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SMARTPHONE AS NEXT-GENERATION MONITORING DEVICES FOR CONSTRUCTION-INDUCED VIBRATION AND NOISE

RESEARCH SUMMARY

Construction Industry Council

Smartphone as Next-generation Monitoring Devices for Construction-induced Vibration and Noise

Research Summary

Authors

Prof. Songye ZHU
Prof. Siu-Lai CHAN
The Hong KongPolytechnic University

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Enquiries

Enquiries on this research may be made to the CIC Secretariat at:

CIC Headquarters
38/F, COS Centre, 56 Tsun Yip Street, Kwun Tong, Kowloon

Tel.: (852) 2100 9000

Fax: (852) 2100 9090

Email: enquiry@cic.hk

Website: www.cic.hk

PREFACE

With the rapid development of scientific and technological innovation, fast-changing portable electronic devices have brought great convenience to human beings and enriched our daily life. Mobile phones, as a representative product with unique and powerful features, have made revolutionary changes in various areas. For example, the novel sensing functions of modern smartphones, including the recording of vibration and noise, have opened a new window for the operators and engineers to monitor and assess construction-induced impacts, which may adversely affect structural safety, human comfort, and equipment functionality.

The next-generation monitoring system by using smart mobile phones with specialised supporting software for assessing the impact of vibration and noise on the surrounding environment during construction has been born at the right moment. In this project, the hardware of the iPhone series was proven to be qualified in undertaking the due measurement requirements. A corresponding phone application was created to collect and display GPS information, add photo/word remarks, package the measurement data and results through email, and upload data to the cloud. The user-friendly display and operation interface in the online system builds an excellent bridge for staff in the management team to check the facts during construction.

Laboratory experiments and field measurements have been successfully conducted to verify the accuracy of measurements using iPhone models as compared to traditional high-sensitivity accelerometers or vibrometers. Vibration and noise generated by different construction activities, including sheet pile, socket H-pile, and mini pile, were measured and compared. The values of the key indicator—peak particle velocity—measured by these two methods confirmed the accuracy, feasibility, and applicability of the proposed system. The unique merits, including cheap price, strong mobility, flexible range, various functions, convenient operation, friendly interface, cloud-based independent storage, statistical analysis, report generation, and other characteristics, will make this smartphone application a very promising choice for on-site vibration and noise monitoring, and equip the local construction industry with this state-of-art monitoring technology.

RESEARCH HIGHLIGHTS

Excessive vibration and noise generated by a variety of construction activities (such as piling or excavation) may cause structural damage, noise pollution, human discomfort, and disfunction of vibration-sensitive equipment. Vibration and noise monitoring are regarded as effective auxiliary measures to protect construction sites and surroundings against such disturbances. However, traditional construction vibration monitoring devices used in Hong Kong are becoming obsolete due to limited function, high cost, and incapability to provide multiple vibration indices. Given the powerful computing, various built-in sensors, versatile functions, and easy internet access of modern smartphones, they can be an ideal alternative for both vibration and noise measurement, which would not only overcomes the deficiencies associated with traditional vibrometers but also meets global trends in the mobile era.

Although a few apps capable of vibration or noise measurement using smartphone built-in sensors are available on the market, most of them cannot provide advanced and comprehensive indices (such as velocity responses in time and frequency domains, peak particle velocity (PPV), root-mean-square (RMS) velocity in 1/3 octave band spectrum, A-weighted noise levels, etc.) required for construction impact assessment, together with photo-taking, cloud data storage and sharing functions.

Aiming to develop a next-generation monitoring device for assessing the impact of construction-induced vibration and noise, this project developed an app that enables vibration monitoring concerning multiple indices and limit states. Specifically, the app provides measured acceleration and velocity data in both time and frequency domains, PPV, RMS velocity in a 1/3 octave band, and equivalent noise level, which are individually required for the assessment of structural damage, equipment functionality, human comfort, etc. Besides noise and vibration indices, the developed app features diversified functions which cannot be provided by traditional portable seismographs or geophones, such as the recording of GPS information, adding of photo/text remarks, sending or sharing of measurement data and results through email, uploading of data to the cloud, and so on. In addition, this app creates an interactive circumstance by grouping registered users of the same construction project so that users within one group can easily check and share measurement results. By taking advantage of an Internet connection, an online system with the function of flexible data storage and export, as well as report generation is also developed.

To implement and validate the developed monitoring app, laboratory experiments and field measurements on real construction sites were conducted. Three iPhone models were tested and used, all of which are equipped with a tri-axis MEMS accelerometer and inner microphone. The measurement range for the embedded MEMS accelerometer is from ±2 g up to ±16 g, and the corresponding sensitivity is 16384 lbs/g to 2048 lbs/g, which could satisfy the requirements for construction-induced vibration measurement.

The purpose of laboratory experiments was to calibrate vibration measurement using an iPhone against a traditional high-sensitive accelerometer, wherein the measurement using an iPhone does not require any extra signal amplifier and data acquisition system, as the traditional setup does. The sampling frequency of the iPhone was set to be 100 Hz. Different excitation frequencies in the typical range (4–26 Hz) for construction-induced vibration and different amplitude levels ranging from 0.05 to 0.5 mm/s^2 were tested. The measurements of both devices were subsequently compared. The majority of the relative differences were generally less than 3%, except for the extremely low vibration level. The lowest vibration level was represented by the RMS velocity of 100 to 150 μm/s, which corresponded to the PPV level of 0.5 mm/s and the maximum relative difference of 5%. Considering the actual vibration levels of interest in construction, the measurement from the smartphone showed acceptable accuracy. Similar to vibration calibration, the noise calibration was conducted in comparison with a standard sound level meter. Both slow-weighting and fast-weighting were tested. The average difference was less than ±2 dB.

The objective of the field measurements was to validate the smartphone app in the real circumstance of construction sites. With the support of the Civil Engineering and Development Department (CEDD), Architectural Services Department (ArchSD), Hong Kong Housing Authority (HKHA), and Chevalier (Construction) Co. Ltd., a total of eight field measurements were conducted on selected construction sites. Vibration and noise generated by three representative construction activities, namely, sheet pile, mini pile, and socket H-pile, were measured and compared. iPhone models were installed on the soil nail inserted into the soil, together with traditional accelerometers and portable vibrometers for parallel comparison. The PPV measurements, which are of the most interest to the construction industry, were compared in a series of tests. The measured PPV ranged from 0.7 to 3.2 mm/s for socket H-pile driving, 0.186 to 1.972 mm/s for mini pile driving, and 0.4 to 44.0 mm/s for sheet pile driving. In general, the PPVs measured by iPhones were in agreement with the values measured by the other two monitoring devices. When PPV was larger than 2 mm/s, the average relative differences were lower than 5%. However, PPV levels lower than 0.4 mm/s (e.g., the vibrations induced by bored piling in the field tests) were too small to be measured by iPhone. It should be noted that the relative differences were more likely due to the difference in the installation of these devices and in the time intervals used in the calculation of PPV. The dominant frequencies recorded by the smartphone app in three orthogonal directions were also consistent with the values recorded by the traditional accelerometer or portable vibrometer, with differences less than 1 Hz.

In noise measurement, one commercial sound level meter was used as a reference. Compared with the sound level meter, the noise level recorded by the smartphones was generally consistent, but showed more changes due to the influence of environmental noise (such as wind noise and traffic noise) that overlaid the construction-induced noise. In contrast, the sound level meter with windscreen was less influenced by airflow noise.

Besides vibration and noise measurement, other functions of the smartphone app were also tested in both the laboratory tests and field trial measurements, which include adding remarks, sending email, and uploading photos and data to the cloud. The app worked smoothly and no crashes happened in the current version. During the development of the app, questionnaires from two users were collected. The user feedback was generally positive.

The appealing features of a smartphone include, but are not limited to, cheap price, great mobility, flexible range, multiplex functions, convenient operation, friendly interface, cloud-based autonomous saving, statistical analysis, and report generation, which will render this smartphone app a very promising option for future vibration and noise monitoring on construction sites and provide the local construction industry with this emerging technique.

CONTENTS

1 INTRODUCTION

1.1 Background

Construction activities, including piling, excavation, demolition, breaking, and other impact and vibratory processes, often generate excessive ground-borne vibrations associated with noise pollution. Therefore, construction-induced vibrations have attracted great attention over the past several decades. Vibration and noise pollution have become a more severe problem in metropolitan cities (like Hong Kong), where the shortage of land supply results in many new construction projects located in high-density areas with little separation from existing structures. The California Department of Transportation [1] summarised the empirical formulae for typical vibration-exciting construction activities. BS 7385-2:1993 [2] provided a good collection of historical measurement data of construction-induced vibrations. The ground-borne vibration propagates to a distant receiver as an elastic wave. Wave propagation is a rather complex process affected by soil, wave, and receiver structures. The vibration amplitudes attenuate with the travelled distance due to geometric and material damping. [1]

The environmental impact of such vibrations can be classified into four levels: buried pipework damage, structural damage, human discomfort, and harmful environment to sensitive equipment. These four levels impose different vibration limits on construction activities. Noise level is usually quantified by dBA level, whereas vibrations are quantified by different indices, including peak particle velocity (PPV), peak particle acceleration (PPA), root-mean-square (RMS) velocity and acceleration in the 1/3 octave band spectrum. These vibration limits or criteria are defined in various specifications and codes:

Level 1 - Pipework Safety: The vibration limits in consideration of potential damage to nearby gas, water, and electricity pipes are often expressed in terms of PPV. For example, DIN 4150-3 [3] defines the allowable PPV of 100, 80, and 50 mm/s for steel, concrete, and plastic pipes, respectively. Eurocode 3 [4] proposes a PPV of 40 mm/s to prevent damage to buried services.

Level 2 - Structural Safety: The vibration limits considering potential structural damages are usually expressed using PPV as well. With reference to Foundation Design and Construction (GEO Publication No. 1/2006) [5], without detailed engineering analysis and as a general guideline, a limiting PPV of 15 mm/s is acceptable for buildings, sewerage tunnels and major public utilities. A more stringent limit of 7.5 mm/s is required for more sensitive structures such as water retaining structures, water tunnels, masonry retaining walls, and dilapidated buildings. For buildings of historical significance, the limiting PPV values recommended in various overseas codes are in the range of 2 to 3 mm/s. Limited experience in Hong Kong indicates that a PPV of 6 to 8 mm/s can be acceptable.

Level 3 - Human Comfort: Human comfort is affected by both vibration and noise levels. During the last two to three decades, numerous criteria on floor vibration have been proposed. The most widely accepted one in the world is the ISO Scale. ISO 2631-2 [6] covers different building vibration environments and presents acceleration limits by considering vibration frequency and exposure time in different directions. A baseline standard curve corresponding to a perception level is expressed in terms of the weighted RMS acceleration in the 1/3 octave band spectrum. Since the baseline curve is quite conservative, the ISO standard adopts different multipliers for different service conditions such as hospitals, residential, office, and workshop buildings.

Level 4 - Equipment Functionality: The vibration criteria suggested by ASHRAE [7] are most widely adopted for a variety of sensitive equipment and facilities (e.g., in BS5228 [8]). The vibration criteria are defined using RMS velocity in the 1/3 octave band spectrum. The vibration limits for sensitive equipment are very stringent. It needs to be satisfied when constructions are located close to high-tech facilities, hospitals, and semiconductor factories.

