Use of Smart Devices in Civil and Geotechnical Works for Vibration, Noise and Temperature Measurement

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doi: https://doi.org/10.21467/proceedings.133.32

ABSTRACT

The Construction Industry Council (CIC) was set up with a vision to drive for excellence of the construction industry in Hong Kong. The CIC encourages and facilitates research activities and the use of innovative techniques for the construction industry, as one of the many functions. The CIC engages consultants, academic institutions, in-house resources, etc., to carry out study and research work on practical construction problems in response to the needs of the construction industry. Recently, work on the development of an App for iPhones for real-time monitoring and assessment of construction-induced vibration and noise, and the application of the maturity method for estimation of concrete strength in concrete structures was completed.

In this paper, a detailed description of the laboratory calibration and site validation of the App developed for iPhones for vibration and noise monitoring, and the results obtained, including the setting-up requirements, are presented. This is followed by a discussion of the use of the maturity method for concrete strength measurement. The application of the maturity method to a case, involving installation of temperature sensors to measure the temperature development in a retaining wall structure to estimate the gain in strength, and a detailed interpretation of the results, are given.

Keywords: Vibration, Noise and Temperature Monitoring, Sensors, Concrete Maturity

1 Introduction

In civil and geotechnical works, there is a requirement for vibration and noise monitoring to check that the effect of vibration and noise as a result of the works will not produce any adverse effects on the structures and geotechnical features in the vicinity of both private and public project works. It is a practice that commercial seismograph/sound level meter units are used. These units are expensive, so usually only one to two units are kept on site at most. This makes vibration and noise monitoring an expensive and inconvenient exercise. The use of a smartphone, such as an iPhone, with a built-in App has made the vibration and noise monitoring a simple and inexpensive exercise.

In construction, in-place concrete strength is determined by performing compression tests on concrete test cube or cylinder samples collected on site in laboratory. Concrete samples are made on site as the concrete arrives on site. There is a waiting time for these test samples to gain strength before they can be tested. Using the maturity method and by measuring the temperature in the concrete in the structures, concrete strength can be evaluated in real-time. This will cut away the time needed for performing compression tests on the samples at the specified times. The number of the test samples required for quality control/quality assurance will also decrease. This method will enhance construction productivity, because by knowing the concrete strength early, many construction works that follow, such as stressing of tendons in pre-stressed concrete structures, stripping and removal of formworks and shoring, application of loads, etc., can move ahead of the construction schedule.

Proceedings DOI: 10.21467/proceedings.133; Series: AIJR Proceedings; ISSN: 2582-3922; ISBN: 978-81-957605-1-0

In this paper, a detailed description of the laboratory calibration and site validation of the App developed for iPhones for vibration and noise monitoring, and the results obtained, including the setting-up requirements, is given. A comparison of the vibration and noise results as obtained from iPhones from a site with those obtained from a seismograph/sound level meter is given and discussed. This is followed by a discussion of a case using temperature sensors to measure the temperature development in a retaining wall structure to estimate the gain in strength. The procedures of laboratory calibration and site validation for the method and a detailed interpretation of the results obtained are presented.

2 Use of V&N App aor Measurement of Vibration and Noise

2.1 Background

In 2019, the CIC engaged Prof. Songye Zhu of the Hong Kong Polytechnic University (PolyU) to develop a new method for construction-induced vibration and noise monitoring, making use of the latest smartphone technology (CIC, 2021a). There are three main tasks of investigation under the study: (1) laboratory calibration; (2) App development; and (3) site validation. In this study, focus was put on the App development for iPhones (iOS environment) only. The App developed is called V&N App. User guidelines and details of the data input and output for the V&N App are given in CIC (2022). This paper focuses on the procedures and findings of Tasks (1) and (3).

2.2 Data Interpretation

2.2.1 Peak Particle Velocity (PPV)

PPV is defined as the maximum velocity of the measured surface during a time interval (BSI, 1993) in mm/s. The V&N App measures the acceleration signal ($a(t)$), and then converts it to a velocity signal v(t) by integrating $a(t)$. PPV limits are set as a requirement in most civil and geotechnical works. The V&N App measures and reports PPV in three perpendicular directions (PPVx, PPVy, and PPVz) every 5 seconds. The resultant PPV is given by the peak vector sum, which is given by the square root of the sum of the squares of the individual PPV values in the three directions.

2.2.2 Root-mean-square (RMS) Velocity

The evaluation of vibration impact on sensitive equipment is based on the RMS velocity in the 1/3 octave band spectrum, in accordance with BS 5228-2 (BSI, 2009). The V&N App provides the RMS velocity in the 1/3 octave band spectrum in both the time and frequency domains. The transformation from the time domain to the frequency domain is conducted through the fast Fourier transform (FFT).

2.2.3 A-weighting Noise Level

In the A-weighting scale, the sound pressure levels for the low-frequency bands and high-frequency bands are reduced by certain amounts before they are combined together to give one single sound pressure level value. This value is designated as dB(A). The dB(A) is used for environmental noise measurement as it reflects more accurately the frequency response of the human ear (see EPD (2022)). The V&N App provides this noise level, including the instantaneous level.

