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Study on wavelet entropy for airport pavement inspection using a multi-static GPR system

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<http://dx.doi.org/10.1190/geo2020-0361.1>

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Study on Wavelet Entropy for Airport Pavement Inspection using a Multi-Static GPR System

Journal:	<i>Geophysics</i>
Manuscript ID	GEO-2020-0361.R3
Manuscript Type:	Shallow Void, Tunnel, and Other Anomaly Detection
Keywords:	common midpoint (CMP), engineering, ground-penetrating radar (GPR)
Manuscript Focus Area:	Engineering and Environmental Geophysics, Ground-Penetrating Radar

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ABSTRACT

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6 2 The multi-layer nature of airport pavement structures is susceptible to the
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10 3 generation of voids at the bonding parts of the structure, which is also called interlayer
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13 4 debonding. Observations have shown that the thickness of the resulting voids is usually
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17 5 at the scale of millimeters, which makes it difficult to inspect. The efficient and accurate
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20 6 characteristics of ground penetrating radar (GPR) make it suitable for large area
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24 7 inspections of airport pavement. In this study, a multi-static GPR system was used to
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27 8 inspect the interlayer debonding of a large area of an airport pavement. A special antenna
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31 9 arrangement can obtain common mid-point (CMP) gathers during a common offset
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34 10 survey. The presence of interlayer debonding affects the phase of the reflection signals,
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38 11 and the phase disturbance can be quantified by wavelet transform. Therefore, an
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41 12 advanced approach that uses the average entropy of the wavelet transform parameters
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45 13 in CMP gathers to detect the interlayer debonding of airport pavement is proposed. The
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48 14 results demonstrate that the regions with high entropy correspond to the regions where
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52 15 tiny voids exist. The new approach introduced in this study was then evaluated by a field-
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55 16 base experiment at an airport taxiway model. The results show that the proposed
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4 17 approach can detect interlayer debonding of the pavement model accurately and
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7 18 efficiently. The on-site coring results confirm the performance of the proposed approach.
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For Peer Review

19 INTRODUCTION

20 Maintaining pavement facilities (runway, taxiway) at the airport faces many unique
21 challenges. A significant amount of economic costs and a large number of airport
22 engineering and maintenance personnel are required to provide all-weather facilities for
23 the safe operation of the airport. The integrity and flatness of airport pavement facilities
24 plays an important role in the safe operation of aircraft. Even a small defect and the
25 resulting debris can cause catastrophic accidents. So, the anomalies must be accurately
26 detected before major damage occurs due to the particular requirements of airport
27 pavement facilities. Hence, it is important to develop a low-cost, reliable and effective
28 detection technology to detect anomalies in the concrete structure of the airport, thus
29 providing integrity and safety services to aircraft operating at airport road facilities
30 (Frederickson and LaPorte, 2002).

31 ~~In order~~ to meet the high standard requirements of perfect flatness, toughness,
32 and uniformity of airport road facilities, multi-layer designs with different materials are
33 usually used for construction (Fwa, 2003). Normally, the multi-layer structure consists of