Because of environmental impact, construction-induced ground-borne vibrations have been routinely monitored on sites as a common practice. Traditional vibration monitoring uses portable seismographs consisting of recording units, triaxial geophones, and connecting cables, or vibrometers with similar functions. In Hong Kong, there is mandatory guidance on using portable seismographs or vibrometers on construction sites. However, such vibration monitoring practice is associated with several apparent deficiencies, such as the incapability of providing multiple vibration indices, a fixed range, lack of real-time display, difficulty in long-term measurement, separate units for vibration and noise measurements, bulky size, high cost, and so on. The manual retrieval of stored data afterward is very time-consuming.

1.2 Aims and Objectives

This project aims to develop a new monitoring paradigm for construction-induced vibration and noise by taking advantage of the recent advances in smartphone technology. This new-generation monitoring device can conduct real-time monitoring of construction-induced vibration and noise simultaneously. In particular, it can automatically assess the environmental impact with respect to different indices (dBA, PPV, PPA, RMS velocity in the 1/3 octave band spectrum, and weighted acceleration) and different limit states (e.g., structural and utility safety, human comfort, and equipment functionality). In addition, the vibration and noise monitoring are conveniently combined with the information of time, duration, measurement locations, operator's name, photos of construction sites, text remarks, and other customised settings. The recorded information can automatically be saved to the cloud system and can be conveniently shared or reported to concerned parties immediately.

The major objectives of this project include:

1. To develop the first smartphone application (app) for real-time monitoring and assessment of construction-induced vibration and noise;
2. To establish a standard monitoring process, including the selection of phone models, the standard installation accessories and process, and a user operation guideline;
3. To implement and validate the developed monitoring approach through laboratory experiments and field measurements on construction sites; and
4. To promote the developed monitoring app to the local construction industry.

The key deliverables of this research include:

1. The first smartphone app for real-time monitoring and assessment of construction-induced vibration and noise impact with respect to various limit indices;
2. An online system with the functions of data storage, data sharing, and report generation; and
3. A user operation guideline for standard installation accessories, monitoring process, and app operations.

1.3 Scope

The project has been carried out in two phases. The scope of each phase is as follows:

Phase 1

- To examine the sensor sensitivity of smartphones through laboratory experiments;
- To validate the sensor sensitivity of smartphones through the field implementations on construction sites;

Phase 2

- To develop the first smartphone application (app) for real-time monitoring and assessment of construction-induced vibration and noise;
- To establish a standard monitoring process, including the selection of phone models, the standard installation accessories and process, and a user operation manual; and
- To promote the developed monitoring app to the local construction industry.

2 RESEARCH METHODOLOGY

The iPhone series has been selected as smartphone models in this project because of its consistent quality control among different models. Therefore, the app is developed based on the latest iOS system. The research program has been organised into three major tasks.

2.1 Sensitivity Inspection for Sensors

All iPhone models are equipped with six-axis MEMS vibration sensors (triaxial accelerometer plus triaxial gyroscope) and internal microphones. Considering different sensor sensitivity and measurement ranges among different iPhone models, vibration measurement accuracy was first examined through laboratory experiments. As a comparative reference, a high-sensitivity triaxial PCB accelerometer was tested in parallel. The selected iPhone models and the PCB sensor were mounted on the same shaking table and tested under motions with the frequency of 1–100 Hz. Relative differences of the measured accelerations, particularly after conversion from acceleration to velocity, were calculated to calibrate accuracy. Meanwhile, the sensor sensitivity of iPhone models was also compared with two other Android phones.

The noise level measured by the iPhone models was calibrated with a portable sound level meter. Line charts were used to compare the differences between two measured noise records. Subsequently, based on the sensitivity and measure ranges, a list of qualified iPhone models was presented for future selection.

2.2 App Development

The app for real-time vibration monitoring and assessment was developed for the latest iOS system. The coding was done by using Swift, a specialised programming language for developing iOS programmes. The app consists of data measurement module, data processing module, user interface module, and data transmission module. Figure 1 shows the data flow within different modules. Finally, the monitoring records are automatically saved to Google Firebase, which provides affordable cloud services.

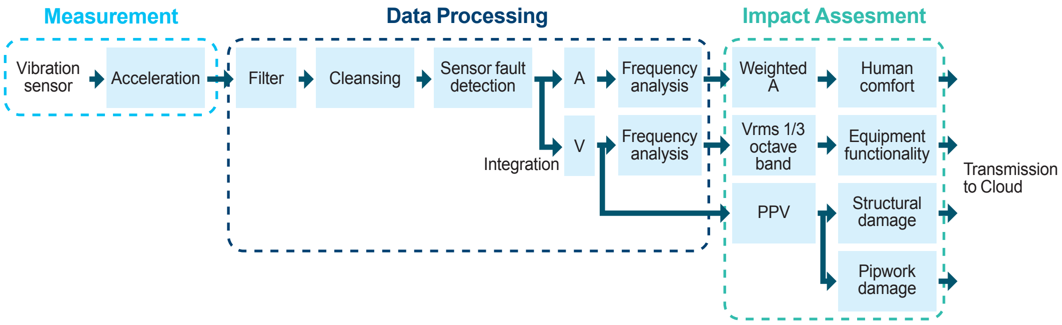


Figure 1 The flowchart of the app functions

The database hosted in Firebase will store all historical monitoring records from different users/operators, including data, annotations, photos, and maps (as shown in Table 1). Users/operators in one construction project are able to share data among themselves, which could establish the correlation between vibration/noise levels and different construction activities. The Google Firebase also provides various views of statistical analysis for report generation, including active users, average daily engagement, event logs, and many other customised functions.

Table 1 The monitoring records saved to the Firestore Database

Project	No.	Time	GPS location	Operators	Duration	Photo
PolyU	99	2021-05-03 11:01:55	N22.306649, E114.179559	S. Zhu	5.8 s	JPG

PPV	Vrms	Arms	Noise	Limit state 1	Limit state 2	Raw data	Remarks
2.5mm/s	360μm/s	13.5mg	95 dB	YES	YES	2021-05-03 11:01:55	Mini piling

2.3 Installation Accessory and Field Validation

A steel soil nail has been designed and fabricated to facilitate the quick installation of smartphones on site. Smartphone models were adhered to the soil nail to be inserted into the ground. On concrete or rock foundations, a steel plate adhered to the surface by glue is used. Using strong magnets to mount smartphones on a steel surface has been proven very efficient and reliable in the past monitoring studies. It provides great convenience when installing monitoring devices on different selected checkpoints. A user guide is also provided, which covers the software operation manual, standard monitoring process, and demonstration examples.

The objective of the field measurement was to validate the developed smartphone app for the measurement of construction-induced vibration and noise. Several construction sites with various ongoing construction activities were selected for trial tests. The results were compared with traditional seismographs or vibrometers. Some site engineers were also invited to use the smartphone app. Based on problems identified in the field tests and feedback from different users/operators, the app functions and interfaces were further optimized.

3 RESEARCH FINDINGS AND DISCUSSION

3.1 Sensor Sensitivity

To prove the qualification of iPhones in construction-induced vibration and noise measurement, the calibration tests of sensor sensitivities for iPhone models were conducted. First, a selected iPhone model (e.g., iPhone 8) was calibrated with a traditional accelerometer at different excitation frequencies and different amplitudes. The test was conducted in Phase 1. Later, another round of laboratory tests was conducted by comparing iPhones with other Android smartphones. The tested smartphone models included iPhone 6, iPhone 7, iPhone X, iPhone 11 Pro Max, Samsung Note 9, and VivoNex. The results proved that iPhone series has stable performance and is more suitable than Android phones in vibration measurement. In addition, noise calibration was also carried out with a portable sound level meter in the laboratory. Based on the calibration results, the recommended iPhone models were listed in Appendix I.

3.1.1 Calibration at different excitation frequencies with various amplitudes

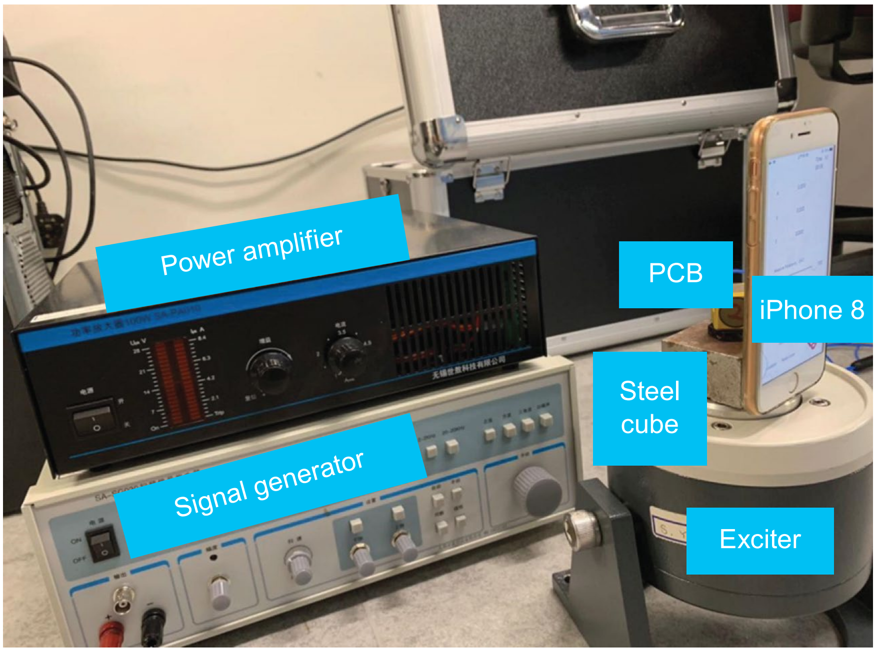


Figure 2 The experimental setup for calibration tests

As shown in Figure 2, the calibration test was conducted by using an electric exciter. A steel cube was fixed on the top of the exciter. The iPhone 8 model was mounted on a steel cube through a strong magnet, while a traditional high-fidelity triaxial accelerometer (PCB 356b18) was installed on the same steel cube. Other components in the measurement system include the signal generator, power amplifier, DAQ system (NI-USB-6346(BNC)), and laptop. The exciter was connected to a power amplifier, while the latter was connected to a signal generator that can generate harmonic sinusoidal waves. The signal generator was used to generate excitations with a specific frequency, and the power amplifier was used to control the excitation amplitude. The measurement data from the PCB accelerometer was used to calibrate the accuracy of the vibration measurement using the smartphone.

The frequencies of the harmonic excitations selected were 4 Hz, 6 Hz, 8 Hz, 10 Hz, 16 Hz, 20 Hz, and 25 Hz, which covered a common range of piling-induced vibrations. Different amplitude levels were also tested. The sampling frequency of the measurement was set to 100 Hz. The corresponding measurement results from the two systems were compared.

