Pressure Cell	PUSHADAPT-CPT
Push-In Pressure Cell male adapter for 1.5" NPT female	PUSHADAPT-1.5NPT
Push-In Pressure Cell male adapter with female adapter for AW drill rod	PUSHADAPT-AW
1-1/2" Steel pipe Sch40 X 5ft threaded	FIPS00150
1-1/2" Steel pipe coupling	FIPSC0150

13 SERVICE, REPAIR AND CONTACT INFORMATION

This product does not contain any user-serviceable parts. Contact RST for product services or repairs.

- For sales information: sales@rstinstruments.com
- For technical support: support@rstinstruments.com
- Website: www.rstinstruments.com
- Toll free: 1-800-665-5599

RST Canada Office (Head Quarters)

Address: 11545 Kingston Street, Maple Ridge, BC, Canada V2X 0Z5

Telephone: 604-540-1100

Fax: 604-540-1005

Business hours: 7:30 a.m. to 5:00 p.m. (PST) Monday to Friday, except holidays

RST UK Office

Address: Unit 4 Charles Industrial Estate Stowupland Road, Stowmarket
Suffolk, UK, IP14 5AH

Telephone: +44 1449 706680

Business hours: 9:00 a.m. to 6:30 p.m. (GMT) Monday to Friday except holidays

APPENDIX A: SENSOR CALIBRATION CERTIFICATES



Calibration Record

RST Instruments Ltd., 11545 Kingston Street, Maple Ridge, BC, Canada V2X 0Z5
Tel: 604-540-1100 • Fax: 604-540-1005 • Toll free: 1-800-665-5599 (North America only)
www.rstinstruments.com

Vibrating Wire Push-In Pressure Cell

Total Earth Pressure Sensor (Glycol Sensor)

Model Number: VWPC2100-2.0-NPT
Calibration Date: November 22, 2024
Serial Number: [REDACTED]
Mfg number: [REDACTED]
Range: 2000.0 kPa
Temperature: 24.0 °C
Sales Order Number: [REDACTED]
Cable Length: 50 m
Cable Type: EL380006
Cable Colour Code: Red/Black (earth pressure sensor), Orange/Blue (water pressure sensor), Green/White (thermistor)
Thermistor Type: 3 kΩ

Applied Pressure (kPa)	First Reading (B units)	Second Reading (B units)	Average Readings (B Units)	Average Pressure (kPa)	Calculated Linear (kPa)	Linear Error (% FS)	Polynomial Fit (% FS)
0.00	8555.0	8559.6	8557.3	0.0	8.884	0.444	0.033
400.0	7930.3	7933.4	7931.9	400.0	397.594	-0.120	-0.042
800.0	7294.6	7297.3	7296.0	800.0	792.799	-0.360	-0.027
1200.0	6650.3	6652.5	6651.4	1200.0	1193.380	-0.331	0.011
1600.0	5997.4	5998.9	5998.2	1600.0	1599.367	-0.032	0.064
2000.0	5341.1	5341.9	5341.5	2000.0	2007.468	0.373	-0.039
Max Error (%)						0.44	0.06

This instrument has been calibrated using standards traceable to the NIST in compliance with ANSI Z540-1

Linear Calibration Factor (CF): 6.21489E-01 kPa/B unit, Regression Zero (at Calibration): 8571.6 B unit

Polynomial Gauge Factors:

A: -6.0400E-06 B: -5.3754E-01 C: 5.0428E+03

Users must establish site zero readings for calculation purposes. Polynomial C (MPa) = - [A(L₀) + B(L₀)]

Pressure is calculated using the following equations:

Linear: $P = CF (L_0 - L) + (S_0 - S)$

Polynomial: $P = A(L^2) + B(L) + C + (S_0 - S)$

L₀, L = initial (at installation) and current readings, in B units

S₀, S = initial (at installation) and current barometric pressure readings, in kPa

B units = B scale output of VW 2102, VW 2104, VW 2106, and DT 2011 readouts

B units = Hz² / 1000 i.e. 1700 Hz = 2890 B units

Shipped Zero Readings:

Date: 22-Nov-2024 VW Readout (Pos. B (L₀)): 8557.3 Temp. (deg. C): 24.0

Calibrated by: [REDACTED] Date: 22-Nov-2024



Calibration Record

RST Instruments Ltd., 11545 Kingston Street, Maple Ridge, BC, Canada V2X 0Z5
Tel: 604-540-1100 • Fax: 604-540-1005 • Toll free: 1-800-665-5599 (North America only)
www.rstinstruments.com