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4 34 3 to 4 layers. They are a surface asphalt layer, base asphalt layer, sub-base layer, and
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7 35 bottom layer from the surface to bottom. Typically, the thickness of each layer is about
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11 36 several centimeters (Zou et al., 2018). However, the multi-layer design of airport
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14 37 pavement has its disadvantages. A small raindrop or snow flake on the surface can be
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17 38 pressed into the pavement structure when an aircraft moves over the pavement. This
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21 39 small amount of water can remain in the small area of the shallow pavement. With
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24 40 changes in pavement surface temperature, the volume of water becomes larger (when
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27 41 the temperature is high, it becomes water vapor; when the temperature is low, it turns to
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31 42 ice), expands and extends as a void on the layer bonding region (usually called interlayer
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35 43 debonding phenomenon). At the same time, the temperature and pressure change
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38 44 generated by the aircraft moving over the pavement can further accelerate this procedure.
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42 45 The integrity of the airport pavement becomes weaker as the interlayer debonding
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45 46 extends further and further, and the pavement surface could be distorted and collapse,
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48 47 thus affecting the safe operation of aircraft. The interlayer debonding plays an important
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52 48 role in the remaining life of airport pavement facilities. Therefore, it is important to detect
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4 49 interlayer debonding at its early stage and repair it. This is the priority for airport road
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7 50 maintenance.
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12 51 In recent years, non-destructive testing (NDT) has been widely used in airport
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15 52 pavement inspection and maintenance due to the reliable and efficient information that it
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18 53 can provide (Breysse, 2012; Liu et al., 2020). Ground Penetrating Radar (GPR), Infrared
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22 54 Thermal Imaging, Acoustic or Ultra-Sounding Detection, and Microwave Remote Sensing
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26 55 are widely used to detect the inner anomalies of concrete infrastructure. The accuracy
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29 56 and economy of these technologies fully guarantee the integrity and safety of the
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33 57 pavement infrastructure. At present, the conventional methods of anomaly detection in
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36 58 airport pavement facilities are acoustic imaging and infrared irradiation methods. Acoustic
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39 59 imaging needs a large number of experienced engineers and technicians, while infrared
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43 60 radiation cannot be applied to large-scale rapid detection due to the strict conditions and
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46 61 limited size for pavement inspection (Zou, et al., 2020). However, due to the existence of
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50 62 tiny voids, the small density change in the depth direction can be used for inspection.
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54 63 Based on this idea, both nuclear densitometer and ultrasonic measurements have
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4 64 achieved accurate results in laboratory experiments. But, these two methods are not
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7 65 suitable for real-life application to large-scale inspection of airport pavement.
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11 66 As an NDT method, GPR can provide optimal resolution of different applications
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15 67 in civil engineering (Alani and Tosti, 2018; Benedetto et al., 2017; Eskelinen and Pellinen,
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18 68 2018; Liu et al., 2020; Saarenketo and Scullion, 2000; Shangguan et al., 2016;
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22 69 Spagnolini, and Rampa, 1999; Lai et al., 2018) due to the ultra-wide frequency band that
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26 70 is used. For the detection of airport pavement facilities by GPR, the challenge mainly
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29 71 comes from how to extract information from the reflection generated by the small
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32 72 anomalies. This is quite different from the data processing for most pavement inspection
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36 73 cases, which focuses on large-scale anomalies in the deep region of the pavement.
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39 74 Meanwhile, the anomalies inside the structural layers of airport pavement are millimeter
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43 75 order in size (Zou, et al., 2020). These thin layers are difficult to directly observe on the
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47 76 GPR profile given the system resolution, as pointed out by Bradford and Deeds (2006)
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50 77 and Hartikainen et al., (2018). Besides, the thin layers in airport pavement facilities are
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54 78 usually shallow (a few centimeters depth); (Zou, et al., 2020). The complex
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4 79 electromagnetic response generated by the electromagnetic wave at the boundary of air
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7 80 and pavement cannot be separated from the response of small shallow anomalies. How
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10 81 to interpret, from a GPR signal with a center frequency of several GHz, the responses
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14 82 from such small, shallow anomalies has become a difficult task and a challenge. In
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17 83 addition, in the light of the slight dielectric coefficient difference or the change in velocity
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21 84 of the shallow pavement structure due to the presence of tiny voids, GPR measurements
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24 85 have made it possible to further identify the anomalies of the airport pavement. However,
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28 86 the small change of dielectric coefficient does not produce an obvious anomaly by the
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31 87 conventional survey and processing.
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36 88 Further expanding on the above idea, considering the size, location of the thin
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39 89 layer, and the system resolution, the small change of dielectric coefficient along the
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43 90 horizontal direction can also be used to judge the existence of anomalies in the airport
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46 91 pavement structure. Because this change is extremely small, a reference or level should
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50 92 be considered. The reference or level can be the reflection from a certain point or a
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53 93 multichannel response. Based on the above idea, Yi et al. (2018) proposed an approach
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4 94 that analyzes the tiny deviation of the asphalt layer depth and velocity by using the phase
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7 95 deviation of the common mid-point (CMP) gather for airport pavement inspection. Zou et
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10 96 al. (2020) proposed another method that uses the energy deviation of the lateral wave in
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14 97 a CMP gather for the airport pavement inspection. Both of these methods are verified by
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17 98 real measurements carried on pavement at Tokyo International Airport (Japan). However,
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21 99 due to the difficulty of parameter adjustment, there are some limitations in practical
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24 100 application (Yi et al., 2018; Zou et al., 2020) of the above methods.