2.3 Laboratory Calibration

2.3.1 Vibration Calibration

Most iPhones and Android phones are equipped with a six-axis MEMS vibration sensor (triaxial accelerometer and triaxial gyroscope) and an internal microphone. These sensors can be used for vibration and noise monitoring.

To check the accuracy of the vibration measurements from the smartphones, laboratory calibration tests were carried out. The test set-up is shown in Plate 1. A high-fidelity triaxial accelerometer (PCB

356b18) was used. The smartphones, together with the PCB accelerometer, were mounted on a steel cube on an exciter. The smartphones were attached to the steel cube by a strong magnet. Harmonic sinusoidal excitations were provided to the exciter by a signal generator and a power amplifier at a specific frequency and amplitude respectively.

The smartphones tested included iPhone 6, iPhone 7, iPhone 8, iPhone X, iPhone 11 Pro Max, Samsung Note 9 and VivoNex, as shown in Plates 1 & 2. The frequencies of the harmonic sinusoidal excitations applied were 4 Hz, 6 Hz, 8 Hz, 10 Hz, 16 Hz, 20 Hz and 25 Hz, which covered the common range of the construction-induced vibrations. Different amplitude levels were applied. The sampling frequency of the measurement was set at 100 Hz.

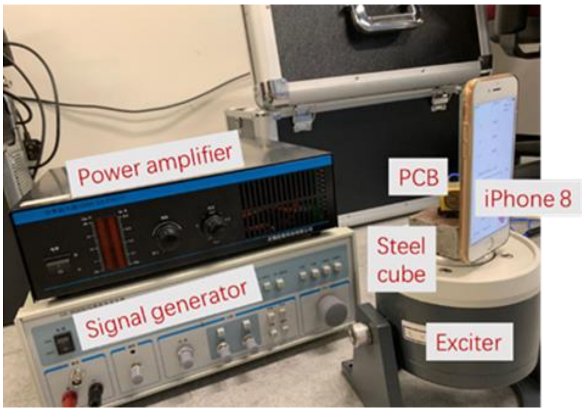


Plate 1: Set-up for vibration calibration

Plate 2: Calibration test of various smartphone models on a shaking table

A typical comparison of the acceleration time histories at 4 Hz harmonic sinusoidal excitation recorded by iPhone 8 and the PCB accelerometer is shown in Figure 1. The measurement results from iPhone 8 coincide well with those from the PCB accelerometer over the time domain examined.

A typical comparison of the RMS velocity in the 1/3 octave band spectrum is given in Figure 2. The results obtained from iPhone 8 and the PCB accelerometer were almost the same in the frequency domain. The location and the amplitude of the peaks coincide well, and the variation trend over the frequency range is the same.

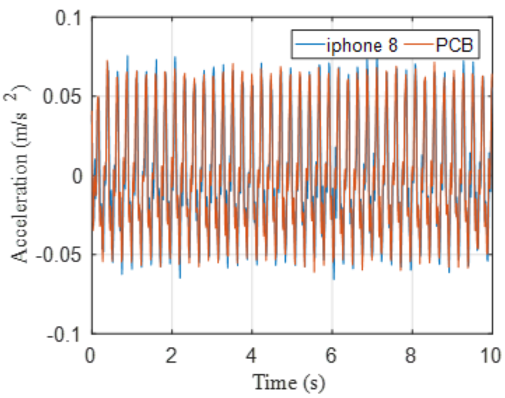


Figure 1: Comparison of acceleration at 4 Hz excitation between iPhone and PCB accelerometer

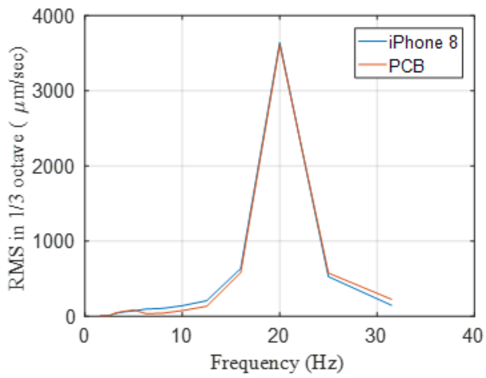


Figure 2: Comparison of RMS velocity in 1/3 octave band spectrum at 20 Hz excitation between iPhone and PCB accelerometer

The performance of the different iPhone models used was examined, in terms of the relative difference (RD) between the measurement results of the smartphones and the PCB accelerometer, as follows:

$$\mathrm{RD}(\%) = \left|\frac{\mathrm{A-B}}{\mathrm{A}}\right| \times 100\% \quad \textbf{(1)}$$

where A is the measurement recorded by the PCB accelerometer, in terms of acceleration, PPV or RMS velocity in the 1/3 octave band spectrum, and B is the corresponding measurement recorded by the smartphone. A direct comparison of the measurement results, in terms of PPV every 10 sec and RMS velocity in the 1/3 octave band spectrum under different vibration amplitudes at 25 Hz excitation, between those obtained by iPhone 8 and the PCB accelerometer, is shown in Figures 3 and 4. The measurement results coincide very well.