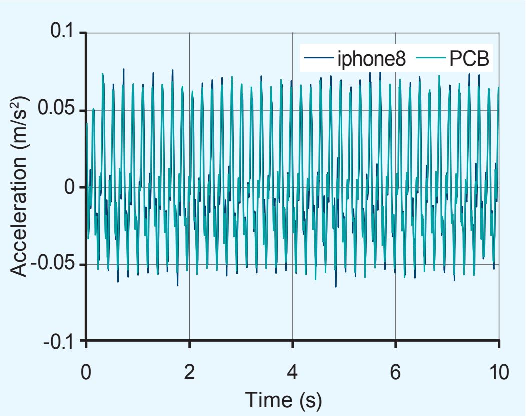


Figure 3 Comparison of acceleration in time domain at 4 Hz excitation

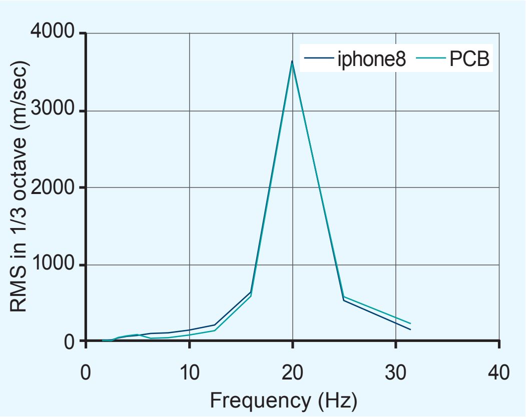


Figure 4 Comparison of RMS velocity in frequency domain at 20 Hz excitation

Figure 3 shows a typical comparison example of the acceleration time histories at 4 Hz harmonic excitation. The measurement results from the smartphones and traditional accelerometer coincide with each other very well in time domain. Figure 4 shows an example of the comparison of RMS velocity in the 1/3 octave band spectrum. The results obtained from the smartphone and high-fidelity PCB accelerometer were almost the same in frequency domain. The location and the amplitude of the peaks coincide well, and the variation trend over the frequency range is the same.

Figure 5 and Figure 6 demonstrate direct comparisons of the measurement results (the PPV every 10 seconds and RMS velocity in the 1/3 octave band spectrum) by two systems with different vibration amplitudes at 25 Hz excitation. It is observed that the measurements of the two sensors coincided very well.

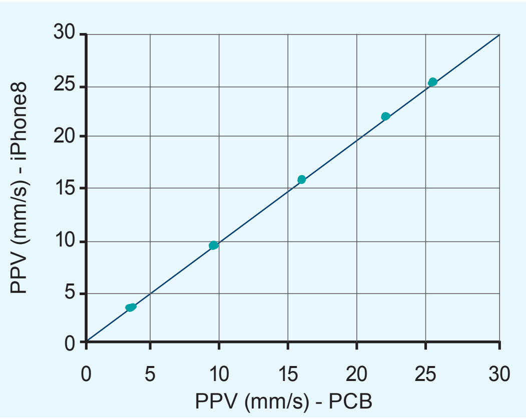


Figure 5 PPV comparison at 25 Hz excitation

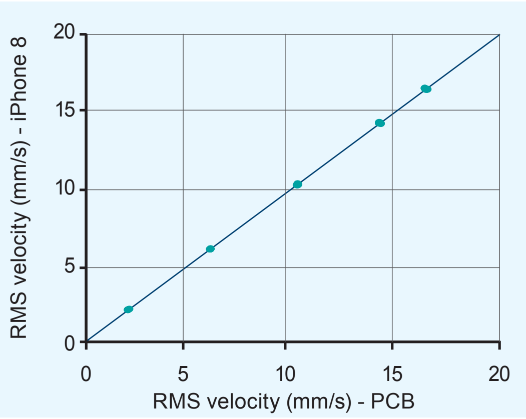


Figure 6 RMS velocity comparison at 25 Hz excitation

To further quantify the performance of iPhone models, the relative differences (as Equation 1) regarding acceleration (RD1), peak velocity (RD2), and RMS velocity in 1/3 octave band (RD3) were computed through data processing for the purpose of comparison.

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

In general, most of the relative differences were less than 3%, except for the lowest vibration level. The lowest vibration level is represented by the RMS velocity of 100-150 μm/s, which corresponds to the PPV level of 0.5 mm/s and the maximum relative difference of 5%. Considering the actual vibration levels of interest in construction, the measurement by the smartphone shows acceptable accuracy. In summary, an iPhone with satisfactory sensitivity can be treated as a promising alternative to the traditional accelerometers or vibrometers.

3.1.2 Comparison between iPhone models and Android smartphones

Since this project is focused on app development in the iOS environment, different iPhone models were tested in order to have a more comprehensive understanding of their performances. The selected iPhone models included iPhone 6, iPhone 7, iPhone X, and iPhone 11 Pro Max. Two Android smartphones, Samsung Note 9 and VivoNex were also tested only for parallel comparison. The acceleration measured by these smartphones was compared to the measurement of a highly sensitive traditional accelerometer (PCB 356b18).

Figure 7 Calibration tests of various smartphone models on a shaking table

Figure 7 shows a photo of the laboratory calibration tests of multiple smartphone models that were mounted on a shaking table, with a traditional accelerometer installed on the same shaking table as well. Various calibration vibrations were measured at the same time at excitation frequencies of 2 Hz, 4 Hz, and 6 Hz.

The results show that most RD1 are less than 4% among the tested iPhone models, except for very low vibration level (i.e., acceleration ranging from 0.1 - 0.15 m/s^2). It is noticed that the older iPhone models have relatively higher RD1 than other models, especially iPhone 6. For newer generation smartphones, such as iPhone X and iPhone 11 Pro Max, the RDs are around 3%. At acceleration ranging from 0.5 to 1.2 m/s^2, iPhone 11 Pro Max shows very good consistency with RD less than 2%. Compared with acceleration differences, the velocity differences (i.e., RD2) are larger than RD1, which may be due to different signal filtering and processing. In terms of vibration indicator, RMS velocity in a 1/3 octave band spectrum, the relative differences (RD3) are much smaller among all vibration levels. Most of the RD values are less than 3%. Considering the actual vibration levels of interest in construction activities, the measurements from the iPhone series show satisfactory accuracy. Two Android smartphones (i.e., Samsung Note 9 and VivoNex) were also tested, and the results indicated that Note 9 has acceptable accuracy, while the performance of VivoNex is not stable.

Compared with a wide variety of Android smartphones and inconsistent performance among different types, it has been proved that iPhone series is more suitable for this project. Based on the presented comparison results, the recommended iPhone models have been listed in Appendix I.

3.2 Noise Calibration

Similar to vibration calibration, the noise data were acquired by using the internal microphone of iPhone models (iPhone 8 and iPhone 11). The measurement results were calibrated through comparison with a standard sound level meter (BSWA 308). Both slow-weighting and fast-weighting were tested. Figure 8 shows the testing setup for noise calibration. Figure 9 shows the noise levels recorded by iPhone 11 using fast-weighting and relative differences from BSWA sound level meter. The average difference is less than ±2 dB.

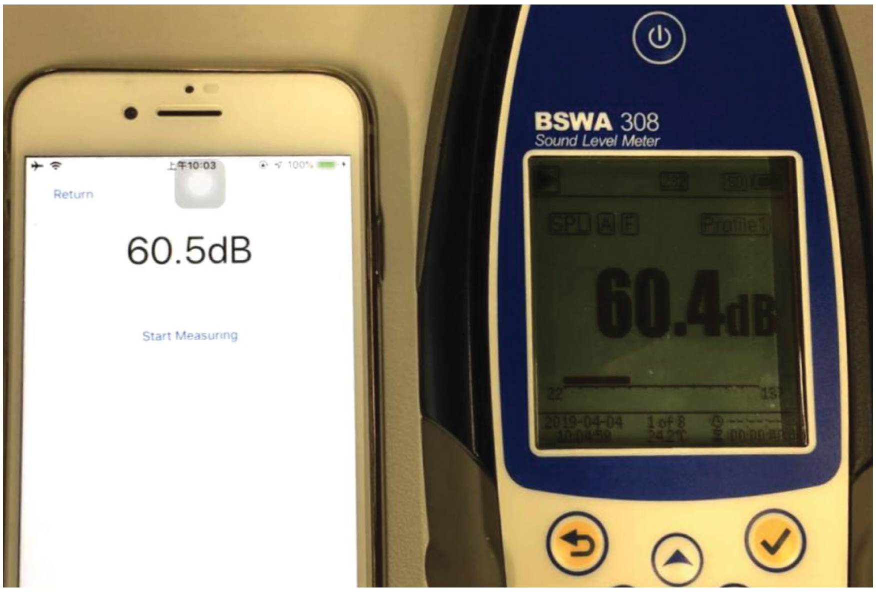


Figure 8 Smartphone and sound level meter for noise measurement

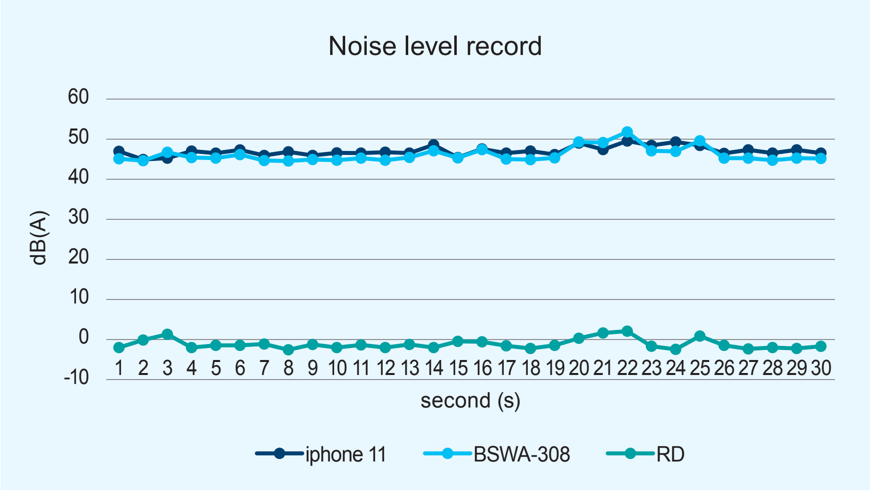


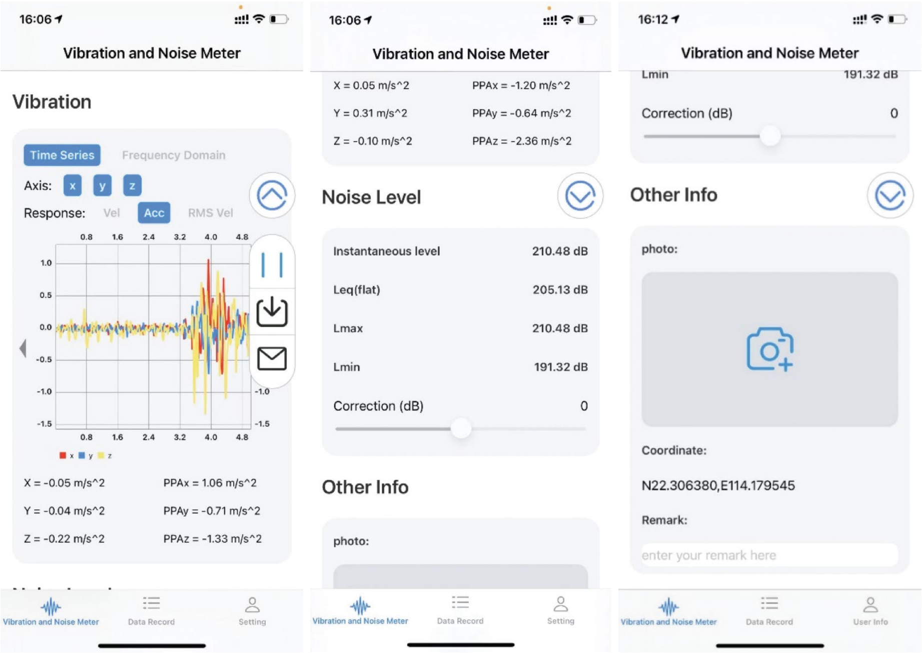
Figure 9 Noise level comparison between iPhone 11 and sound level meter

3.3 App Development

The app development was performed in the second phase of this project, which included design of the user interface, user interaction, signal processing, and other internal functions.

