HKCI: TM 3

Determination of Geometry of Vertical Shaft Excavation by Ultrasonic Echo Sounding

Issue 2

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Dr Fiona CHAN Wan Yin	Hong Kong Council for Testing and Certification, HKSAR
Mr Raymond CHU Lap Man	Labtech Testing Ltd.
Dr Garfield GUAN	Qualitech Testing & Consultancy Ltd.
Dr Eric HO Tak Cho	FT Laboratories Ltd.
Mr Alex HUI Kin Chung	The HK Institute of Clerks of Works
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Mr WONG Yik Man	Alliance Testing (HK) Co., Ltd.

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1. Scope

1.1 This test method covers calibration of measuring apparatus and determination of field procedures for measuring the profile of a vertical shaft excavation, such as dimension of a bell-out and verticality of an excavation using Ultrasonic Echo Sounding (UES) technique.

1.2 This test method does not purport to address all of the safety concerns, if any, associated with its working procedures. It is the responsibility of the user of this test method to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2. Terminology

2.1 UES – Ultrasonic Echo Sounding

2.2 UES profile – A graphical record of measured distances against depth

2.3 Ultrasonic sensor head – A combination of transmitters and receivers of an UES equipment

2.4 Scaling factor – A factor used to convert the values measured on an UES profile into horizontal dimensions of the tested shaft excavation. A scaling factor shall be determined with the use of two first-arrival-time signals in each test.

3. Principle of the Test Method

3.1 UES measurements involve measuring the propagation time of an ultrasonic pulse for a reflection off the sidewalls (such as steel casing, bedrock, soil layer, concrete guide wall, etc.) of a vertical shaft excavation.

3.2 It is important to fill the excavation with a propagation medium (such as water, bentonite slurry, etc.) to obtain a good coupling effect for ultrasonic wave propagation.

3.3 The transmitted ultrasonic pulses are reflected as a result of changes of the acoustic impedance at different material interfaces. A typical flow path of such transmission is shown in Figure 1 [1]:

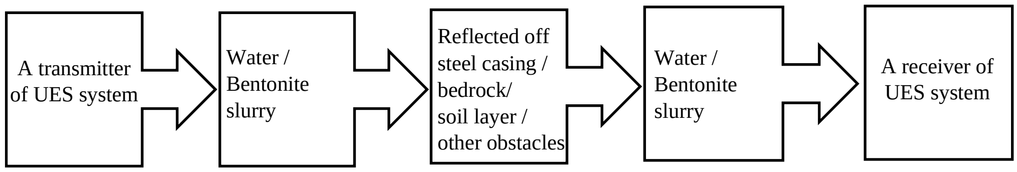


Figure 1 A typical flow path of ultrasonic pulses of an UES system [1]

When an acoustic wave traveling in one medium encounters another medium, reflected and transmitted waves are generated from the boundary. The ratios of the intensities of the reflected and transmitted waves to the incident wave depend on the characteristic acoustic impedances (Z_1, Z_2) of the two media.

The intensity reflection (R) and transmission (T) coefficients are:

$$\mathrm{R} = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2 \qquad \text{--- Equation (1)}$$

$$\mathrm{T} = \frac{4Z_2Z_1}{(Z_2 + Z_1)^2} \qquad \text{--- Equation (2)}$$

Simply, if $Z_1 = Z_2$, there is no reflected wave or the transmitted wave has the same amplitude as the incident wave. If Z_1 and Z_2 differ significantly, most of the sound is reflected.

3.4 Each interface of two different materials (i.e. difference in acoustic impedance) produces partial reflection (i.e. receiving signals) and transmission to occur at normal incidence, and even makes the receiving signals vary.

Table 1 Acoustic impedance of different materials

Material	Acoustic impedance (kg/(m^{2}s))
Air	0.0004
Water	1.5 x 10^6
Bentonite	2.4 – 3.2 x 10^6
Steel	47 x 10^6
Concrete	8 – 10 x 10^6
Soil	1 – 3 x 10^6
Granite	15 – 17 x 10^6
Quartz rock	14 – 15 x 10^6

4. Measuring Apparatus

4.1 Apparatus for allowing excavation inspection – To provide access for an ultrasonic sensor head of an UES equipment, steel casings, if any, are installed during the drilling of a vertical shaft excavation. The internal space of the excavation hole shall be sufficient to allow easy passage of the ultrasonic sensor head over the entire excavation depth. A vertical shaft excavation shall be filled with water/bentonite slurry to provide a propagation medium for ultrasonic pulse propagation.