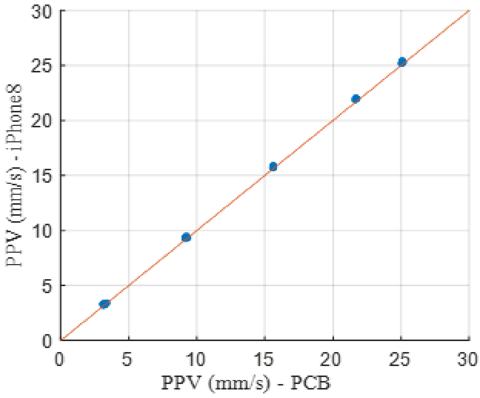


Figure 3: Comparison of PPV at 25 Hz excitation between iPhone 8 and PCB accelerometer

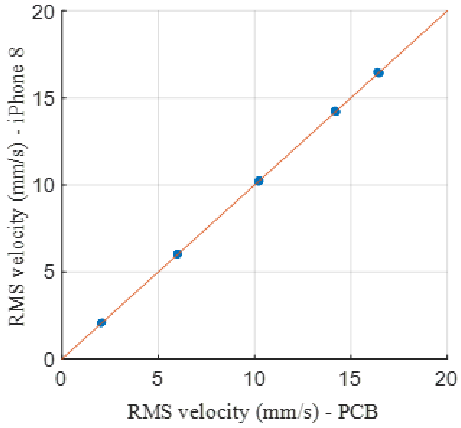


Figure 4: Comparison of RMS velocity at 25 Hz excitation between iPhone 8 and PCB accelerometer

In general, the RD is less than 3%, except at the lowest vibration level where the maximum RD could reach 5%. The lowest vibration level is defined as the acceleration level at 0.1 to 0.15 m/s^2, the PPV level of less than 0.5 mm/s, and the RMS velocity in the 1/3 octave band spectrum of 100 to 150 μm/s. This small value of RD is considered accurate enough for the purpose of construction monitoring.

Two Android smartphones (Samsung Note 9 and VivoNex) were tested for parallel comparison, as shown in Plate 2. Excitation frequencies of 2 Hz, 4 Hz, and 6 Hz were applied. The results indicated that Samsung Note 9 had acceptable accuracy, while the performance of VivoNex was not stable. The iPhone series was found more suitable for vibration monitoring, as compared with the Android smartphones, due to the consistency in performance.

2.3.2 Noise Calibration

The noise data were acquired using the internal microphone built inside the iPhones and were compared with those obtained by a sound level meter (BSWA 308). For this calibration, iPhone 8 and iPhone 11 were used. The test set-up is shown in Plate 3. Both the slow-time weighting and fast-time weighting measurements were tested (fast corresponds to a 125 ms time constant whereas slow corresponds to a 1 second time constant). Figure 5 shows the noise level recorded by iPhone 11 using fast-time weighting measurement, in terms of dB(A) and the RD computed. The difference in the sound level recorded is less than ±2 dB(A).

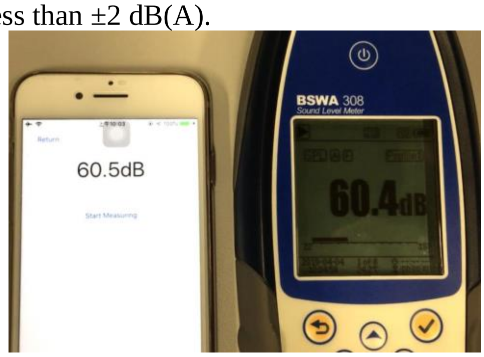


Plate 3: Set-up for noise calibration

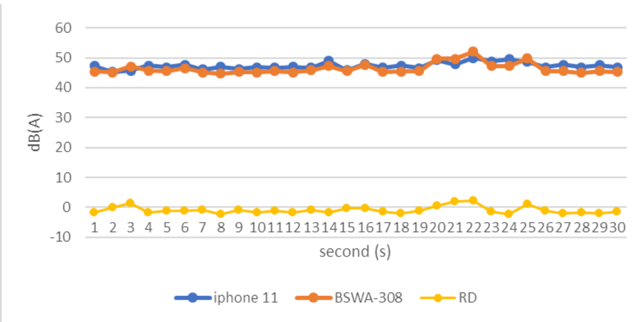


Figure 5: Comparison of noise level recorded by iPhone 11 and sound level meter

Proceedings DOI: 10.21467/proceedings.133
ISBN: 978-81-957605-1-0

Series: AIJR Proceedings
ISSN: 2582-3922

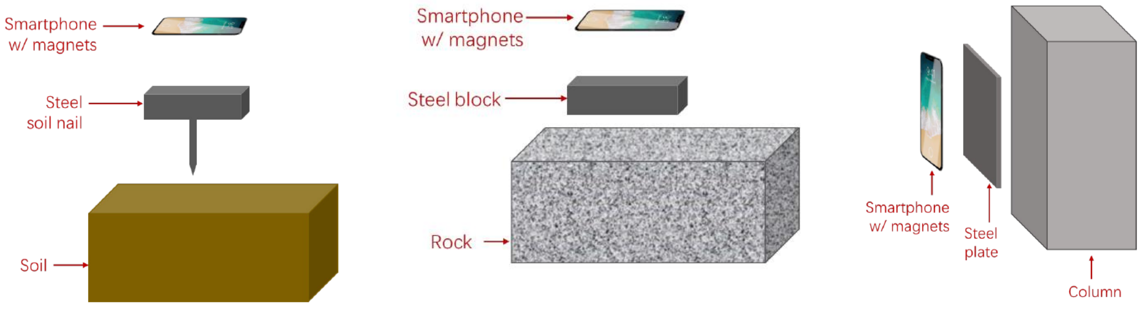
2.4 Site Validation

To validate the V&N App developed for measuring the construction-induced vibration and noise, eight field measurements were carried out, as shown in Table 1, for various construction activities, including socketed H-piling, sheet piling, mini-piling and rock excavation works.