3.3.1 User interface

The app was developed using the Xcode software and Swift programming language, which realised the user interface display, user experience, and user interaction design. Three major modules, namely, Vibration and Noise Meter, Data List, and User Info, were developed. This section describes the design of the user interface. Figure 10 shows screenshots of the main functions.



X = -0.05 m/s^2
Y = -0.04 m/s^2
Z = -0.22 m/s^2
PPAx = 1.06 m/s^2
PPAy = -0.71 m/s^2
PPAz = -1.33 m/s^2

X = 0.05 m/s^2
Y = 0.31 m/s^2
Z = -0.10 m/s^2
PPAx = -1.20 m/s^2
PPAy = -0.64 m/s^2
PPAz = -2.36 m/s^2

Instantaneous level	210.48 dB
Leq(flat)	205.13 dB
Lmax	210.48 dB
Lmin	191.32 dB
Correction (dB)	0

Lmin	191.32 dB
Correction (dB)	0

Coordinate:
N22.306380,E114.179545
Remark:

(a) Vibration measurement (b) Noise measuremen (c) Other Info page

Figure 10 Screetshots of main user interfaces

3.3.2 Signal processing

The signal processing algorithm includes filtering, integration, fast Fourier transform (FFT), inverse fast Fourier transform (IFFT), and RMS computation, resulting in weighted acceleration and velocity in time and frequency domain, PPA, PPV, and RMS velocity in a 1/3 octave band spectrum, as well as instantaneous, equivalent, maximum and minimum sound level in dB. Figure 11 below shows a flowchart of vibration data processing. The app only collects the acceleration data from the vibration sensor during the data acquisition process. After completing data collection, integration and other analysis functions are unified and proceeded, which gives accurate velocity curve and RMS velocity in 1/3 octave band in both time domain and frequency domains.

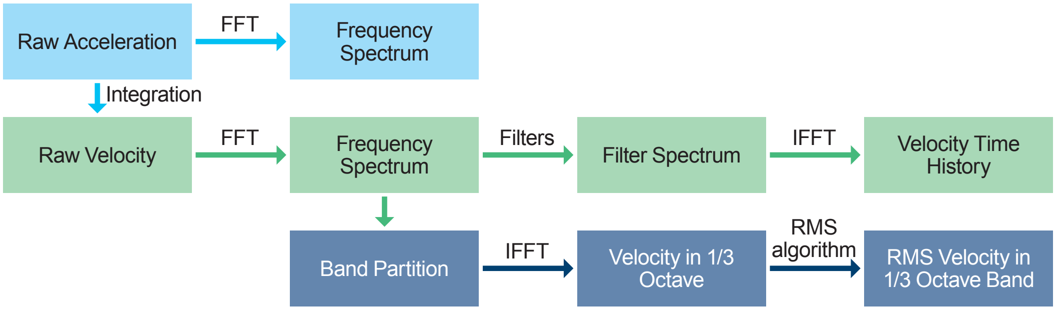


Figure 11 Flowchart of signal processing

3.3.3 Cloud connection

The development of the app is integrated with an online cloud system, named Firebase, which is responsible for data storage and sharing. Firebase is a mobile application cloud development platform that supports multiple operating systems and has been commonly adopted by many apps. It assists developers in building backend services efficiently and reducing development time. The developed app adopts several services provided by Firebase, principally the Build module and Analytics module. The Build module includes Authentication, Firestore Database, and Firebase Cloud Storage. Firebase Authentication provides backend services to authenticate users signing into the app using emails, phone number, and popular federated identity providers like Google. The logic of authentication verification is shown in Figure 12.

Firestore Database and Firebase Cloud Storage are responsible for data storage. The Firestore Database is a NoSQL database that provides hierarchical data storage. The first hierarchical layer contains three categories, which are data, groups, and users. The second hierarchical layer is IDs for each category. There are group IDs below the group category. The user IDs are below both the user category and data category. However, the user category only contains user information, while the data category contains data records grouped by a unique user ID with a specific identifier. Each uploaded data record is stored as a document in a specific user/operator collection, as the next hierarchical layer. The final hierarchical layer contains detailed information within each document. As shown in Figure 13, a document in this project contains the basic information of operator, timestamp, and GPS location of data collection, noise level, RMS acceleration and velocity in the 1/3 octave band spectrum, PPV, and limit states. Raw data is stored in binary form. The cloud storage for Firebase focuses on real-time data synchronisation and offers offline support to build responsive data requests regardless of network latency.

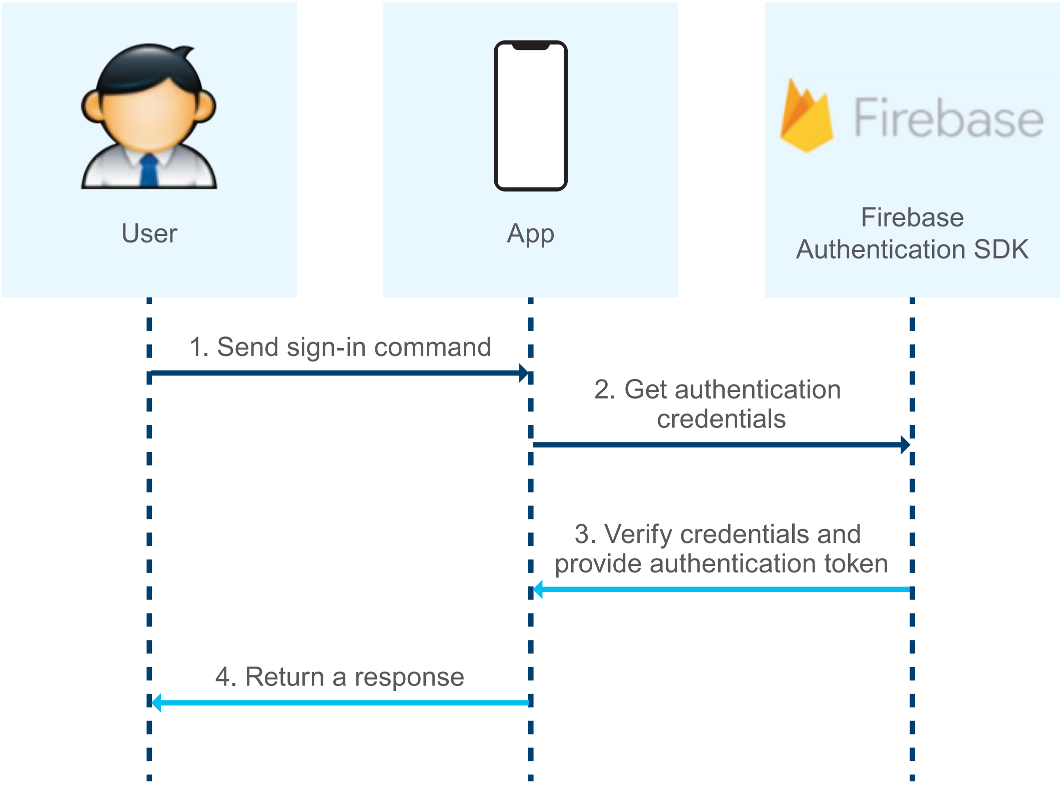
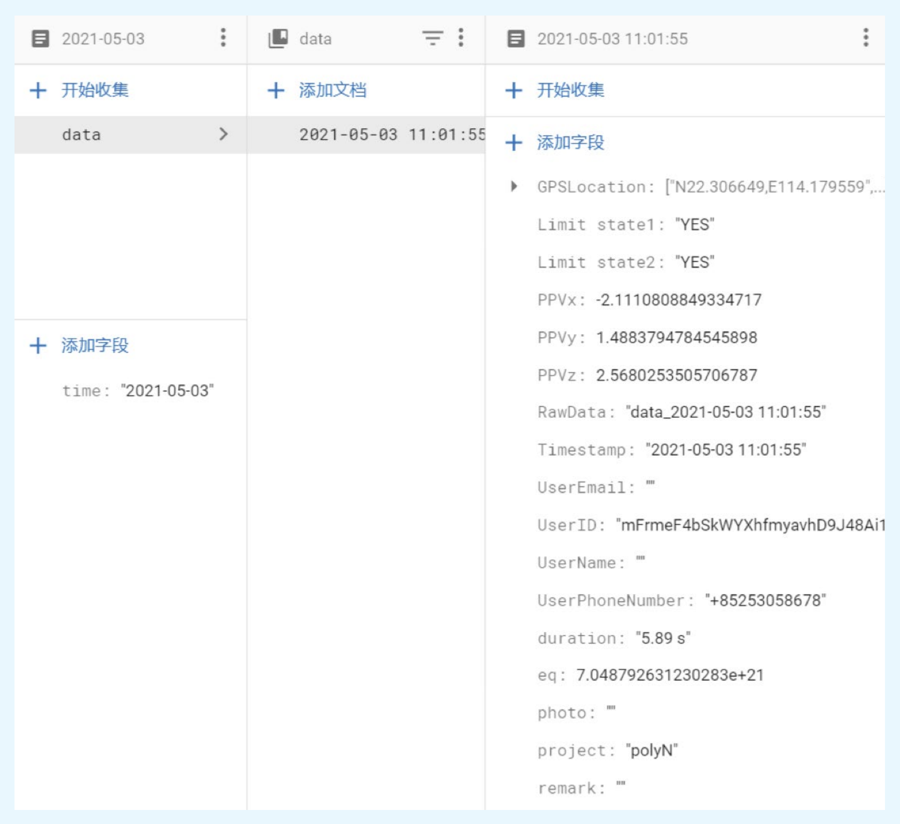


Figure 12 Implementation path of Firebase Authentication



time: "2021-05-03"

GPSLocation: ["N22.306649,E114.179559",...
Limit state1: "YES"
Limit state2: "YES"
PPVx: -2.1110808849334717
PPVy: 1.4883794784545898
PPVz: 2.5680253505706787
RawData: "data_2021-05-03 11:01:55"
Timestamp: "2021-05-03 11:01:55"
UserEmail: ""
UserID: "mFrmeF4bSkWYXhfmyavhD9J48Ai1
UserName: ""
UserPhoneNumber: "+85253058678"
duration: "5.89 s"
eq: 7.048792631230283e+21
photo: ""
project: "polyN"
remark: ""

Figure 13 Hierarchical structure of each data record

3.3.4 Report generation

Google Analytics has been added to generate reports, which helps to track and analyse users' behaviour and generate general statistic reports. Google Analytics is a web analytics service offered by Google which can interact with Firebase. By uploading data to the Firebase, Firebase SDK will automatically capture a number of pre-defined events and user properties. Once the data is captured, it is available in a dashboard through the Firebase console. The information in the dashboard includes active users, daily user engagement, app version adoption, user properties, and so on. The events that are automatically monitored in the dashboard include app update, app openings, OS updates, app starts, and so on. Besides these, three specific events have been added, which are data collection, data email, and data saving. When users conduct the above behaviours, they will be recorded in statistic reports.