4.2 Apparatus for determining physical test parameters

4.2.1 Weighted measuring tape – A plumb bob connected to a measuring tape with at least ± 0.5% accuracy shall be used as a dummy probe to check free passage through and determine unobstructed length of a vertical shaft excavation.

4.2.2 Measuring tape – with at least ± 0.5% accuracy, used for on-site measuring horizontal dimensions of a vertical shaft excavation.

4.2.3 Temperature measuring device – used for measuring the temperature of the water/bentonite slurry in the excavation to ensure that the temperature of the propagation medium does not exceed the allowable temperature value as recommended by the manufacturer of the UES equipment.

4.2.4 Spirit leveller – used to ensure an UES equipment in a horizontal position prior to testing.

4.2.5 Compass or gyroscope – used for determining direction relative to the Earth's magnetic poles at the test excavation.

4.3 Apparatus for obtaining measurements

4.3.1 Ultrasonic sensor head – The ultrasonic sensor head shall consist of a transmitter(s) and a receiver(s). The transmitter(s) shall generate an ultrasonic pulse with a frequency of between 80,000 and 110,000 Hz.

4.3.2 Signal transmission cable – The signal cable used to deploy an ultrasonic sensor head and transmit data from the sensor head shall be sufficient robust to support the sensor head's weight. The cable shall be abrasion resistant to allow repeated field use and maintain flexibility in the range of operating temperatures. All cable connector or splices, if any, shall be watertight. The total length of cable shall be enough to cover the measured depth.

4.3.3 Sensor head depth-measuring device – The signal cable with a depth-encoding device shall determine the depth to the location of the ultrasonic sensor head in a vertical shaft excavation throughout the test. The design of the depth-measuring device shall be able to prevent occurrence of cable slippage. The depth-measuring device shall be checked prior to each test against a calibrated weighted measuring tape. The difference between the readings obtained by the depth-measuring device of the UES equipment and the calibrated weighted measuring tape shall be within 1 % of the shaft length or 0.3 m which is greater.

4.4 Apparatus for recording and displaying measured data

4.4.1 Apparatus for recording data – Each transmitted ultrasonic pulse shall immediately start the acquisition for the corresponding receiver. Analog signals of an ultrasonic pulse measured by the ultrasonic sensor head shall be digitized by analogy to digital converter with a minimum sampling frequency of 4 Hz. The apparatus shall have adjustable gain to optimize detection of the transmitted pulse by the ultrasonic sensor head under test.

4.4.2 Apparatus for displaying measured data – The recording apparatus shall be capable of displaying the ranges of the sidewalls of a vertical shaft excavation (in either one or both of two orthogonal directions, or others depends on the design of the instrumentation of an UES equipment) at any one time in an UES profile, and some important test information including date and time of the measurement carried out, and depth of a vertical shaft excavation shall also be displayed on an UES profile. An example of an UES profile is shown in Figure 2.

4.5 Apparatus for measuring value(s) on an UES profile – A calibrated calliper with at least ±0.5% accuracy is used for measuring value(s) on an UES profile for determination of horizontal and vertical dimensions of a vertical shaft excavation.

5. Equipment Calibration and Verification

Type of equipment	Recommended maximum period between successive calibration/verification	Recommended calibration/verification procedure or guidance documents and equipment requirements
Oscilloscope or cathode ray tube (CRT) or frequency analyser (Reference device for calibration of signal recording apparatus)	5 years	By a 'competent calibration body' as defined in HOKLAS SC-02
Echo sounder signal recording apparatus (check the time base over the measuring range at designated frequency)	2 years	Calibrate using a reference oscilloscope, CRT, frequency analyser or any reference measuring device. The calibration shall be conducted by a 'competent calibration body' as defined in HOKLAS SC-02 and the calibration results shall be reported in an endorsed calibration report(s).
Sensor head depth-measuring device	Before each test on site	Check against a plumb-weighed measuring device.
Plumb-weighed measuring tape	1 year	Calibrate using a reference rule (weight of the equipment to be taken into account). The calibration shall be conducted by a 'competent calibration body' as defined in HOKLAS SC-02 and the calibration results shall be reported in an endorsed calibration report(s).
Verification of echo sounder to known profiles and fluid properties	1 year	Verify by means of known profiles of different geometrical characteristics (e.g. distances, roughness, curvatures and inclinations, etc.) in water / various physical models and known fluid properties.