Table 1: Field measurement project information

Co-ordinator	Project	Location	Type of works
QMH	Queen Mary Hospital Expansion Project	Pok Fu Lam	Rock excavation
Chevalier Group	Tuen Mun Hospital Expansion Project	Tuen Mun	Concrete breaking
Chevalier Group	Kwun Tong Preliminary Water Treatment Works	Kwun Tong	Sheet piling & Mini-piling
CEDD	Contract No. ND/2019/04 - Fanling North New Development Area, Phase 1: Fanling Bypass Eastern Section (Shek Wu San Tsuen North to Lung Yeuk Tau)	Fanling	Pre-bored socketed H-piling
CEDD	Contract No. NE/2017/05 – Tai Po Road, Sha Tin Section	Sha Tin	Sheet piling
CEDD	Contract No. ND/2018/01- Kong Nga Po construction site	Fanling	Sheet piling
ArchSD	Contract No.SSH502 -Design and Construction of Joint-user Government Office Building in Area 67	Tseung Kwan O	Bored piling
HD	Sheung Shui Areas 4 & 30, Site 1 Phase 1	Sheung Shui	Pre-bored socket H-piling

In the test set-up, two or more strong magnets were attached to the back of the smartphones using strong tapes, and a steel soil nail, steel block or steel plate was used for vibration monitoring on soil surface, rock or ground surface or vertical structural surface respectively, as shown in Plate 4.



(a) On soil surface (b) On rock or ground surface (c) On vertical structural surface

Plate 4: Set-up for smartphones on different types of surfaces

In the site validation, the operational performance of the V&N App was tested. The vibration and noise measurements were acquired and processed by the V&N App installed in the iPhones, and the data, including photo, text remarks, etc., were uploaded to the cloud (Google Firebase in this case), and test emails were sent.

The results obtained from the monitoring the Sheung Shui site involving socketed H-piling works are presented herein.

Two smartphones (iPhone 8 and iPhone 12) were used, and they were installed at different locations for vibration measurement. Soil nails were first inserted into the soil ground at the monitoring locations.

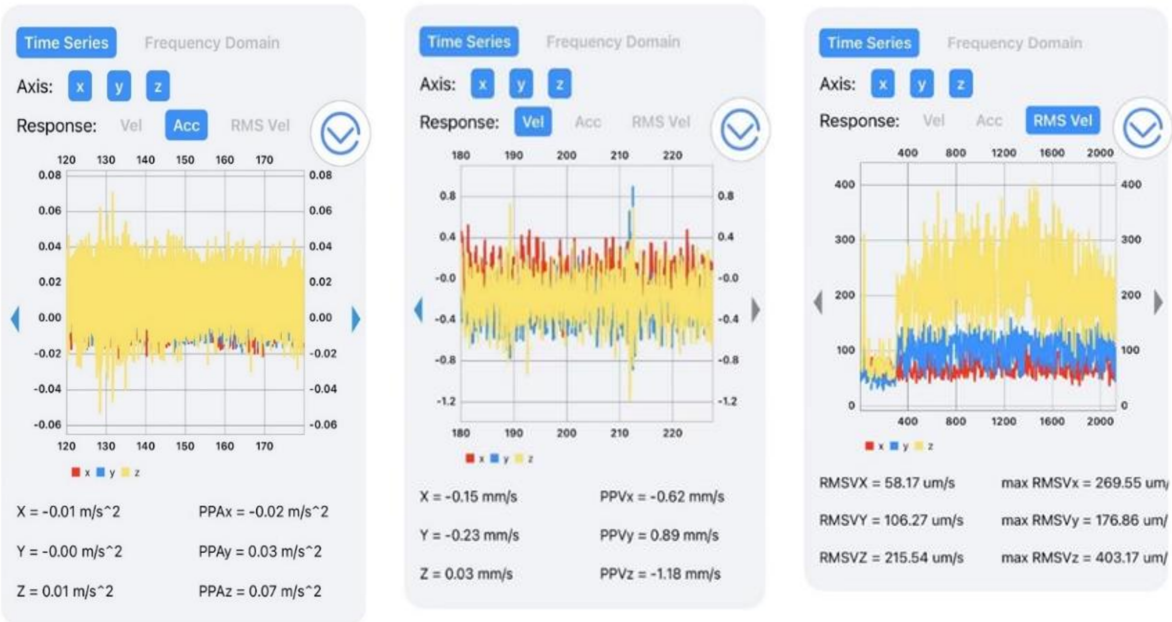
The distances from the socketed H-pile to iPhone 8 and iPhone 12 were 3.3 m and 10.8 m respectively, as shown in Plate 5. An accelerometer (PCB 356b18) was used to measure the vibration at the iPhone 12 location.