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29 101 In this paper, we investigate a new approach, which is robust, easy to understand,
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32 102 and practical in terms of implementation and results. The proposed approach analyzes
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36 103 the average wavelet entropy of the shallow region reflection in a CMP gather. Compared
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39 104 to the Fourier transform, the wavelet transform has many advantages for representing the
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43 105 detailed information in a signal. The wavelet transform can deconstruct and reconstruct
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46 106 any aperiodic signals accurately. It can analyze the localization of time- or space-
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50 107 frequency by stretching and shifting the signal step by step. The detailed information in
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53 108 the signal can be represented by time subdivision at high frequency and frequency

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4 109 subdivision at a low frequency through the wavelet transform (Kumar, and
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7 110 Fofoula-Georgiou, 1997; Sinha et al., 2005). The entropy, which analyzes and
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11 111 compares the probability distribution, can provide a measure of the signal stability.
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14 112 The wavelet entropy, which combines wavelet analysis and entropy, can be used as
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18 113 a measure of the degree of order/disorder of the signal. Therefore, it can provide
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22 114 useful information about signal dynamical stability. In recent years, wavelet entropy as
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25 115 a robust method has been widely applied for fault detection (Rosso et al., 2001; EI-
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29 116 Zonkoly and Desouki, 2011; Dasgupta et al., 2012).

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33 117 Due to presence of a thin void or a micro-damaged zone, the waveform of the
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37 118 backward reflection has some slight changes compared to the sound zone. This small
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40 119 change can be illustrated by an entropy change throughout the parameters of the wavelet
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44 120 transformation. So, the proposed approach is based on the wavelet entropy difference
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47 121 between the anomalies and sound pavement reflections. The signal processing
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51 122 procedure for the proposed approach is also succinct. First, a band-pass filter is applied
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54 123 to the raw frequency domain data and then the Fourier transform was performed to get
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4 124 time-domain CMP gathers. Next, the trace balance of each CMP gather is applied. Trace
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7 125 balance is a procedure that scale amplitudes to a common root mean square (RMS) level
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11 126 for all traces. Lastly, the mean wavelet entropy of the shallow region reflection is
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14 127 calculated and formed into a 2D entropy map of the entire measurement area. The simple
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17 128 processing procedure makes the real-time pavement inspection much easier perform.
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21 129 Real experiment data obtained from a pavement model have demonstrated the excellent
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24 130 performance of the proposed approach. The processed results also matched with on-site
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28 131 coring results very well.

132 MULTI-STATIC GPR SYSTEM AND PAVEMENT MODEL

133 Multi-static Ground Penetrating Radar System and Survey Strategy

134 With the further increase of GPR application in civil and environmental
135 engineering, several array radar systems have been developed (Gerhards et al., 2008;
136 Jol, 2008; Xu et al., 2002). To better carry out large-scale measurement, Tohoku
137 University (Japan) developed an array radar system in 2012 (Liu et al., 2013; Sato et al.,

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4 138 2016, Yi et al., 2018; Kikuta et al., 2019), shown in Figure 1. The system consists of 8
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7 139 bowtie antennas that form the transmitting array and the receiving array as shown in
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10 140 Figure 2. The receiving array and the transmitting array are staggered with a half antenna
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14 141 interval. It is a step frequency continuous wave radar system and the operating frequency
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17 142 varies from 0.05 GHz to 1.5 GHz. The system is a multi-static system which means all
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21 143 the combinations of transmitter and receiver antenna are recorded. Overall, 64 channel
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24 144 data can be obtained by a single measurement. It uses a distance-measuring wheel to
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28 145 trigger and record the data every 0.01 m interval. The system length is 2 m and can cover
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31 146 an area of 2 m at a time. It can be hung on the vehicle and also can be pulled manually.
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35 147 The fastest measuring speed can reach 7km / h. Based on the above advantages, the
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38 148 system can cover a large survey area and acquire a dense GPR dataset in a short time.
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42 149 Table 1 shows the main parameters of the multi-static GPR system. By operating this
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45 150 system, a large-scale GPR survey can be carried out efficiently.
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50 151 In addition to the advantages described above, CMP gathers can be extracted from
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53 152 the antenna arrangement of this system at the same time during a common
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4 153 measurement. Of course, this cannot be achieved by the common parallel survey, and so
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7 154 an improved survey strategy is needed. By separating the transmitting and receiving
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10 155 antenna by a relatively small distance simultaneously, a series of reflections from the
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14 156 middle point can be obtained. The reflections can be formed as a CMP gather. As shown
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17 157 in Figure 3, a CMP gather can be extracted by judicious choice of traces from the 64
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21 158 channel data. A point located in the middle of the system can have 8 CMP traces, while
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24 159 the edge point only has 1 trace. Set each parallel survey line interval as 0.84 m and this
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28 160 way can guarantee that each center point has at least 4 CMP trace. Therefore, the dense
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31 161 CMP gathers with a 0.12 m interval along the cross-survey direction, and a 0.01 m interval
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35 162 along the survey direction can be extracted with at least 2 parallel surveys. In this paper,
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38 163 4 traces with antenna offsets 0.13 m, 0.21 m, 0.32 m, and 0.44 m were used for all the
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42 164 CMP gathers. Although 4 traces in a CMP gather is sparse compared to traditional CMP
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45 165 acquisition, the CMP gathers extracted by this multi-static GPR system still could be used
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49 166 for further signal processing.