5. Equipment Calibration and Verification (cont'd)

Type of equipment	Recommended maximum period between successive calibration/verification	Recommended calibration/verification procedure or guidance documents and equipment requirements
Measuring tape for on-site measuring horizontal dimension (e.g. diameter) of a vertical shaft excavation	2 years	Calibrate using a reference length standard with a higher accuracy and the calibration shall be conducted at a minimum of 5 points covering the required measurement range. The calibration shall be conducted by a 'competent calibration body' as defined in HOKLAS SC-02 and the calibration results shall be reported in an endorsed calibration report(s).
Calliper for measuring value(s) on an UES profile	1 year	Calibrate using reference gauge blocks or callipers checker. A sufficient number of readings shall be taken covering the expected working range. The calibration shall be conducted by a 'competent calibration body' as defined in HOKLAS SC-02 and the calibration results shall be reported in an endorsed calibration report(s).

6. Testing Procedures

6.1 Identify the location of a vertical shaft excavation to be tested throughout the test and keep the record for the traceability of test results.

6.2 Measure the unobstructed depth of a vertical shaft excavation by a calibrated plumb-weighted measuring tape and record the depth.

6.3 Measure the horizontal dimension(s) of a vertical shaft excavation (e.g. diameter) using a calibrated measuring tape.

6.4 Measure the ambient temperature and shade the equipment especially on sunny days if necessary to ensure that the operating temperature specified by the manufacture of the UES equipment is met. Measure the temperature of water/bentonite slurry in a vertical shaft excavation to ensure that the temperature of the propagation medium does not exceed the allowable temperature value as recommended by the manufacturer of the UES equipment.

6.5 Set up the ultrasonic sensor head of the UES equipment as close to the centre of a vertical shaft excavation as practicable.

6.6 Check the horizontal level of the UES equipment using a spirit leveller.

6.7 Input date and time of the test, select an appropriate measurement range in the controller of the UES equipment.

6.8 Check the performance of the UES equipment by lowering the ultrasonic sensor head inside the propagation medium of the excavation of a pile shaft and set an appropriate signal gain to obtain a clear UES profile.

6.9 Identify the orientation of channels (e.g. X-X', Y-Y' or more) using a compass or gyroscope.

6.10 Lowering/Lifting up the ultrasonic sensor head (subject to the design of the UES equipment) in a vertical shaft excavation at a steady rate not exceeding 15 m/min.

6.11 Adjust the sensitivity setting during the test if necessary to produce an UES profile as clear as possible.

6.12 After completing data acquisition in all channels, take/print out the UES profile obtained from the UES equipment.

6.13 Based on the UES profile obtained, calculate the linear dimensions of the shaft and 'bell-out' of the vertical shaft excavation, and also express the verticality of the shaft excavation as stated in Section 7 below.

7. Calculation and Expression of Results

Figure 2 shows a typical UES profile of a vertical shaft excavation. The 'bell-out' dimension and verticality of a vertical shaft excavation are calculated by Equation (3) – (6) below.