(a) Set-up for iPhone 12, accelerometer and soil nail (b) Set-up for iPhone 8 and soil nail

Plate 5: Set-up for site validation

The V&N App operated normally during the whole measurement process. The acceleration time history, velocity time history, and RMS velocity in time domain recorded by iPhone 8 are given in Figure 6.

The acceleration measured by iPhone 12 ranges from -0.231 m/s^2 to 0.192 m/s^2, whereas that measured by iPhone 8 ranges from -0.381 m/s^2 to 0.251 m/s^2. The vibration attenuates with distance.

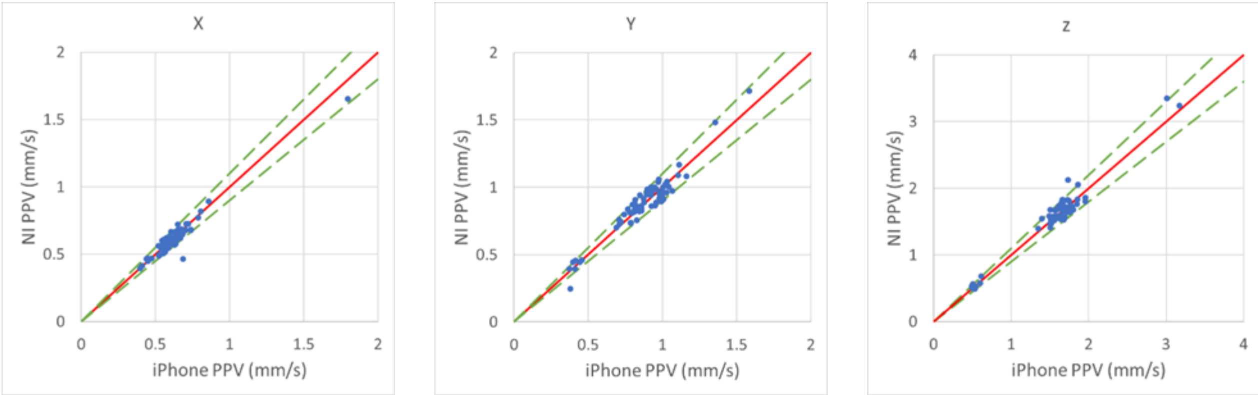


(a) Acceleration time history (b) Velocity time history (c) RMS velocity in time domain

Figure 6: Screen shots of vibration results from V&N App

Proceedings DOI: 10.21467/proceedings.133
ISBN: 978-81-957605-1-0
Series: AIJR Proceedings
ISSN: 2582-3922

A comparison of the PPV values recorded by iPhone 12 and the accelerometer (PCB 356b18) is shown in Figure 7. The green dashed lines show the 10% difference bounds. The average RD of PPVx, PPVy and PPVz is 5.27%, 5.86%, and 4.87% respectively. The measured PPV ranges from 0.493 to 3.175 mm/s. In general, there is good comparison between the PPV values measured by iPhone 12 and the accelerometer. The dominant frequencies recorded by iPhone 12 in x, y and z directions were 32.01 Hz, 33.53 Hz, and 32.73 Hz respectively, whereas those by iPhone 8 were 24.46 Hz, 24.91 Hz, and 24.64 Hz.



(a) PPVx b) PPVy (c) PPVz

Figure 7: Comparison of PPV between iPhone 12 and accelerometer

Noise was also measured. A sound level meter (BSWA 309) was used, as shown in Plate 6. A comparison of the noise levels obtained by iPhone 12 and iPhone 11 with that obtained by the sound level meter is shown in Figures 8 and 9. The noise levels measured by iPhone 12 ranged from 89.47 to 93.10 dB, whereas those by iPhone 11, ranged from 89.49 to 96.29 dB. There is good agreement between the noise levels recorded by the iPhones and the sound level meter.

Plate 6: Noise measurement by iPhone 11 and sound level meter

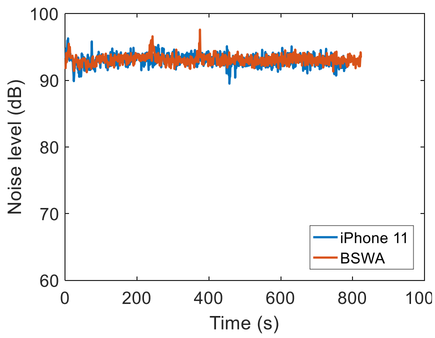


Figure 8: Noise level recorded by iPhone 12 and sound level meter

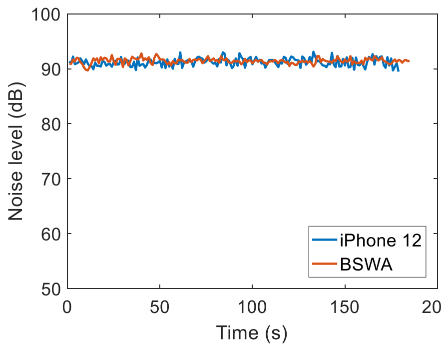


Figure 9: Noise level recorded by iPhone 11 and sound level meter

3 Use of Maturity Method for Concrete Strength Estimation

3.1 Background

In 2020, the CIC engaged Ove Arup & Partners Hong Kong Ltd. (Arup) to prepare a Practical Guideline on the use of maturity method to estimate early concrete strength (CIC, 2021b). The maturity method has been used commonly in other parts of the world, and the procedures are given in ASTM (2011) and

Carino & Lew (2001). In the Arup's research project, 5 site trials to test the maturity method had been carried out (HyD Central Kowloon Route (Trial nos. 1 and 3), DSD Shek Wu Hui (Trial no. 2), ArchSD Kai Tak Station Square (Trial no. 4) and CEDD Kwu Tung North Retaining Wall (Trial no. 5)). The procedures of laboratory calibration and site validation for the maturity method for Trial no. 5 and a detailed interpretation of the results obtained are presented herein.