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53 167 **Survey Site and Pavement Structures**
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4 168 ~~In order~~ to provide adequate support for the frequent operation of aircraft, it is
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7 169 important to construct a sufficiently strong, stable and smooth airport pavement. First, the
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10 170 pavement structure must be of adequate thickness and strength to withstand the loads
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14 171 imposed by the aircraft. Secondly, it must have good wear resistance under frequent
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17 172 operation, and will not produce small debris to affect the safety of the aircraft. Finally, it
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21 173 must also be able to withstand the effects of extreme weather to ensure the safe operation
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24 174 of the aircraft. To find the pavement that meets the above requirements, many factors
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28 175 such as design, construction, and material combinations need to be coordinated to find
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31 176 the best combination.

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36 177 In order to find the best material combination and to monitor its performance under
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39 178 high loads, a pavement model was built in the Port and Airport Research Institute located
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43 179 in Nobi, Kanagawa, Japan, as shown in Figure 4 (a). The size of this model is 4 m in width
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46 180 and 50 m in length. It is a multi-layer structure consisting of a surface layer, a base layer,
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50 181 and a leveling layer. The structural strength was provided primarily by the surface and the
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53 182 base layers. They can reduce the load stress produced by the aircraft to a degree that is
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4 183 adequately sustained by the subgrade. This model was divided into 7 parts with different
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7 184 kinds of material combinations, as shown in Figure 5. Two side areas are 10 m in length.
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10 185 The middle of this model was divided into 5 zones all 6 m in length. The surface layer and
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14 186 leveling layers are asphalt layers with 0.05 m thickness and 0.04 m thickness,
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17 187 respectively. Figure 6 (a)-(e) show the side view of Area I to Area V. The base layers
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21 188 located in Area I to Area V are gravel (Figure 6 (f)), low-density asphalt, low-density
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24 189 asphalt, high-density asphalt, and high-density asphalt, respectively. The base layers on
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28 190 the side of this model are also high-density asphalt, as shown in Figure 6 (g). The
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31 191 thickness of the base layer is 0.06 m. Under the base layers of Area I, Area II and Area
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34 192 V, nonwoven fabrics were buried. Water tanks were built on the outside of these areas
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38 193 and continuous water injection was performed during the monitoring. Such a design
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42 194 imitates the natural procedure of the interlayer debonding phenomenon of airport
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45 195 pavement. The non-woven fabric can bring water into the layer bonding part to imitate the
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49 196 process of pressing raindrops or snow into the pavement when an aircraft moves over it.
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52 197 After the model was built, a 20-ton truck (Figure 6 (h)) repeatedly ran over the model to
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56 198 imitate the loads imposed by the aircraft for 30 days until November 30th, 2017. Four
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4 199 GPR surveys were conducted from the initial build to the end of the 30 days load test.
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7 200 The first measurement was performed just after the model was built. The second test was
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10 201 performed after 7 days of loading and injection of water. The third measurement was
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13 202 taken 10 days after the second measurement. And the last measurement was completed
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17 203 by the end of the evaluation.

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22 204 Three survey lines were designed at 1.08 m, 1.92 m, and 2.76 m in the X-direction.
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25 205 In this way, a large number of CMPs can be collected from 0.6 m to 3.24 m with 0.12 m
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28 206 intervals in the X direction and every 0.01 m in the Y direction. Overall, more than 100
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32 207 thousand CMP gathers were available for further analysis in this survey area.
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36 37 208 SIGNAL PROCESSING 38 39 40 41