Vibrating Wire Push-In Pressure Cell

Pore Water Pressure Sensor (Water Sensor)

Model Number: VWPC2100-2.0-NPT
Calibration Date: September 27, 2024
Serial Number: [REDACTED]
Mfg number: [REDACTED]
Range: 2000.0 kPa
Temperature: 23.0 °C
Sales Order Number: [REDACTED]
Cable Length: 50 m
Cable Type: EL380006
Cable Colour Code: Red/Black (earth pressure sensor), Orange/Blue (water pressure sensor), Green/White (thermistor)
Thermistor Type: 3 kΩ

Applied Pressure (kPa)	First Reading (B units)	Second Reading (B units)	Average Readings (B Units)	Average Pressure (kPa)	Calculated Linear (kPa)	Linear Error (% FS)	Polynomial Fit (% FS)
0.00	8538.0	8538.0	8538.0	0.0	3.375	0.17	-0.01
400.0	7839.0	7839.0	7839.0	400.0	399.732	-0.01	0.02
800.0	7138.0	7139.0	7138.5	800.0	796.939	-0.15	-0.01
1200.0	6433.0	6433.0	6433.0	1200.0	1196.982	-0.15	-0.01
1600.0	5723.0	5724.0	5723.5	1600.0	1599.292	-0.04	0.00
2000.0	5010.0	5011.0	5010.5	2000.0	2003.587	0.18	0.00
Max Error (%)						0.18	0.02

This instrument has been calibrated using standards traceable to the NIST in compliance with ANSI Z540-1

Linear Calibration Factor (CF): 5.67034E-01 kPa/B unit, Regression Zero (at Calibration): 8544.0 B unit

Temperature Correction Factor (Tk): 1.0000E-03 kPa/°C rise

Polynomial Gauge Factors:

A: -2.1568E-06 B: -5.3781E-01 C: see calculation below

Users must establish site zero readings for calculation purposes. Polynomial C (MPa) = - [A(L₀²) + B(L₀)]

Pressure is calculated using the following equations:

Linear: $P = CF(L_0 - L) - Tk(T_0 - T) + (S_0 - S)$

Polynomial: $P = A(L^2) + B(L) + C - Tk(T_0 - T) + (S_0 - S)$

L₀, L = initial (at installation) and current readings, in B units

T₀, T = initial (at installation) and current temperature, in °C

S₀, S = initial (at installation) and current barometric pressure readings, in kPa

B units = B scale output of VW 2102, VW 2104, VW 2106, and DT 2011 readouts

B units = Hz² / 1000 i.e. 1700 Hz = 2890 B units

Shipped Zero Readings:

Date: 27-Sep-2024 VW Readout (Pos. B (L₀)): 8417.6 Temp. (deg. C): 24.0

Calibrated by: [REDACTED] Date: 27-Sep-2024

APPENDIX B: THERMISTOR TEMPERATURE DERIVATION

Resistance to Temperature Equation 1: $T = \frac{1}{A + B(\ln R) + C(\ln R)^3} - 273.2$

Where:

- T = temperature in °C
- Ln(R) = natural log of thermistor resistance
- A = 1.4051×10^{-3} (coefficient calculated over the -50 to +150°C span)
- B = 2.369×10^{-4}
- C = 1.019×10^{-7}