3.4 Validation through Field Measurement

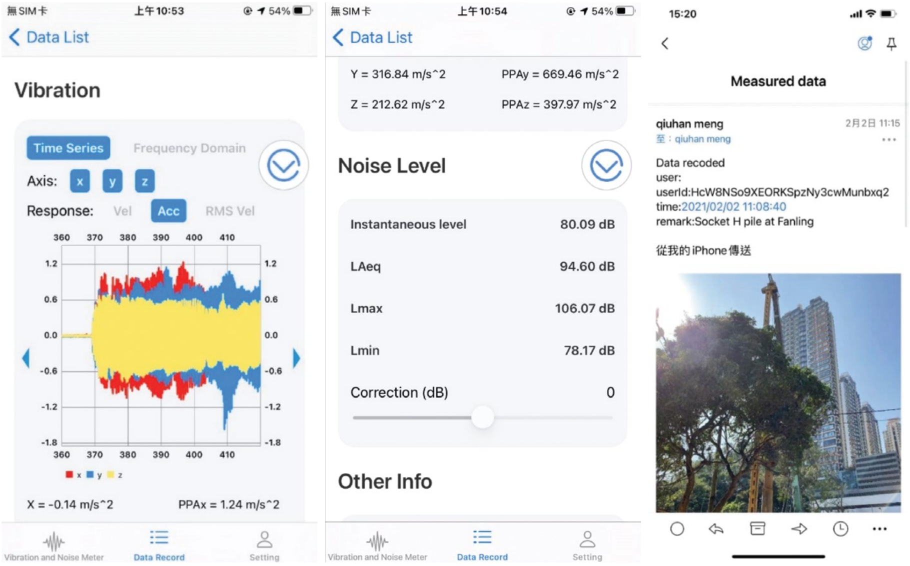
To validate the developed smartphone app for the measurement of construction-induced vibration and noise, eight field measurements were conducted by the research team. During the field measurements, smartphones were mounted on soil nails that were plugged into the ground at different monitoring locations. The developed app was used to measure the vibration generated by various construction activities, including socket H-pile, sheet pile, minipile, and rock excavation. Meanwhile, traditional accelerometers or portable vibrometers were tested and compared to verify the measurement accuracy of the iPhones. The noise was tested and compared similarly. The operational performance of the developed app was also tested by transferring data to the cloud, uploading photo, inputting text remarks, and sending email. In the following section, five selected field measurements will be briefly described, including screenshots of the app interface, measurement results (i.e., PPV and noise), and the comparison with a traditional accelerometer/vibrometer and portable sound level meter, respectively.

3.4.1 Socket H-pile on Fanling site

Pre-bored socket H-pile was conducted on the Fanling construction site. During the field measurement period, three smartphone models, namely, iPhone 8, iPhone 11, and iPhone 12, were tested. In addition, a standard portable vibrometer (Instantel Micromate) and another traditional accelerometer (PCB 356b18) were used to measure and compare the vibration levels. Three soil nails were first inserted into the ground. The portable vibrometer was mounted on the top of the first soil nail, and the iPhone 11 was mounted on the top of the vibrometer. The PCB accelerometer was mounted on the side face of the second soil nail, while the iPhone 12 was mounted on the top of the soil nail. The iPhone 8 was mounted directly on the top of the third soil nail. The distances from the pre-bored socked-H pile source to the soil nails were different. Figure 14 shows the installation of soil nail, portable vibrometer, iPhone 11, and traditional accelerometer.

The smartphone app operated normally during the whole measurement process and all functions could be used normally. Figure 15 contains screenshots of app interfaces that demonstrate acceleration time history, noise level, and the email function.

Figure 14 Installation of soil nail, portable vibrometer, iPhone 11, and traditional accelerometer



Vibration

X = -0.14 m/s^2
PPAx = 1.24 m/s^2

Y = 316.84 m/s^2
PPAy = 669.46 m/s^2
Z = 212.62 m/s^2
PPAz = 397.97 m/s^2

Noise Level

Instantaneous level	80.09 dB
LAeq	94.60 dB
Lmax	106.07 dB
Lmin	78.17 dB
Correction (dB)	0

Other Info

Measured data

qiuhan meng
2月2日 11:15
至：qiuhan meng

Data recoded
user:
userId:HcW8NSo9XEORKSpzNy3cwMunbxq2
time:2021/02/02 11:08:40
remark:Socket H pile at Fanling

從我的 iPhone 傳送

(a) Acceleration time history (b) Noise level record (c) Email function

Figure 15 Screenshots of user interfaces

The acceleration measured by the iPhone ranged from 0.292 m/s^2 to 0.234 m/s^2. The PPV every 30 seconds, compared between the smartphone app and portable vibrometer (shown in Figure 16), ranged from 0.747 to 3.173 mm/s. In general, the PPV values measured by the two devices agreed with each other satisfactorily. The dominant frequencies in x, y, and z directions were 22.12 Hz, 10.9 Hz, and 21.59 Hz, respectively. Instantel Micromate recorded the dominant frequencies as 21.3 Hz, 11.1 Hz, and 20.7 Hz, respectively. The relative differences were 3.85%, 1.80%, and 4.30%, respectively. The comparison indicates that the frequency information is consistent.

Figure 17 further compares the PPV values recorded by the two devices, in which the green dashed lines show the 5% difference bounds. The average relative differences (RD) in each direction were 6.51%, 4.83%, 4.16%, respectively.

Figure 18 demonstrates the noise level records measured by the iPhone 12. The measured noise levels were quite consistent, ranging from 72.25 to 102.37 dB.

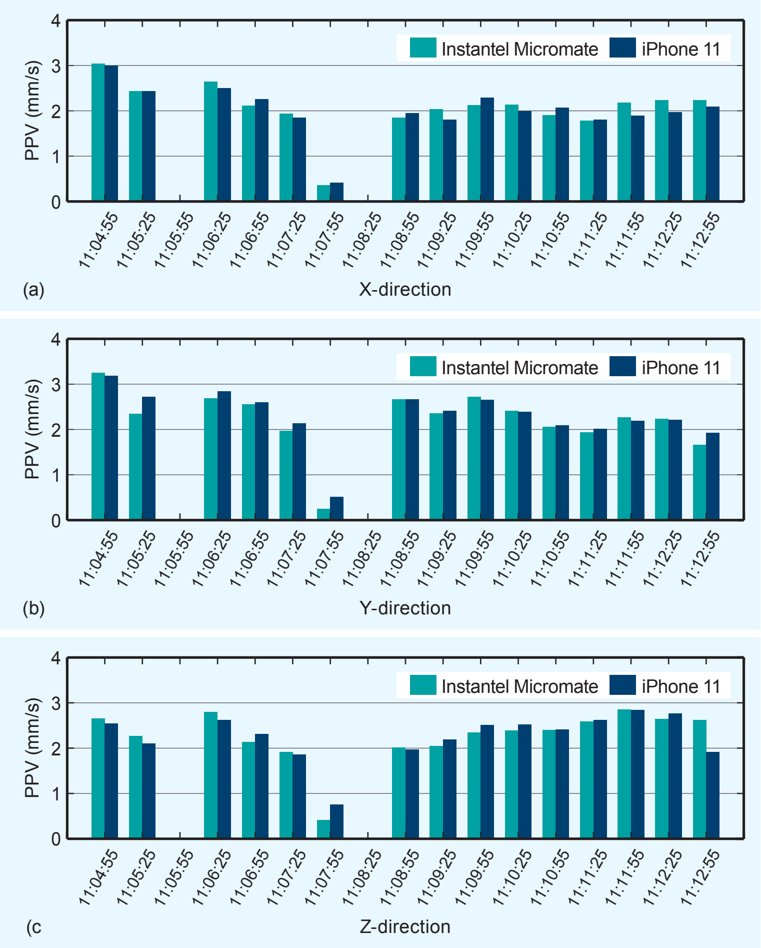
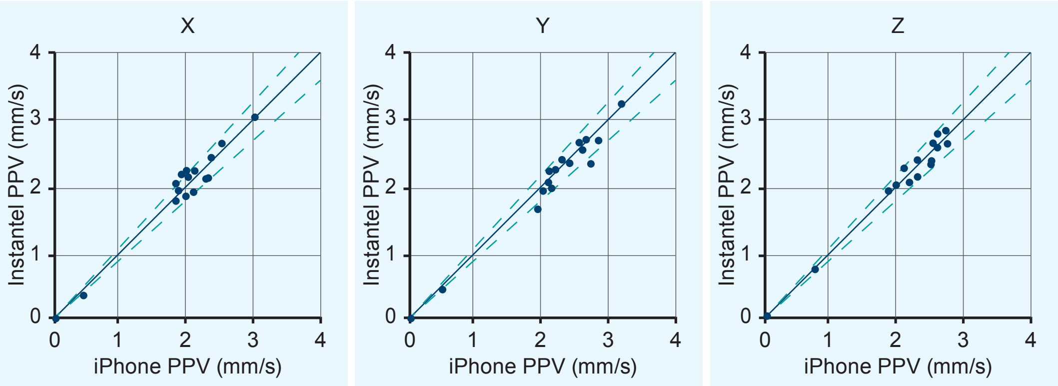