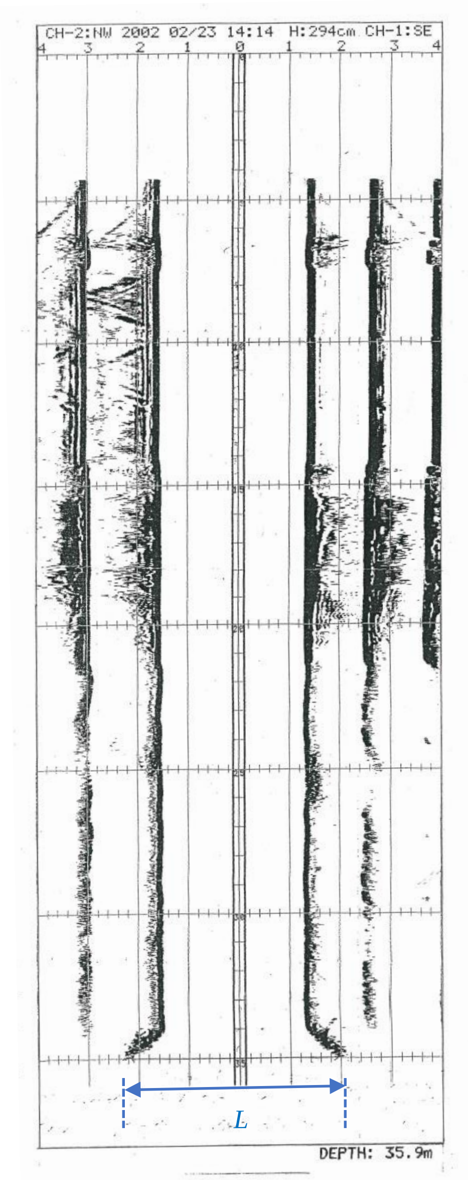


Figure 2 A typical UES profile of a vertical shaft excavation

7.1. Calculation of 'Bell-out' size, L

$$L = r * S_H \qquad \text{--- Equation (3)}$$

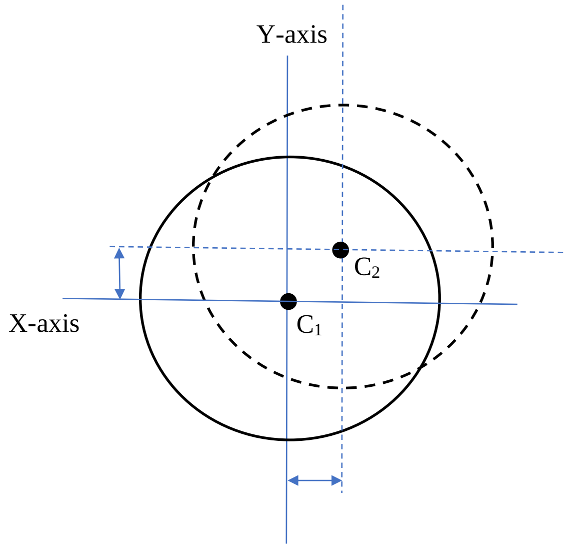
where

r is a horizontal value measured by a calibrated calliper on an UES profile at which a 'bell-out' is located (unit in mm); and

S_H is an average horizontal scaling factor (unit in m/mm) by taking at least three readings.

7.2. Calculation of the Verticality, V of the shaft excavation
[The verticality shall be reported as a ratio (i.e. 1 : V)]

Scenario (1): When the pile is inclined, the centre of the shaft excavation will be shifted from C_1 to C_2 with some displacements in BOTH X-axis and Y-axis.



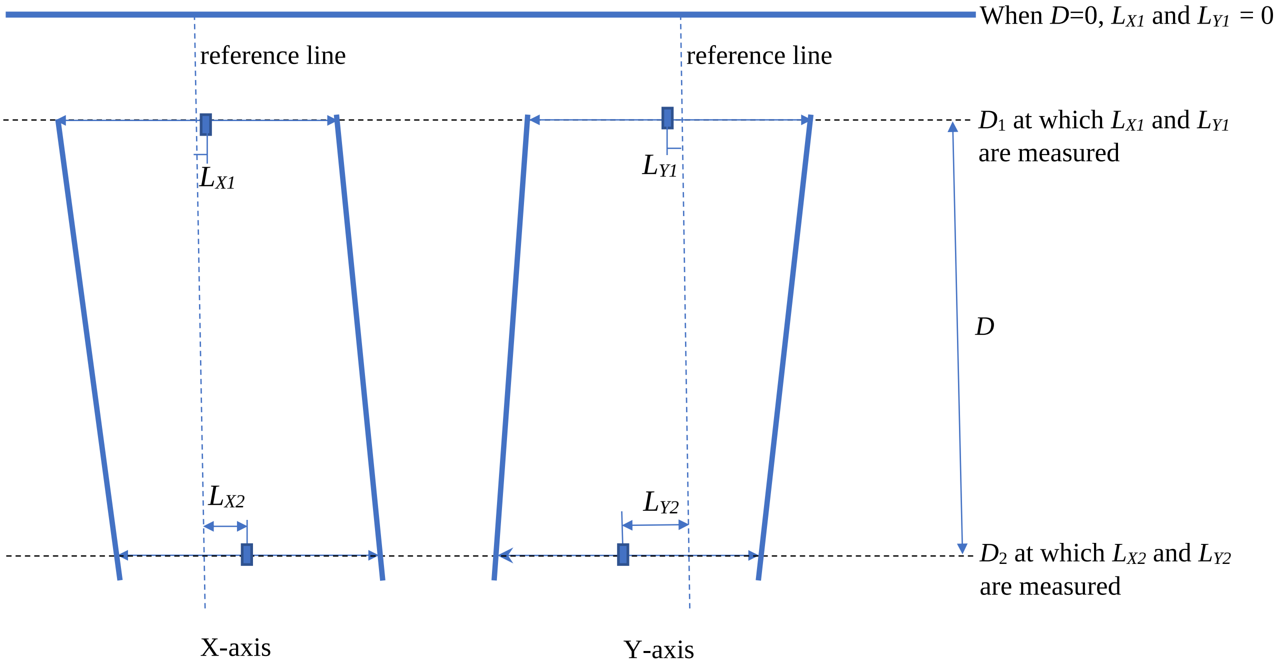
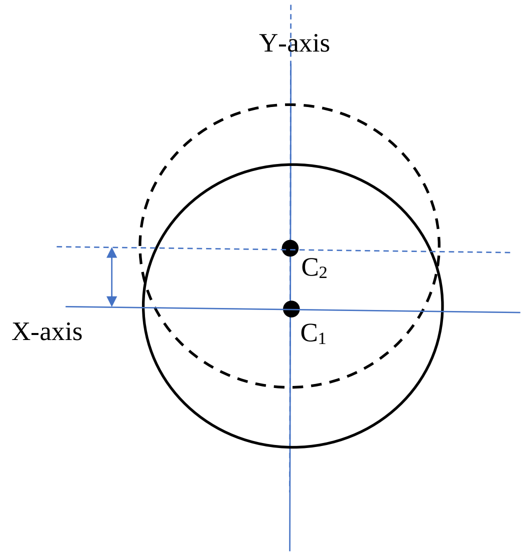