Table 3: Thermistor Resistance Varying with Temperature

Ohms	Temp	Ohms	Temp	Ohms	Temp	Ohms	Temp	Ohms	Temp
201.1K	-50	16.60K	-10	2417	+30	525.4	+70	153.2	+110
187.3K	-49	15.72K	-9	2317	31	507.8	71	149.0	111
174.5K	-48	14.90K	-8	2221	32	490.9	72	145.0	112
162.7K	-47	14.12K	-7	2130	33	474.7	73	141.11	113
151.7K	-46	13.39K	-6	2042	34	459.0	74	137.2	114
141.6K	-45	12.70K	-5	1959	35	444.0	75	133.6	115
132.2K	-44	12.05K	-4	1880	36	429.5	76	130.0	116
123.5K	-43	11.44K	-3	1805	37	415.6	77	126.5	117
115.4K	-42	10.86K	-2	1733	38	402.2	78	123.2	118
107.9K	-41	10.31K	-1	1664	39	389.3	79	119.9	119
101.0K	-40	9796	0	1598	40	376.9	80	116.8	120
94.48K	-39	9310	+1	1535	41	364.9	81	113.8	121
88.46K	-38	8851	2	1475	42	353.4	82	110.8	122
82.87K	-37	8417	3	1418	43	342.2	83	107.9	123
77.99K	-36	8006	4	1363	44	331.5	84	105.2	124
72.81K	-35	7618	5	1310	45	321.2	85	102.5	125
68.30K	-35	7252	6	1260	46	311.3	86	99.9	126
64.09K	-33	6905	7	1212	47	301.7	87	97.3	127
60.17K	-32	6576	8	1167	48	282.4	88	94.9	128
56.51K	-31	6265	9	1123	49	283.5	89	92.5	129
53.10K	-30	5971	10	1081	50	274.9	90	90.2	130
49.91K	-29	56.92	11	1040	51	266.6	91	87.9	131
46.94K	-28	5427	12	1002	52	258.6	92	85.7	132
44.16K	-27	5177	13	965.	53	250.9	93	83.6	134
39.13K	-25	4714	15	895.8	55	236.2	95	79.6	135
36.86K	-24	4500	16	863.3	56	229.3	96	77.6	136
34.73K	-23	4297	17	832.2	57	222.6	97	75.8	137
32.74K	-22	4105	18	802.3	58	216.1	98	73.9	138
30.87K	-21	3922	19	773.7	59	209.8	99	72.2	139
29.13K	-20	3748	20	746.3	60	203.8	100	70.4	140
27.49K	-19	3583	21	719.9	61	197.9	101	68.8	141
25.95K	-18	3426	22	694.7	62	192.2	102	67.1	142
24.51K	-17	3277	23	670.4	63	186.8	103	65.5	143
23.16K	-16	3135	24	647.1	64	181.5	104	64.0	144
21.89K	-15	3000	25	624.7	65	176.4	105	62.5	145
20.70K	-14	2872	26	603.3	66	171.4	106	61.1	146
19.58K	-13	2750	27	582.6	67	166.7	107	59.6	147
18.52K	-12	2633	28	562.8	68	162.0	108	58.3	148
17.53K	-11	2523	29	543.7	69	157.6	109	56.8	149
								55.6	150

APPENDIX C: USING THE SECOND ORDER POLYNOMIAL TO IMPROVE THE ACCURACY OF THE CALCULATED PRESSURE

Most Vibrating Wire Pressure Transducers are sufficiently linear (<0.2% FS) that the use of a Linear Equation and a Linear Calibration Factor will satisfy most normal output requirements. However, it must be noted that the accuracy of the calibration data used to establish the Linear Calibration Factor is dictated by the accuracy of the calibration procedure and apparatus, which is always <0.1 % FS.

The level of accuracy for a VW Pressure Transducer can be improved, especially when the transducer output is non-linear, by using the Second Order Polynomial Expression, which is better suited to the actual pressures than the Linear Equation.

The Second Order Polynomial Expression has the following form:

$$P \text{ (pressure)} = A(L)^2 + B(L) + C$$

Where,

- L = Current VW reading (in B-units)
- A, B and C = Polynomial coefficients determined by calibration

Appendix A shows sample calibration sheets for VW pressure transducers with a comparatively low non-linearity. In this case, there will only be a very small difference between the value of pressure calculated by the linear equation and by the second order polynomial expression.

In cases where the VW transducers have a high non-linearity (greater than 0.2% FS), the second order polynomial expression method will provide more accurate pressure values.

The VW calibration sheets contain a column labelled "Linearity Error (% FS)" which displays the calculated linear error percentage for the calibration steps. If the average of these percentages exceeds 0.2%, RST recommends calculating all pressure values using the second order polynomial expression.

The Linearity Error (% FS) is calculated as follows:

$$\text{Linearity Error (\% FS)} = \frac{(\text{Calculated Pressure} - \text{Applied Pressure})}{\text{Full Scale Pressure}} \cdot 100 \%$$



NOTE: In cases where the accuracy of absolute pressure measurement is not required, such as monitoring relative water level changes, either equation can be used.

APPENDIX D: REFERENCES

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2. Richards, D.J., Clark, J., Powrie, W. and Heymann, G. (2007). "Performance of push-in pressure cells in overconsolidated clay". *Geotechnical Engineering* 160, January 2007, Issue GE1, pp.31-41.
3. Richards, D. J., Powrie, W., Roscoe, H. and Clark, J. (2007). "Pore water pressure and horizontal stress changes measured during construction of a contiguous bored pile multi-propped retaining wall in Lower Cretaceous clays" *Geotechnique* 57, No. 2, 197–205.
4. Clements, D.J., and A.C. Durney (1982); "Instrumentation Developments", *Proceedings of the Autumn Conference on the British National Committee on Large Dams (BNCOLD)* Keele University, Institution of Civil Engineers, London, pp. A5-55.