Figure 16 PPV comparison between iPhone 11 and Instantel Micromate



(a) X axis (b) Y axis (c) Z axis

Figure 17 PPV comparison between iPhone 11 and portable vibrometer

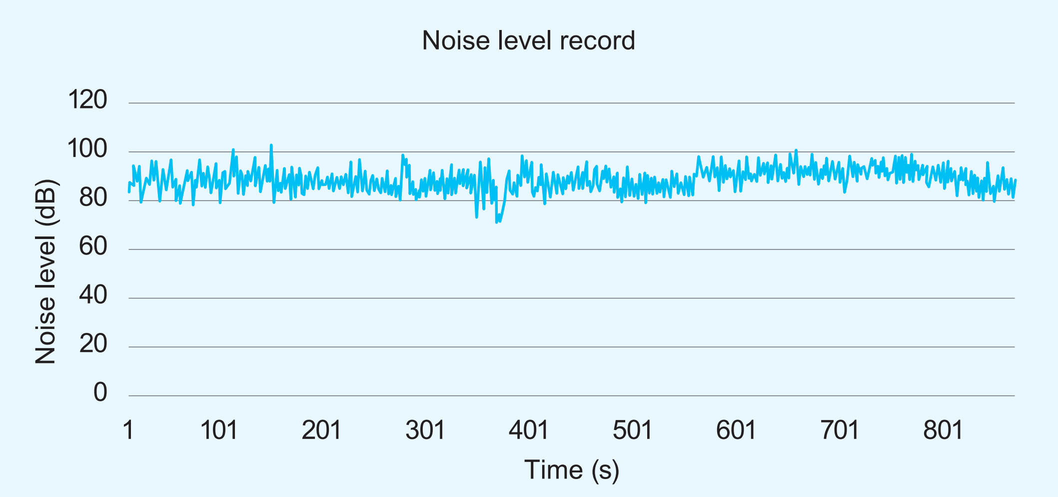


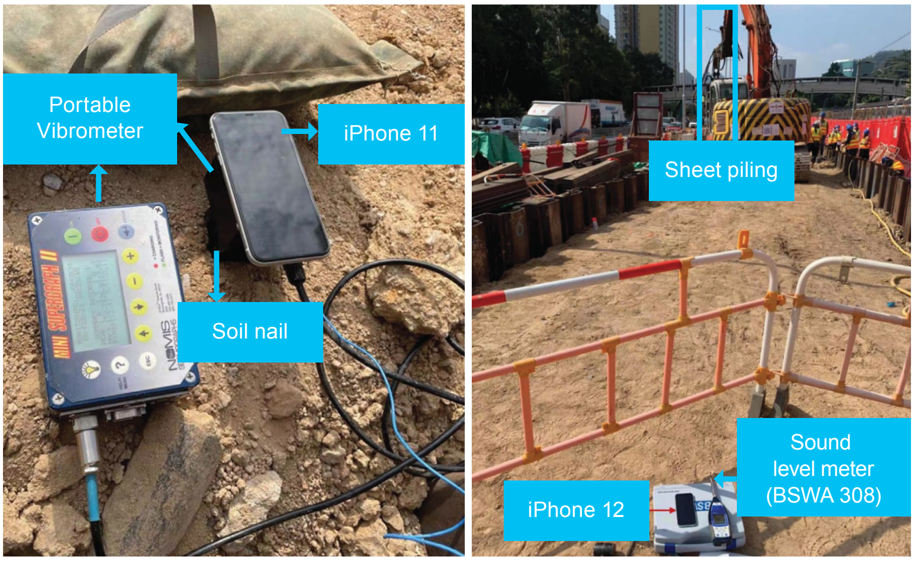
Figure 18 Noise levels record by iPhone 12

3.4.2 Sheet piling on Sha Tin site

Sheet piling work was conducted on the Sha Tin construction site. Two smartphone models, iPhone 11 and iPhone 12, were tested. During the test, soil nails were first inserted into the soil ground. A standard portable vibrometer (Nomis Seismographs Mini Supergraph II) was used to compare with acceleration measured by the iPhone 11. A portable sound level meter (BSWA 308) was used to compare with the noise level measured by the iPhone 12. The installation method and devices used are shown in Figure 19.

The developed app worked normally during the measurement process. Figure 20 shows screenshots of acceleration time history, noise level, and a photo sent by email.

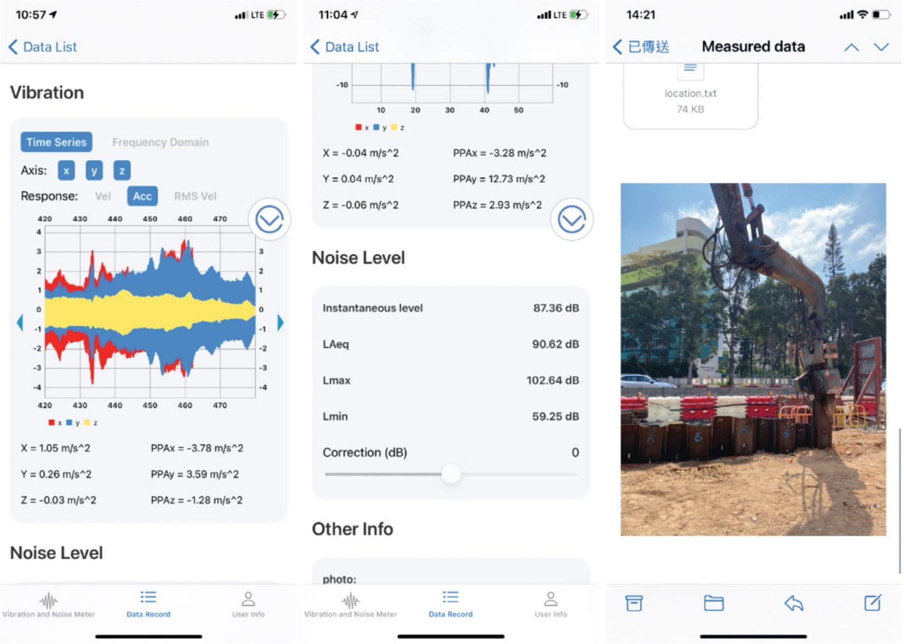
The measured acceleration ranged from -5.584 m/s^2 to 5.727 m/s^2 in the x-direction, -9.775 m/s^2 to 10.190 m/s^2 in the y-direction, and -1.726 m/s^2 to 2.139 m/s^2 in the z-direction. The comparison conducted is the square root of the sum of the squares of the PPV values in all three vector directions. The peak vector sum (PVS) value ranged from 1.56 to 43.98 mm/s. Where PVS was more than 2 mm/s, the average RD was less than 10%. Figure 21 shows the comparison between the iPhone 11 and the portable vibrometer. In general, the PVS values measured by the two devices agreed with each other satisfactorily. The dominant frequencies in x, y, and z-directions were 30.54 Hz, 25.75 Hz, 30.87 Hz respectively. The portable vibrometer recorded the dominant frequencies as 29,68 Hz, 26.60 Hz, and 32.51 Hz, respectively. The comparison indicates that the frequency information was consistent. The relative differences were 2.8%, 3.2%, 5.0%, respectively.



(a) Installation of portable vibrometer, soil nail, and iPhone 11

(b) Installation of sound level meter and iPhone 12

Figure 19 Installation method



X = 1.05 m/s^2
Y = 0.26 m/s^2
Z = -0.03 m/s^2
PPAx = -3.78 m/s^2
PPAy = 3.59 m/s^2
PPAz = -1.28 m/s^2

X = -0.04 m/s^2
Y = 0.04 m/s^2
Z = -0.06 m/s^2
PPAx = -3.28 m/s^2
PPAy = 12.73 m/s^2
PPAz = 2.93 m/s^2

Instantaneous level	87.36 dB
LAeq	90.62 dB
Lmax	102.64 dB
Lmin	59.25 dB
Correction (dB)	0

(a) Acceleration time history (b) Noise level (c) A photo sent by email

Figure 20 Screen shots of app functions

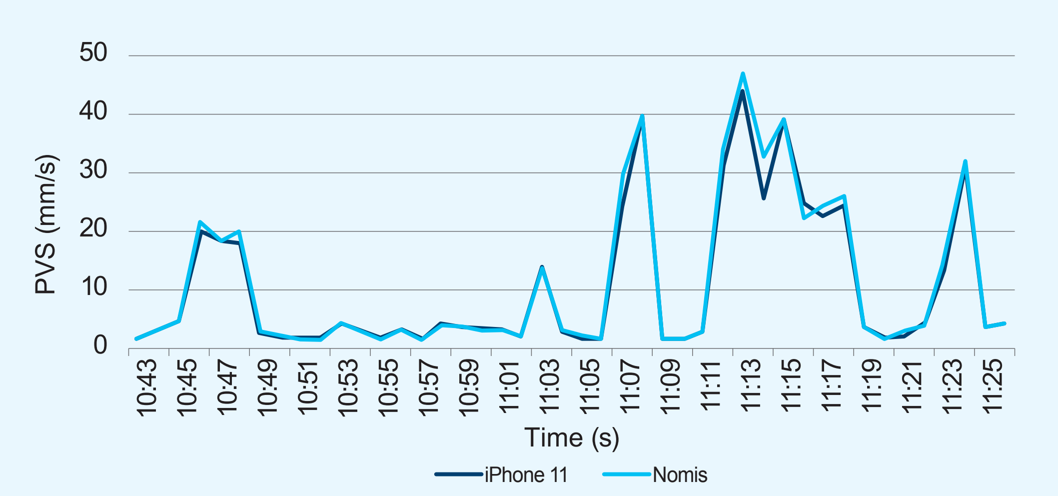


Figure 21 PVS comparison between the iPhone 11 and Nomis Vibrometer

Figure 22 below demonstrates the comparison of noise level records between the iPhone 12 and the commercial sound level meter (BSWA 308). In general, the measured noise levels were quite consistent, ranging from 79.25 to 98.92 dB.