Figure 3 A schematic drawing of UES profile in Scenario (1)

7.2 Calculation of the Verticality, V of the shaft excavation (cont'd)
[The verticality shall be reported as a ratio (i.e. 1 : V)]

Scenario (2): When the pile is inclined in Y-axis, the centre of the shaft excavation will be shifted from C_1 to C_2 with some displacement in Y-axis ONLY.



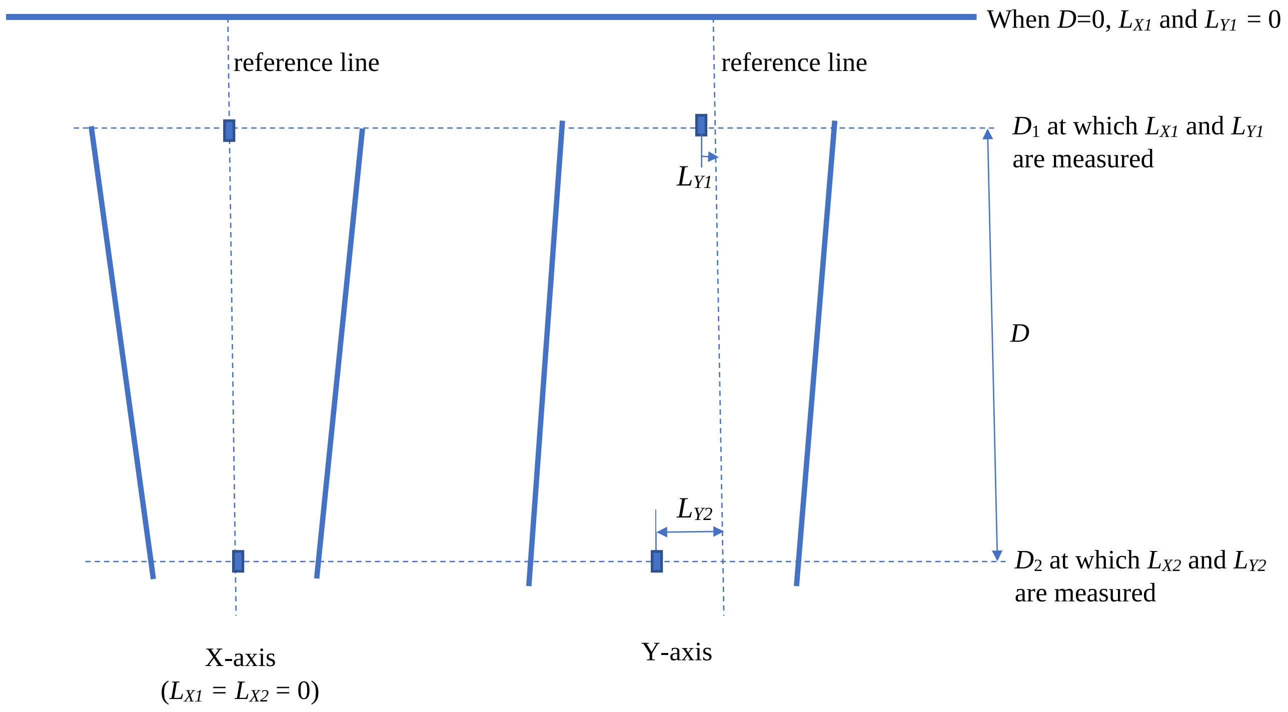


Figure 4 A schematic drawing of UES profile in Scenario (2)