42 209 The processing procedure for the proposed approach consists of three sequential
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45 210 stages. Pre-processing algorithms include band-pass filtering and trace balancing of each
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48 211 CMP gather to increase the overall signal to noise ratio. Subsequently, the wavelet
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52 212 transform was performed in the shallow region reflection. In this paper, the asphalt
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4 213 dielectric coefficient is presumed to be 4 and the wavelet analysis was performed using
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7 214 a response signal from 0 to 4 ns. The 4 ns lapse signal is adequate to contain all the
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10 215 reflecting layers compared to the 0.15 m thick pavement model. In the last stage, the
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14 216 entropy value was calculated on the basis of the wavelet coefficients and thus the mean
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17 217 entropy values of each CMP could be obtained. Finally, a 2D mean wavelet entropy map
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21 218 of the entire measurement field is produced for interlayer debonding detection.
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26 219 The stability of the reflection signal phase is the main point of the proposed
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29 220 approach. Ideally, the reflection of the GPR is a direct function of the coefficient of
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32 221 reflection. But many factors will affect the stability of the reflection at the target boundary.
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36 222 It will make the inspection of anomalies difficult. However, some considerations and
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39 223 assumptions can be assumed to mitigate this impact by considering the airport asphalt
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43 224 pavement properties.
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48 225 The basic assumption of this proposed approach is that the material itself does not
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51 226 change the reflection phase with the offset. The first assumption is the transmission loss
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55 227 of the asphalt can be assumed as a constant with offset (Shang and Umana, 1999;
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4 228 **Jaselskis et al., 2003).** Another assumption is that the asphalt is a frequency-independent
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7 229 **material for the operating bandwidth of the GPR system (Lai et al., 2011).** It is a basic and
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10 230 reasonable assumption of the proposed approach because it could significantly affect the
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14 231 phase information of different offset reflections.
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23 233 **Mean Wavelet Entropy**

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28 234 **Compare to Fourier analysis, wavelet analysis can process a signal with different**
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31 235 **scales and resolutions.** A large window can be applied in wavelet analysis which results
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35 236 in the global features. **Similarly, analyzing a signal with a small window can pick out**
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38 237 **localized features.** Based on these characteristics, wavelet analysis has been
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42 238 successfully applied in many applications, such as image analysis, transient signal
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45 239 analysis, and other signal processing applications.
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Wavelet is a kind of smooth and fast fading wave, which has good localization both in frequency and time. The wavelet family $\Theta_{a,b}$ is a set of basic functions, which are generated by the expansion and translation of a unique mother wavelet $\Theta(t)$:

$$\Theta_{a,b}(t) = |a|^{-\frac{1}{2}}\Theta\left(\frac{t-b}{a}\right) \quad (1)$$

where t is the time, a indicates the scale parameter, and b indicates the translation parameter. The duration of the wavelet increases with the increase of the scale parameter a . Therefore, wavelet analysis has a unique analysis model, which uses different scales and variable time to analyze the signal.

The continuous wavelet transform (CWT) of a signal $s(t)$ is defined as the correlation between a and b parameters with the family wavelet $\Theta_{a,b}$

$$Coef(a,b;s(t)) = \int_{-\infty}^{\infty} s(t)\frac{1}{a}\Theta\left(\frac{t-b}{a}\right)dt \quad (2)$$

Not only will the selected wavelet affect the coefficients of a CWT, but so will the values of scale and position. The CWT coefficients $Coef(a,b)$ can be obtained by continuously changing the values of scale parameter a and translation parameter b .

254 Discrete wavelet transform (DWT) provides a non-redundant representation of the
 255 signal, and its values constitute the coefficients in the wavelet transform. Wavelet
 256 coefficients can provide complete information of signals. Moreover, the local energy can
 257 be directly estimated at different scales through the wavelet coefficients. The DWT of a
 258 discrete signal $s(n)$ can be derived from CWT and expressed as

$$259 \text{Coef}(m,u;s(n)) = \sum_{n=1}^N s(n) \frac{1}{a} \Theta\left(\frac{u - nb_0 a_0^m}{a_0^m}\right) \quad (4)$$

260 where a_0^m indicates the discrete scale parameter and $nb_0 a_0^m$ indicates the discrete
 261 translation parameter. m indicates the scale parameter and u indicates the translation
 262 parameter of the wavelet transform.

263 Then, the wavelet energy of the analyzed signal can be calculated throughout the
 264 wavelet coefficients and expressed as:

$$265 \text{Energy}_m = \sum_k |\text{Coef}(m,u)|^2 \quad (5)$$

266 Finally, the total wavelet energy can be obtained as:

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$$Energy_{total} = \sum_m Energy_m \quad (6)$$

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8 268 Then, the relative wavelet energy can be expressed as:

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$$RE_m = \frac{Energy_m}{Energy_{total}} \quad (7)$$

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18 270 From the above equations, the relative wavelet energy RE_m can be considered as

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21 271 a time-scale density and satisfies the following relationship:

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$$\sum_m RE_m = 1 \quad (8)$$

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31 273 This provides a suitable tool for detecting and characterizing the time and

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34 274 frequency attributes of signals.