3.2 Maturity Functions

The two maturity functions that are commonly used for computing the maturity are:

a. Nurse-Saul Method

$$M(t) = \Sigma\,(Ta - To)\Delta t \qquad \textbf{(2)}$$

where M(t) = temperature-time factor at age t (°C-day or °C-hr), Ta = average concrete temperature during time interval Δt (°C), To = datum temperature (°C) (the temperature below which strength development ceases) and Δt = time interval (day or hr).

b. Arrhenius Method

$$t_e = \Sigma\,[\,e^{-Q\left(\frac{1}{Ta}-\frac{1}{Ts}\right)}\,]\,\Delta t \qquad \textbf{(3)}$$

where t_e = equivalent age at a specified temperature T_s (day or hr), Q = activation energy (Ea) divided by the gas constant (R) (=8.3114 $Jmol^{-1}K^{-1}$) (in K), T_a = average concrete temperature during time interval Δt (in K), T_s = specified temperature (in K), taken as 25°C (298°K) and Δt = time interval (day or hr).

The Arrhenius method is in most cases better than the Nurse-Saul method because the rate of strength development is assumed to vary exponentially with temperature in the method, which is considered more realistic. In the interpretation that follows, focus is placed on the Arrhenius method.

3.3 Laboratory Calibration

3.3.1 Testings

For the Kwu Tung North retaining wall, a Grade 30/20D concrete with a water/cement ratio of 0.49 and a slump of 75 mm was used. The mix design is given in Table 2.

Table 2: Mix design

Materials	Mass (kg/m^3)
Cement	285
PFA	95 (25%)
20 mm aggregate (crushed rock)	671
10 mm aggregate (crushed rock)	281
Stone fines (crushed rock)	807
Water	187
Admixture: water-reducer and set retarder	3.31

Concrete cubes were made on site and delivered to the laboratory for curing in three water tanks at 25°C, 40°C and 55°C, as shown in Plates 7 sand 8. Alternatively, a temperature matched curing (TMC) system, as shown in Plate 9, can be used. In the system, concrete cubes are stored in the box on the left and the temperature is controlled by the data logger/transmitter on the right in Plate 9, which is received from cloud.

Plate 7: Water curing of concrete cubes in temperature control tank

Plate 8: Maturity equipment

Plate 9: Set-up of temperature matched curing (TMC) system

Maturity sensors were installed in two concrete cubes placed in each water tank to monitor the temperature development. Compression tests on the concrete cubes taken from the three water tanks were carried out at 6-hour, 12-hour, 1-day, 2-day, 3-day, 7-day, 14-day and 28-day intervals.

The following exponential equation, as proposed by Freiesleben Hansen & Pedersen (1985), was used to fit the average cube compression test results as a function of time of testing to determine the Q value, as used in the Arrhenius method, for the three curing temperatures:

$$S = S_u e^{-\left(\frac{\tau}{t}\right)^{\alpha}} \quad \textbf{(4)}$$

where S = average cube compressive strength at age t (MPa), t = test age (day or hr), S_u = limiting strength (MPa), τ = characteristics time constant (day or hr) and α = shape parameter (taken as 1).

Initial values of τ and Su were first assumed in the computation of the compressive strength values. By minimizing the sum of the square of errors (SSE) of the actual and computed compressive strength values for the three curing temperatures, the parameters that give the minimum SSE were determined. The solver function in the Microsoft Excel was used to determine the best fit parameters.

The parameters established to best fit the compressive strength values for the three curing temperatures are given in Table 3.

Table 3: Parameters for exponential equations

Curing temperature (Tc) (°C)	Su (MPa)	τ (hr)	α
25	46.27	28.83	1
40	57.26	22.85	1
55	51.42	17.60	1

The best fit lines, given by the parameters established for the exponential equations, are given in Figure 10. By plotting the natural logarithm of the τ values and the inverse of the curing temperature, the Q value, given by the gradient of the line, is evaluated. A Q value of 1605 K, as shown in Figure 11, was established.