7.2 Calculation of the Verticality, V of the shaft excavation (cont'd)
[The verticality shall be reported as a ratio (i.e. 1 : *V*)]

For X-axis, $V_x = \frac{D}{|L_{x2}-L_{x1}|} = \frac{(D_2-D_1)}{|r_{x2}-r_{x1}|*S_H}$ --- Equation (4)

For Y-axis, $V_Y = \frac{D}{|L_{Y1}-L_{Y1}|} = \frac{(D_2-D_1)}{|r_{Y2}-r_{Y1}|*S_H}$ --- Equation (5)

For resultant verticality, $V = \frac{D}{\sqrt{|L_{x2}-L_{x1}|^2 + |L_{Y2}-L_{Y1}|^2}}$ --- Equation (6)

where

L_{x1} and L_{Y1} are the distances between the middle point (i.e. a half distance between two first-arrival-time on each side of the UES profile) and the reference line at the depth D_1 in X-axis and Y-axis respectively (unit in m);

L_{x2} and L_{Y2} are the distances between the middle point (i.e. a half distance between two first-arrival-time on each side of the UES profile) and the reference line at the depth D_2 in X-axis and Y-axis respectively (unit in m);

D_1 is a depth of a vertical shaft excavation at which L_{X1} and L_{Y1} are located (unit in m);

D_2 is a depth of a vertical shaft excavation at which L_{X2} and L_{Y2} are located (unit in m);

r_{x1} and r_{Y1} are horizontal values measured by a calibrated calliper on an UES profile at the depth D_1 in X-axis and Y-axis respectively (unit in mm);

r_{x2} and r_{Y2} are horizontal values measured by a calibrated calliper on an UES profile at the depth D_2 in X-axis and Y-axis respectively (unit in mm); and

S_H is an average horizontal scaling factor (unit in m/mm) by taking at least three readings.

8. Limitations

7.1 In performing an UES test, the sensor head of the UES equipment is required to be placed in the centre of an excavation to produce reliable UES profiles at an optimal position. However, for inclined shafts, a number of measurements should be carried out to obtain an actual picture of these inclined shafts.

7.2 The transmission medium in diaphragm walls is sometimes filled with bentonite slurry. However, the UES equipment may not be able to detect the sidewalls in muddy water with sufficient clarity [2]. This is due to the high attenuation (including scattering, absorption and reflection) of ultrasonic waves in muddy water. As a result, clear reflecting signals cannot be obtained on UES profiles even though the UES equipment is set in a high signal-to-noise ratio setting.

9. Reporting of Test Results

9.1 General

The test report shall contain the following information:

- Project name and test location
- Customer's information
- Date and time of testing
- Orientation of the test performed
- Description of the UES equipment (such as 2-channel or 4-channel in one go, or others)
- Transmission medium (e.g. water or bentonite slurry)
- Temperature of transmission medium

9.2 Details

The test report shall contain the following details:

- Identification and location of the tested shaft excavation
- Nominal size and length of the tested shaft excavation
- Cut-off and ground levels of the tested shaft excavation
- UES profile without any cuttings of the profile
- Verticality of the tested shaft excavation
- (Optional) Besides the verticality of the entire tested shaft, the verticality of the tested shaft excavation from cut-off level down to intermediate depths of maximum 10 m intervals should be reported.
- Bell-out dimension of the tested shaft excavation

10. References

[1] Chan, W.Y. & Tsang, W.F. 'Earth echo sounding technique for quality control of drilled shaft foundations', SINDT Insight - Non-Destructive Testing and Condition Monitoring, Vol.46, No.1, pp.17-22 (2004)

[2] Lau, H.L. Zhuang ji gong cheng shou ce / 'Zhuang ji gong cheng shou ce' bian xie wei yuan hui, Zhongguo jian zhu gong ye chu ban she, Beijing, p.p.786-799 (1995) (in Chinese).