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39 275 According to the relative wavelet energy and the Shannon entropy theory (Zhang

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42 276 et al., 2015), the wavelet entropy is defined and expressed as:

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$$S_{WE}(p) = - \sum_m RE_m \cdot \ln (RE_m) \quad (9)$$

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52 278 A reflected signal coming from the defects or anomalies in the pavement region

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55 279 can be taken as a combination of two signals. One signal is the reflection coming from

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4 280 the sound pavement. The other signal is a difference signal between the signals that
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7 281 come from the defective and sound pavement. This type of reflection will have its form of
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10 282 wavelet representation and will have an important contribution to all frequency bands. As
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14 283 a result, the relative wavelet energy of all resolution levels will be almost equal, and the
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17 284 wavelet entropy will exceed the maximum value. In addition, this signal can also break
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21 285 the stability of each CMP trace.

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25 286 In this study, the wavelet analysis of shallow region reflection was performed by
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29 287 equation (4) and the wavelet coefficients were obtained. Then the relative wavelet energy
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32 288 was obtained by equations (5) to (7). Next, the wavelet entropy of each CMP trace was
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36 289 calculated by equation (9). Finally, the mean wavelet entropy of a CMP gather can be
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40 290 obtained according to each CMP trace entropy value.

41 42 43 44 291 RESULTS AND DISCUSSIONS

45 46 47 48 49 292 Field Measurement Results

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4 293 In this study, the test was carried from October 30th to November 30th, 2017. Four
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7 294 GPR surveys were conducted from the initial build to the 30 days load test and water
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10 295 injection. The first measurement was conducted on October 30th. The second
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14 296 measurement was conducted on November 6th. The third measurement was conducted
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17 297 on November 14th. And the last measurement was conducted on November 30th.

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22 298 Three survey lines along the Y direction were designed to cover the entire area of
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26 299 the model during each measurement. In order to make each measurement start at the
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29 300 same position, several markers were nailed in the survey area. The three survey lines
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32 301 covered the area of 0.24 m to 3.6 m along the X direction. In this way, 23 CMP gathers
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36 302 were obtained from 0.6 m to 3.24 m with 0.12 m intervals in the cross-survey direction (X
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39 303 direction), and 5001 CMP gathers were obtained from 0 m to 50 m with 0.01 m intervals
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43 304 in the survey direction (Y direction). Overall, more than 100 thousand CMP gathers were
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46 305 acquired in the entire area. The B scans acquired at X=1.08 m of each survey are shown
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50 306 in Figure 7 (a), (b), (c), and (d), respectively. The reflection from the bottom of the level
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54 307 layer can be seen at approximately 0.2 m. The clear reflection around 0.5 m is the
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4 308 boundary of the old pavement structure. All the reflections from the level layer are mixed
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7 309 with the antenna coupling. From Figure 7 (b) to (d), the effect of water injection can be
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10 310 observed around 13 m, 31 m, and 37 m in the Y direction. However, it is hard to judge
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14 311 any anomalies inside the model structure through the B scans.

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18 312 Figure 8 shows the CMP gather at a point in Area I along the survey line X equal
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22 313 to 1.08m for each of the four surveys. There is a strong difference between the first
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26 314 indication of arrival before and after the injection of water. But the difference with the
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29 315 loading test is hard to compare. The dielectric coefficient of asphalt is around 4. In this
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33 316 paper, we select 0.15m/ns as the propagation velocity of the pavement model.
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36 317 Considering the velocity of the pavement material, the reflection signals from 0 to 4 ns
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40 318 were used for further processing. After the entire collection of CMP gathers were
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43 319 processed by the proposed method, the mean wavelet entropy distribution of the entire
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46 320 area was acquired, as shown in Figure 9. Figure 9 (a) shows that the mean wavelet
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50 321 entropy value is around 0 in the entire area. But the contour of buried nonwoven fabrics
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54 322 (red square in Figure 9 (a)) still can be observed and matched with Figure 5 very well. In
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4 323 Figure 9 (b), after several days of water injection and load test, it can clearly see that the
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7 324 average wavelet entropy increases significantly in the area that contained the buried
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10 325 nonwoven fabrics. But this change in Area I, II, and V is not smooth, which means that
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14 326 the change of wavelet entropy is mainly caused by water injection. In other words, the
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17 327 existence of this thin layer of water induces a greater change in the process of shallow
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21 328 reflection than the thin layer of air. The average wavelet entropy of the whole experimental
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24 329 area is changing with the progress of the experiment, as shown in Figure 9 (c) and (d).
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28 330 Overall, the relationship of entropy value is Area I>Area V>Area II>Area IV>Area III. The
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31 331 average wavelet entropy of the area of the nonwoven fabric is around 0.1 with the
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35 332 progress of the experiment. We believe that the pavement structure should not
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38 333 experience large damage during the load test. But, some regions show high entropy value
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42 334 at the end of this test, especially a high entropy value is appearing in Area I where the
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45 335 base layer is constructed by gravel. This means that the base layer constructed by gravel
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49 336 is the weakest structure compared to the other materials. The entropy value of the region
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52 337 located around 1 m in the X direction and 13 m in the Y direction is greater than 0.2, two
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56 338 times higher than the normal nonwoven fabrics region. At this point, we can conclude that
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4 339 the phenomenon of interlayer debonding has occurred in that region. From the results
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7 340 from where no nonwoven fabrics were buried, the high entropy regions during this test
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10 341 are around the anomalous regions in the beginning. The anomalous regions in Figure 9
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14 342 (a) means these regions are not well constructed or the material used is non-uniform.
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17 343 That is to say, the quality of construction and the heterogeneity of the material used both
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21 344 have a significant effect on its service life.
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25 345 Validation by Coring