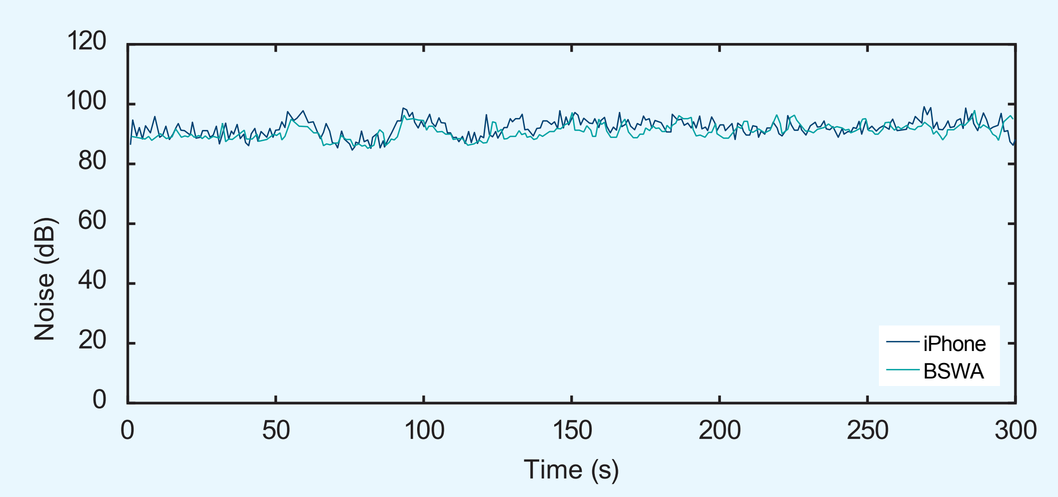


Figure 22 Noise comparison between iPhone 12 and sound level meter

3.4.3 Sheet Piling on Fanling site

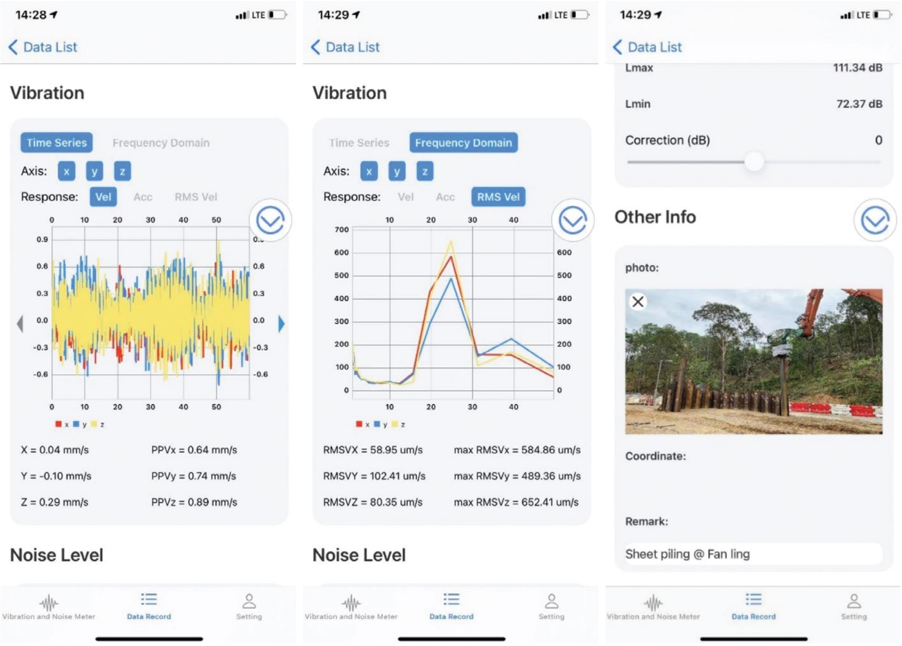
Sheet piling work was conducted on Fanling construction site. During the field measurement, three smartphone models, namely, an iPhone 8, iPhone 11, and iPhone 12, were tested at different distances. In addition, a traditional accelerometer (PCB 356b18) was used to measure and compare the vibration levels. Three soil nails were inserted into the soil ground at different monitoring locations. The distances from the sheet piling to the iPhone 11, iPhone 12, and iPhone 8 were 10.4 m, 16.5 m, and 26.7 m respectively. Two traditional accelerometers were mounted on the top of the soil nails with the iPhone 11 and iPhone 12. The iPhone 8 was mounted directly on the top of the soil nail independently. The measurement locations and installation methods are shown in Figure 23.

The iPhone app operated normally during the whole measurement process. The app shows real-time vibration levels and noise levels on the user interface. Figure 24 below shows velocity time history, RMS velocity in frequency domain, photo, and text remarks.

(a) Measurement location of iPhone 11 (b) Measurement location of iPhone 8

(c) Measurement location of iPhone 12 (d) The installation of iPhone 12, traditional accelerometer, and soil nail

Figure 23 Measurement location and installation method



X = 0.04 mm/s
PPVx = 0.64 mm/s
Y = -0.10 mm/s
PPVy = 0.74 mm/s
Z = 0.29 mm/s
PPVz = 0.89 mm/s

RMSVX = 58.95 um/s
max RMSVx = 584.86 um/s
RMSVY = 102.41 um/s
max RMSVy = 489.36 um/s
RMSVZ = 80.35 um/s
max RMSVz = 652.41 um/s

Lmax 111.34 dB
Lmin 72.37 dB
Correction (dB) 0
Coordinate:
Remark:
Sheet piling @ Fan ling

(a) Velocity time history (b) RMS velocity in frequency domain (c) Photo and text remarks

Figure 24 Examples of screenshots

The acceleration measured by the iPhone 11 ranged from -0.141 m/s^2 to 0.138 m/s^2, and by the iPhone 12 ranged from -0.122 m/s^2 to 0.115 m/s^2. The acceleration measured by the iPhone 8 ranged from -0.064 m/s^2 to 0.061 m/s^2. It can be concluded that the vibration attenuates with distances.

Figure 25 compares the PPV recorded by iPhone 11 and by the traditional accelerometer in three orthogonal directions (x, y, z). The measured PPV ranged from 0.366 to 1.409 mm/s. The average relative differences in each direction were 5.89%, 7.96%, and 5.51%. The dominant frequencies in three orthogonal directions (x, y, z) were nearly the same, which were 22.25 Hz, 22.25 Hz, and 22.26 Hz respectively. The relative difference was 0.05%. The comparison indicated that the frequency information was consistent.

Figure 26 further compares the PPV values recorded by the iPhone 12 and the traditional accelerometer. The measured PPV ranged from 0.424 to 1.325 mm/s. The average relative differences in each direction were 5.89%, 7.81%, and 6.09%, respectively. The dominant frequencies in three orthogonal directions (x, y, z) were nearly the same, recorded as 21.45 Hz and 21.56 Hz respectively. The relative difference was 0.51%. The comparison indicates that the frequency information was consistent.

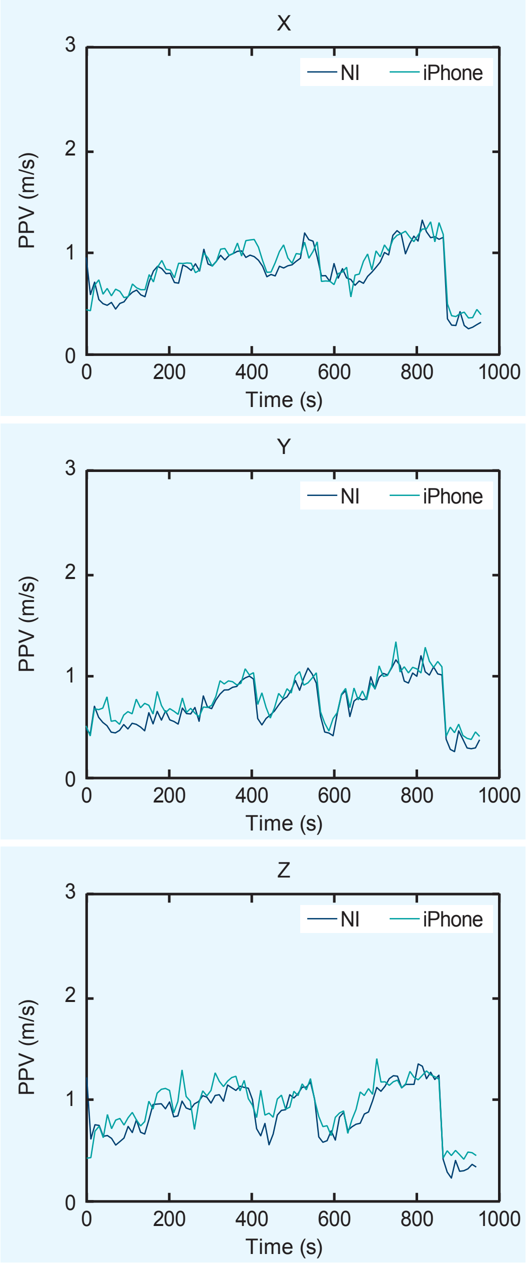


Figure 25 PPV measured by iPhone 11 and traditional accelerometer

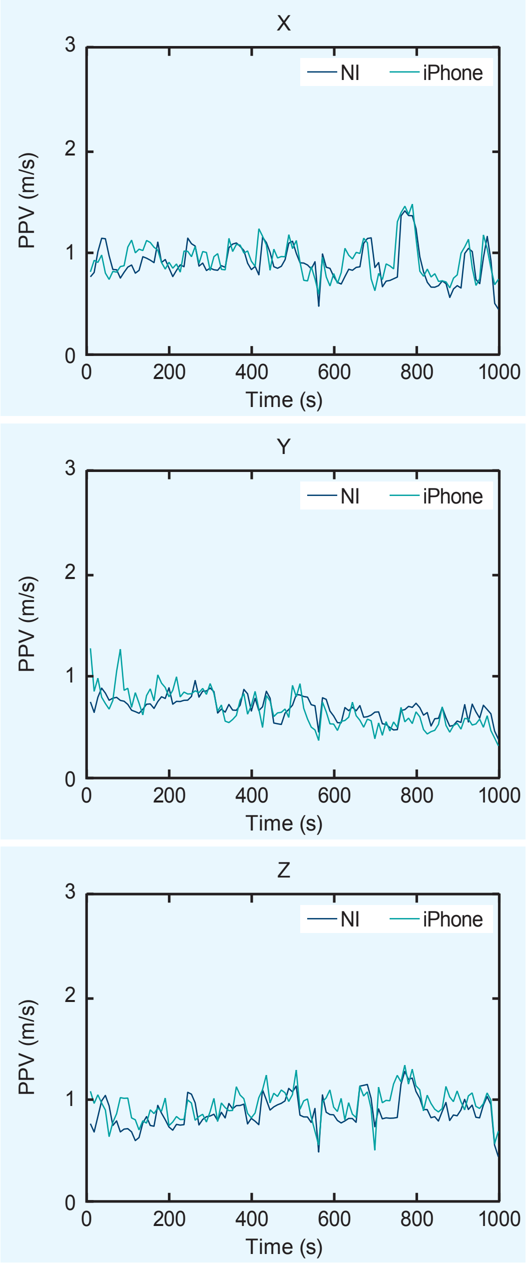


Figure 26 PPV measured by iPhone 12 and traditional accelerometer

Noise was also measured in the field test. Figure 27 below demonstrates the noise level records measured by the iPhone 12, ranging from 86.83 to 100.30 dB. Figure 28 below demonstrates the noise level records measured by the iPhone 8, ranging from 80.76 to 97.09 dB.

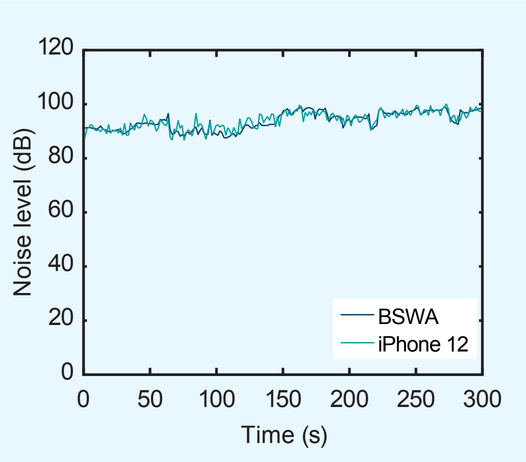


Figure 27 Noise level recorded by iPhone 12 and by BSWA

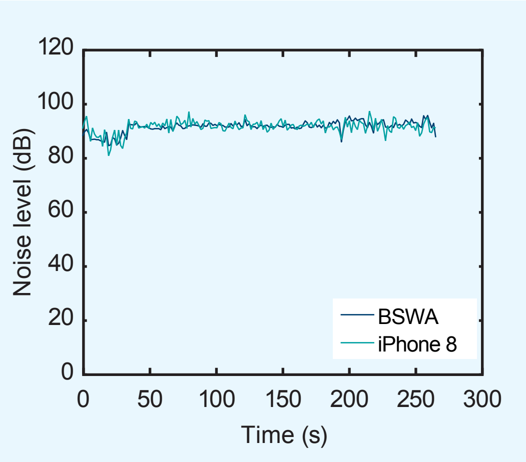


Figure 28 Noise level recorded by iPhone 8 and by BSWA

3.4.4 Socket H-pile on Sheung Shui site

Socket H-pile work was conducted on the Sheung Shui construction site. During the field measurement, two smartphone models, namely, an iPhone 8 and iPhone 12, were installed at different distances for vibration measurement. Two soil nails were first inserted into the soil ground at different monitoring locations. The distances from the socket H-pile to the iPhone 8 and iPhone 12 were 3.3 m and 10.8 m respectively, as shown in Figure 29. Meanwhile, a traditional accelerometer (PCB 356b18) was used to measure and compare the vibration levels with an iPhone 12. In addition, the iPhone 12 and iPhone 11 were also tested for noise measurement.