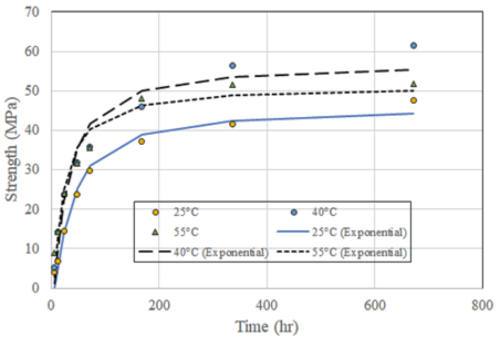


Figure 10: Comparison of actual and computed compressive strength

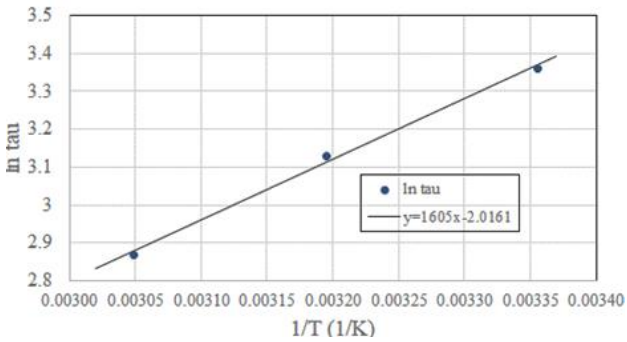


Figure 11: Plot of natural logarithm of τ values versus inverse of curing temperature

3.3.2 Maturity Functions

The maturity function based on the Arrhenius becomes

$$t_e = \Sigma [e^{-1605 (\frac{1}{Ta} - \frac{1}{298})}] \Delta t \quad \textbf{(5)}$$

The strength-maturity relationship for the curing temperature of 25°C is then given by

$$S = 46.27 \, e^{-(\frac{28.83}{te})^1} \quad \textbf{(6)}$$

The development of t_e with time is given in Figure 12, and the strength-maturity relationship for the curing temperature of 25°C is shown in Figure 13. This temperature is used because this is close to the curing temperature in the field. At the curing temperature of 25°C, the Su, τ and α values used are 46.27 MPa, 28.83 hrs and 1 respectively (see Table 3).

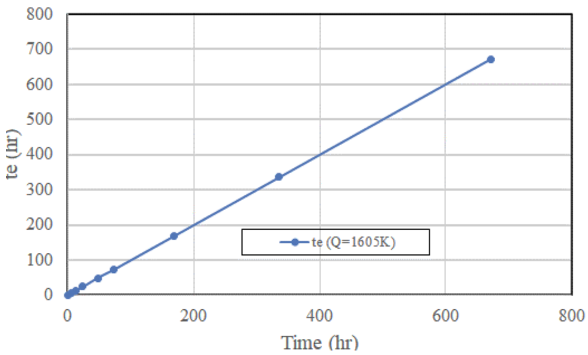


Figure 12: Development of te with time

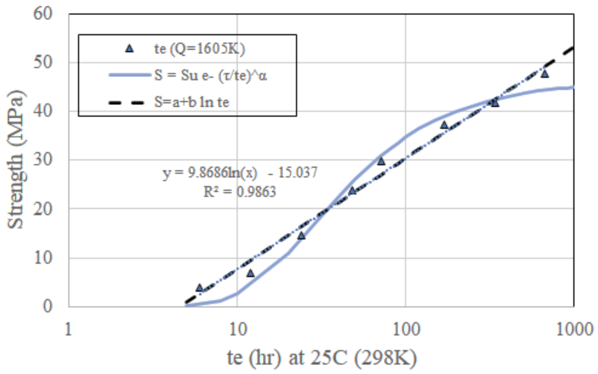


Figure 13: Strength-maturity (te) relationship

3.4 Site Validation

Sensors were installed in a retaining wall structure for a CEDD project at Kwu Tung North (Plate 10). Four brands of sensors were used for result comparison, as shown in Plate 11. Two locations A and C have been selected for sensor installation in the retaining wall, as shown in Figure 14, based on the locations of the highest expected stress level and coldest temperature development. Locations B and D are the designated redundant locations in case of sensor data loss at Locations A and C.

Plate 10: Construction of a retaining wall at Kwu Tung North

Plate 11: Four brands of temperature sensors used (top left: Command Center; top right: LumiCon; bottom left: SmartRock; bottom right: Converge)

Proceedings DOI: 10.21467/proceedings.133
ISBN: 978-81-957605-1-0

Series: AIJR Proceedings
ISSN: 2582-3922

For this paper, focus is put on the temperature data collected at Location C by Command Center sensors, as shown in Figure 15. The Arrhenius method was used by Command Center in the analysis.

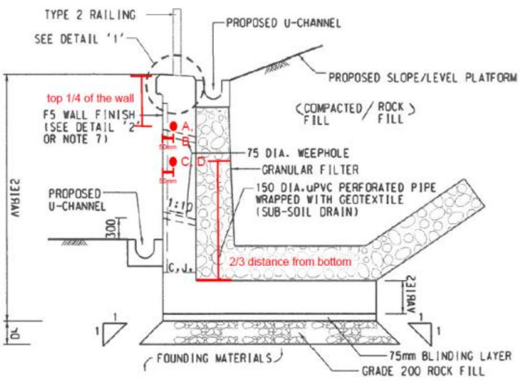


Figure 14: Maturity sensor installation locations

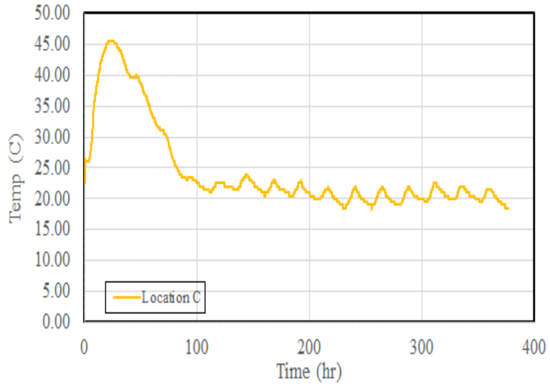


Figure 15: Temperature development profile at Location C recorded by Command Center sensors

Based on this temperature profile, t_e was evaluated, as shown in Figure 16. The strength development corresponding to the curing temperature of 25°C, computed using Equation (6), is shown in Figure 17.