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30 346 ~~In order~~ to obtain more details during this test, on-site coring was performed
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34 347 following the acquisition of multi-static GPR data. Three core samples were drilled in Area
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37 348 I, where the gravel was used as the base layer. The circles with a cross marker in Figure
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41 349 9 (d) and Figure 10 (a) indicate the location for coring. Figure 10 (b) shows the scenario
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44 350 after coring. Figure 10 (c), (e) and (g) show the coring sample of #1, #2 and #3, respectively,
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48 351 and Figure 10 (d), (f) and (h) show the coring section of #1, #2 and #3, respectively. It can
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51 352 be seen that the sampling of coring from #1 is uneven and some debris remains on the
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55 353 surface of the section. But the coring sampling from #2 and #3 are relatively integral and
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4 354 the coring section surface is smooth. As a consequence, defects or anomalies occurred
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7 355 in the region around #1 during the 30-day test. As seen from Figure 9 (d), coring #1 is
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10 356 located in the high entropy region, while coring #2 and #3 are located in the relatively low
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14 357 entropy region. The results of the coring showed that the proposed method showed
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17 358 reliable and excellent efficiency in detecting the defect or anomalies of the airport
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21 359 pavement.

360 CONCLUSION

361 We have presented a robust strategy for anomaly detection in airport pavement
362 with a multi-static GPR system. The main objective of this research was to detect the thin
363 voids that occurred at the bonding region in the shallow parts of airport pavement. The
364 existence of thin water-filled or air-filled voids can be considered an inhomogeneous layer
365 in the structure that influences the phase stability of the reflection signals in a CMP gather.
366 It can be expected that this form of anomaly within the layered structure can be inspected
367 by a tiny signal phase difference. During the experiment, a multi-static GPR system was
368 used to complete the large-scale airport pavement inspection. The antenna configuration

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4 369 of the system and a designed survey strategy made it possible to obtain dense CMP
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7 370 datasets during a common survey simultaneously. Moreover, a wavelet transform was
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10 371 applied to these dense CMPs to evaluate the phase details of the shallow reflection.
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14 372 Furthermore, the mean entropy value of each CMP was used to determine the stability of
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17 373 the reflection phase among surveys throughout different periods. The proposed approach
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21 374 to inspecting anomalous regions in an asphalt layer has been illustrated by numerous
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24 375 field experiments with an airport pavement model. The on-site coring results also indicate
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28 376 the precision of the proposed approach. The proposed approach is easier to understand
29
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31 377 and the measurement process is much simpler, allowing to implement it in real-time
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35 378 inspection.