The app operated normally during the whole measurement process. Figure 30 shows app interfaces for acceleration time history, velocity-time history, and RMS velocity in the time domain.

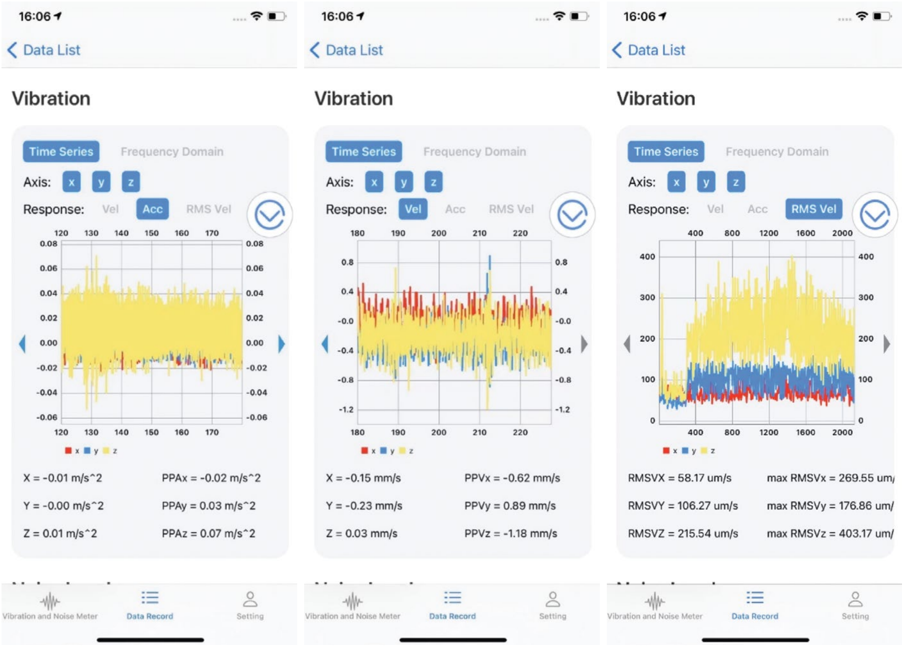
The acceleration measured by the iPhone 12 ranged from -0.231 m/s^2 to 0.192 m/s^2. The acceleration measured by the iPhone 8 ranged from -0.381 m/s^2 to 0.251 m/s^2. It can be concluded that the vibration attenuates with distances.

Figure 31 further compares the PPV values recorded by the two devices, in which the green dashed lines show the 10% difference bounds. The average RD in each direction were 5.27%, 5.86%, and 4.87%. The measured PPV ranged from 0.493 to 3.175 mm/s. In general, the PPV values measured by the two devices agreed with each other satisfactorily. The dominant frequencies recorded by the iPhone 12 app in three orthogonal directions (x, y, z) were 32.01 Hz, 33.53 Hz, and 32.73 Hz respectively. The dominant frequencies recorded by the iPhone 8 app were 24.46 Hz, 24.91 Hz, and 24.64 Hz respectively.

Noise levels were also measured in the field test. Figure 32 shows the noise measurement of the iPhone 11 compared with a commercial sound level meter (BSWA 309). Figure 33 below demonstrates the noise level records measured by an iPhone 12, ranging from 89.47 to 93.10 dB. Figure 34 below demonstrates the noise level records measured by an iPhone 11, ranging from 89.49 to 96.29 dB. In general, the measured noise levels were quite consistent.

(a) Installation of iPhone 12, tradition accelerometer, and soil nail (b) Installation of iPhone 8 and soil nail

Figure 29 Installation of devices and measurement locations



X = -0.01 m/s^2 PPAx = -0.02 m/s^2

Y = -0.00 m/s^2 PPAy = 0.03 m/s^2

Z = 0.01 m/s^2 PPAz = 0.07 m/s^2

X = -0.15 mm/s PPVx = -0.62 mm/s

Y = -0.23 mm/s PPVy = 0.89 mm/s

Z = 0.03 mm/s PPVz = -1.18 mm/s

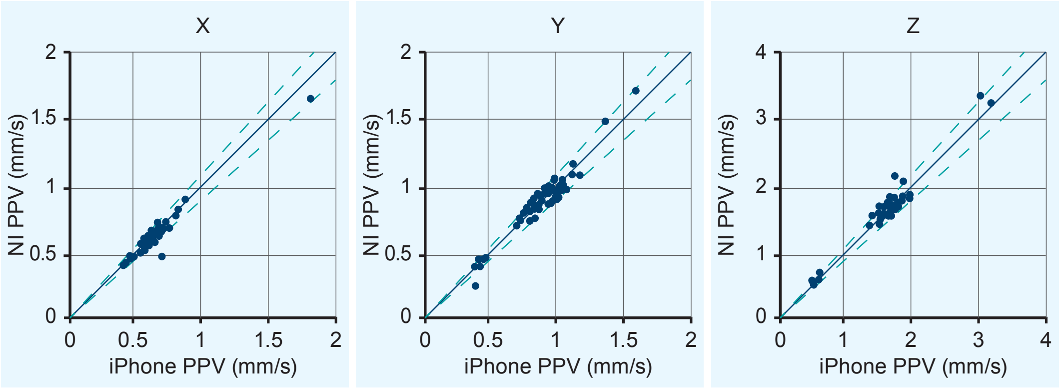
RMSVX = 58.17 um/s max RMSVx = 269.55 um/

RMSVY = 106.27 um/s max RMSVy = 176.86 um/

RMSVZ = 215.54 um/s max RMSVz = 403.17 um/

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

Figure 30 Screen shots of iPhone app



(a) X direction (b) Y direction (c) Z direction

Figure 31 PPV RD between iPhone 11 and traditional accelerometer

Figure 32 Noise measurement of iPhone 11 and portable sound level meter

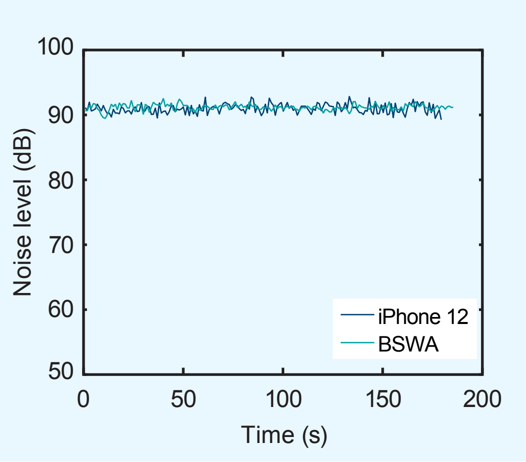


Figure 33 Noise level recorded by iPhone 12 and by BSWA

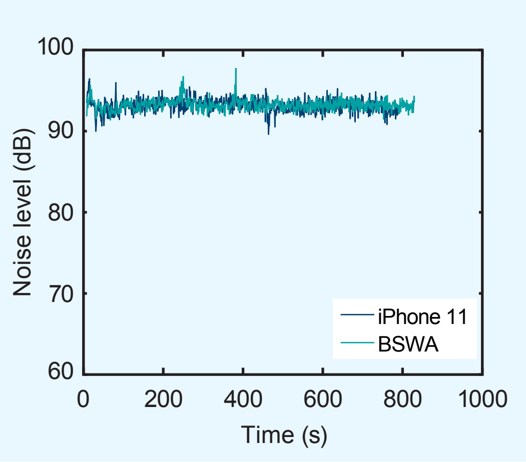


Figure 34 Noise level recorded by iPhone 11 and by BSWA

4 RECOMMENDATIONS

This project explored the potential of using smartphones for construction-induced vibration and noise measurement and assessment in a rapid, automated, and robust way. First, the implementation feasibility of construction-induced vibration and noise measurement using smartphones was examined. By comparing acceleration data with a traditional accelerometer under harmonic vibrations in the laboratory, the sensitivity of smartphone sensors has been proved. Then, an iOS-based app with various vibration and noise indicators and multiple functions was developed. Different from conventional methods which require expensive devices and complicated operations, the proposed app enables the recording of vibration and noise levels and the computation of different indices by using a single smartphone device. The presented app was tested on several construction sites by the research team from The Hong Kong Polytechnic University. The measured construction activities included socket H-pile, sheet pile, mini pile, and so on. Site trial tests show that the smartphone-based measurements with appropriate algorithms can be practically implemented in daily monitoring. The feasibility of the developed app is based on the following major key points:

- Easy installation and operation;
- Continuous and stable data measurement;
- No data loss or crashes during the measurement process; and
- Qualified measurement accuracy compared with traditional accelerometers or vibrometers.

Issues concerning the stability and reliability of the developed app for other construction environments will be addressed by more measurement deployments in the future. The app will be optimised based on user feedback and problems that may be encountered.

Based on the current iOS version, future Android versions can also be developed for some widely used Android smartphones. It has the potential to be extended to more construction activities.

Since the vibration data is easily accessible through the current developed app, more advanced signal processing techniques could be added. With the help of deep learning methods, algorithms like convolution neural network can provide a powerful tool for classification. The construction vibration database could be used to train a comprehensive classification network by extracting the important amplitudes and frequency features. Inserting the trained network to the app would enable the auto-detection of construction vibration types. The users could also label the type of vibration they measured through the app and facilitate the improvement of the classification training. Through the cloud server, groups of phones within a region would be able to make further determination of the vibration source.

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6 APPENDIX I

LIST OF QUALIFIED IPHONE MODELS

Based on the laboratory experimental calibration, the qualified iPhone models include (in chronological order) as of 1 July 2021:

- iPhone 12 Pro Max
- iPhone 12 Pro
- iPhone 12
- iPhone 12 mini
- iPhone 11 Pro Max
- iPhone 11 Pro
- iPhone 11
- iPhone SE (2nd generation)
- iPhone XS Max
- iPhone XS
- iPhone XR
- iPhone X
- iPhone 8 Plus
- iPhone 8

Members of CIC Task Force on Research

Mr. Jimmy TSE
Prof. Christopher LEUNG
Ir Joseph MAK
Prof. James PONG
Prof. Sze-chun WONG
Ir Chi-chiu CHAN
Ir Tommy NG
Mr. Shu-jie PAN

Research Team

Principal Investigator

Prof. Songye ZHU

Co-Investigator

Prof. Siu-Lai CHAN

Research Personnel

Ms Qiuhan MENG
Mr Yiang ZHANG
Mr Shiguang WANG
Mr Junqiao XIE
Dr Jinyang LI
Dr Yingyu HUA
Mr Jian ZHANG
Mr Jubin LU

建造業議會
Construction Industry Council

Address 地址： 38/F, COS Centre, 56 Tsun Yip Street, Kwun Tong, Kowloon
九龍觀塘駿業街56號中海日升中心38樓

Tel 電話： (852) 2100 9000

Fax 傳真： (852) 2100 9090

Email 電郵： enquiry@cic.hk

Website 網址： www.cic.hk

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