Annex

Recommended Test Report Template

Test Report

Ultrasonic Echo Sounder Test

(Test method: HKCI: TM3 Issue 2)

Report No.: Date of Issue:

Page No.: of

Part A – General Information as provided by Customer

Customer:
Address:
Project Title:
Contract No.:
Piling Contractor:
Location of Pile:

Part B – Sample Information as provided by Customer

Pile No.		Pile Type	
Pile Shaft Diameter	(mm)	Casing Interior Diameter	(mm)
Existing Ground Level	(mPD)	Co-ordinate E	
R.C.D Platform Reference Level	(mPD)	Co-ordinate N	
Casing Top Level	(mPD)	Pile Cut-off Level	(mPD)
Casing Toe Level	(mPD)	Pile Base Level	(mPD)
Required Bell-out Diameter	(m)	Total Pile Length	(m)
Maximum Allowable Inclination		Required Rock Socket Diameter	(m)

Part C – Test Equipment

Description	Equipment No.
UES equipment (2-channel or 4-channel)	
Measuring Tape	
Calliper	

Part D – Test Results

Date of Testing: Time of Testing:

Transmission medium: Temp. of transmission medium:

Determination of Horizontal Scaling Factor				
	Channel X-X’		**Channel Y-Y’**	
		Scaling factor (m/mm)		**Scaling factor (m/mm)**
1st measurement	Printed depth on UES profile: ________(m)		Printed depth on UES profile: ________(m)	
	Horizontal reading on UES profile: ________(m)		Horizontal reading on UES profile: ________(m)	
	Measured value: ________(mm)		Measured value: ________(mm)	
2nd measurement	Printed depth on UES profile: ________(m)		Printed depth on UES profile: ________(m)	
	Horizontal reading on UES profile: ________(m)		Horizontal reading on UES profile: ________(m)	
	Measured value: ________(mm)		Measured value: ________(mm)	
3rd measurement	Printed depth on UES profile: ________(m)		Printed depth on UES profile: ________(m)	
	Horizontal reading on UES profile: ________(m)		Horizontal reading on UES profile: ________(m)	
	Measured value: ________(mm)		Measured value: ________(mm)	
	Average scaling factor (m/mm)		**Average scaling factor (m/mm)**	

Part D – Test Results (cont'd)

Pile No.		
Rock Socket Diameter	Channel X-X'	Channel Y-Y'
at the level (mPD)		
Printed depth on UES profile (m)		
Measurement on UES profile (mm)		
Average scaling factor (m/mm)		
Calculated rock socket diameter (m)		
Bell-out Diameter	Channel X-X'	Channel Y-Y'
at the level (mPD)		
Printed depth on UES profile (m)		
Measurement on UES profile (mm)		
Average scaling factor (m/mm)		
Calculated bell-out diameter (m)		
Verticality Check (Overall)	Channel X-X'	Channel Y-Y'
Measurement *from* (mPD)		
to (mPD)		
Depth between two measurements (m)		
Offset from the reference line (mm)		
Average scaling factor (m/mm)		
Calculated displacement (m)		
Inclination (1:*V*)		
Towards		
Resultant displacement (m)		
Resultant inclination (1:*V*)		

Part D – Test Results (cont'd) (Optional)

Verticality Check (1st 10m-interval)	Channel X-X'	Channel Y-Y'
Measurement *from* (mPD)		
to (mPD)		
Depth between two measurements (m)		
Offset from reference line, (L) (mm)		
Average scaling factor, (S) (m/mm)		
Calculated displacement (=L*S) (m)		
Inclination (1:*V*)		
Towards		
Resultant displacement (m)		
Resultant inclination (1:*V*)		

Verticality Check (2nd 10m-interval)	Channel X-X'	Channel Y-Y'
Measurement *from* (mPD)		
to (mPD)		
Depth between two measurements (m)		
Offset from reference line, (L) (mm)		
Average scaling factor, (S) (m/mm)		
Calculated displacement (=L*S) (m)		
Inclination (1:*V*)		
Towards		
Resultant displacement (m)		
Resultant inclination (1:*V*)		

[*Continued…if necessary*]

Appendix A – UES Profile

Appendix B – Pile Location Plan

Appendix C – Pile Information Worksheet

Appendix D – Field Record

Appendix E – Calibration Certificate(s)