Compression tests on TMC concrete cubes were carried out for conformity check. The results are included in Figure 16. A good comparison is obtained between the TMC results and the compressive strength obtained from the temperature development profile. The ratio of the compressive strength obtained to the TMC value at the time of testing is within the allowable limits. The time duration of concern is from 12 hrs onwards to less than 100 hrs.

The criteria for removal of the formwork is the attainment of concrete strength of 30 MPa. From Figure 17, it can be seen that the time allowed to remove the formwork is 51.75 hrs (2.16 days), as compared with 7 days as specified in the Code of Practice for Structural Use of Concrete 2013 (BD, 2020). There was a gain of 4.84 days in the works progress, based on the maturity method for determining the gain in strength in the concrete.

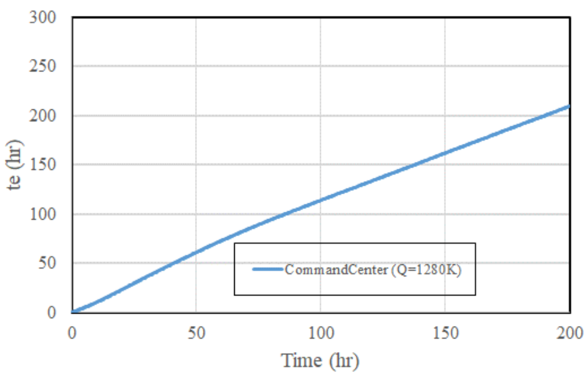


Figure 16: Development of te with time for the temperature profile at Location C

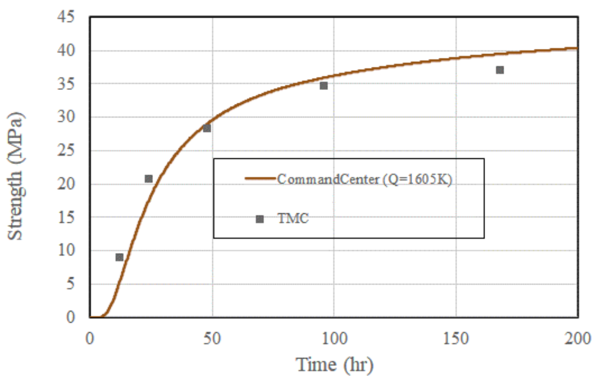


Figure 17: Development of compressive strength with time at Location C

4 Conclusions

The following conclusions can be made from the above studies:

(a) The CIC engaged PolyU to develop a new method for construction-induced vibration and noise monitoring, making use of the latest smartphone technology. The work was completed satisfactorily. A reference material on the method was published on the CIC website and the V&N App is already available for download in the Apple App Store.

(b) The iPhones and the V&N App developed had been calibrated in laboratory and validated on site. It was shown that there was good comparison between the measurement results, in terms of vibration and noise levels, from the iPhones tested and the commercial units. The V&N App developed for iPhones was able to acquire, process and analyse the data accurately for use and reporting. The following iPhones have been checked and verified as acceptable for use with the V&N App (iPhone 12 Pro Max, iPhone 12 Pro, iPhone 12, iPhone 12 mini, iPhone 11 Pro Max, iPhone 11 Pro, iPhone 11, iPhone SE (2nd gen.), iPhone XS Max, iPhone XS, iPhone XR, iPhone X, iPhone 8 Plus and iPhone 8).

(c) The iPhones and the V&N App developed provide a good and accurate method for construction-induced vibration and noise monitoring, as an alternative to the commercial units available. They have edges over the commercial units in that they are cheaper, and they can be installed and operated easily and conveniently. They could provide continuous and stable data measurement, with no data loss or crashes during the measurement process.

(d) The CIC engaged Arup to investigate the application of maturity method for concrete strength estimation in Hong Kong. The work was completed satisfactorily and a practical guideline on the use of maturity method to estimate early concrete strength was issued.

(e) Five site trials to test the maturity method had been carried out. The procedures of laboratory calibration and site validation for the maturity method and a detailed interpretation of the results obtained for Trial no. 5 for a retaining wall structure at Kwu Tung North are presented. The development of strength in the concrete, and hence the time for removal of the formwork was established. There was a gain of 4.84 days in the works progress in this case, based on the maturity method for determining the gain in strength in the concrete.

5 Declarations

5.1 Acknowledgements

The authors would like to thank the CIC, PolyU and Arup for their consent to present and publish the results and findings given in the paper. Thanks are due to PolyU and Arup for conducting the studies and preparing the reference material and practical guideline on the subjects for use by the construction industry.

5.2 Publisher's Note

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