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- 9 479 2 Antenna configuration of the multi-static ground penetrating radar system.
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11 480 3 Measurement survey coordinate aimed for dense CMP gathers extraction.
- 12
13 481 4 Measurement on the airport pavement model: (a) Entire measurement site and survey
14 482 coordinate; (b) Operation of the multistatic GPR system on the site.
- 15
16 483 5 Structure layout of the airport pavement model (plan view and sectional view (X and Y
17 484 Direction)).
- 18 485 6 Airport pavement model; (a) scene of Area I; (b) scene of Area II; (c) scene of Area III; (d)
19 scene of Area IV; (e) scene of Area V; (f) the gravel base layer; (g) the hot asphalt base
20 486 layer; (h) 20 tons truck drove over the model to imitate the load imposed by the aircraft.
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23 488 7 B scans acquired on the survey line $X = 1.08\text{m}$; (a) survey on 30th October; (b) survey on
24 489 6th November; (d) survey on 14th November; (d) survey on 30th November.
- 25
26 490 8 CMP gathers acquired at the point $X = 1.08\text{m}$ and $Y = 13\text{m}$; (a) survey on 30th October; (b)
27 491 survey on 6th November; (d) survey on 14th November; (d) survey on 30th November.
- 28
29 492 9 Mean wavelet entropy maps of the entire model: (a) entropy map of the survey on October
30 493 30th; (b) entropy map of the survey on November 6th; (c) entropy map of the survey on
31 494 November 14th; (d) entropy map of the survey on November 30th.
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35 495 10 Coring on the pavement model in Area I: (a) #1, #2 and #3 indicated the coring position;
36 496 (b) scenario after coring; (c) coring sample of #1; (d) coring section of #1; (e) coring
37 497 sample of #2; (f) coring section of #2; (g) coring sample of #3; (h) coring section of #3.
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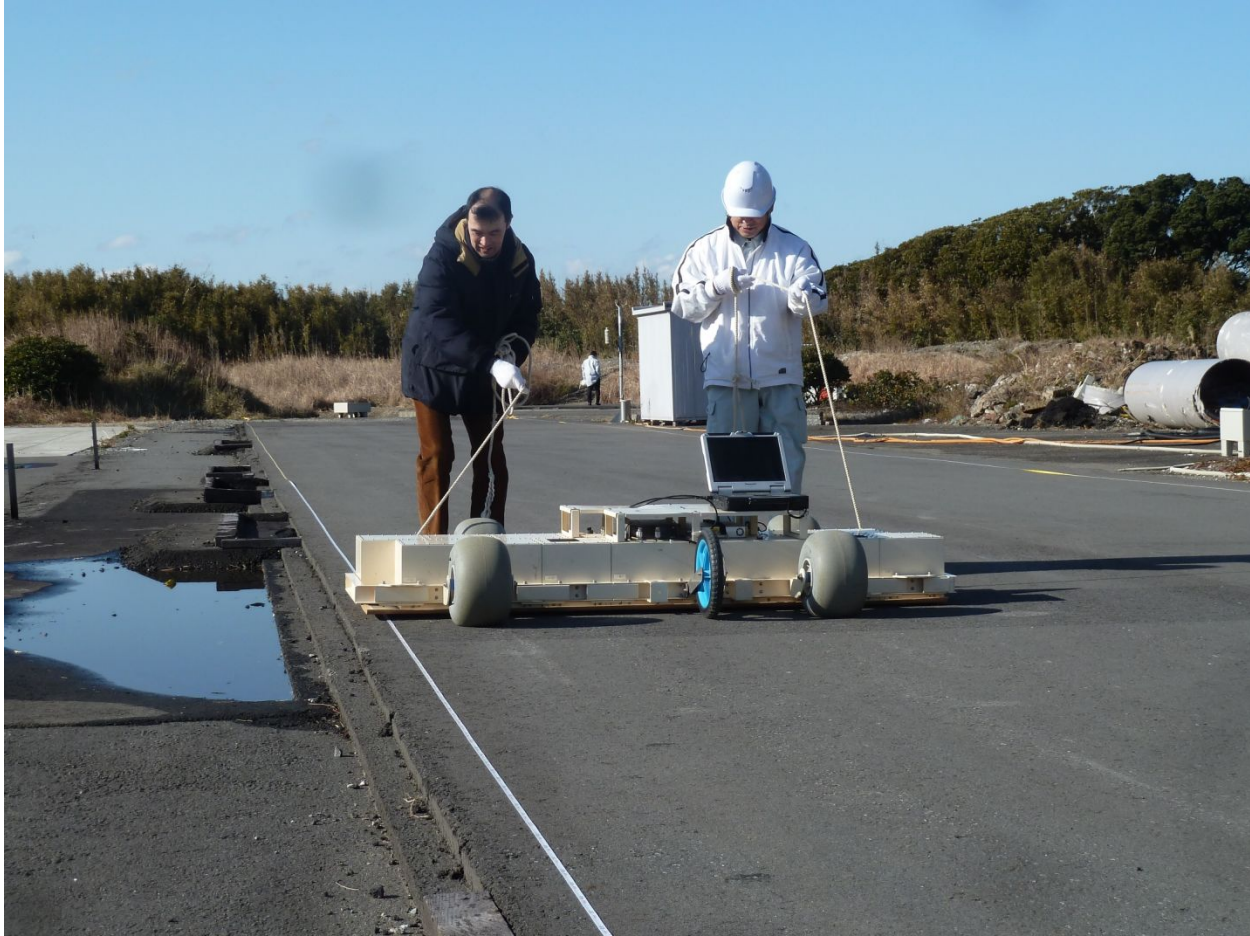
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499

- 1 System Parameters of the multi-static ground penetrating radar system.

For Peer Review



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501 Figure 1. Multi-static ground penetrating radar system.

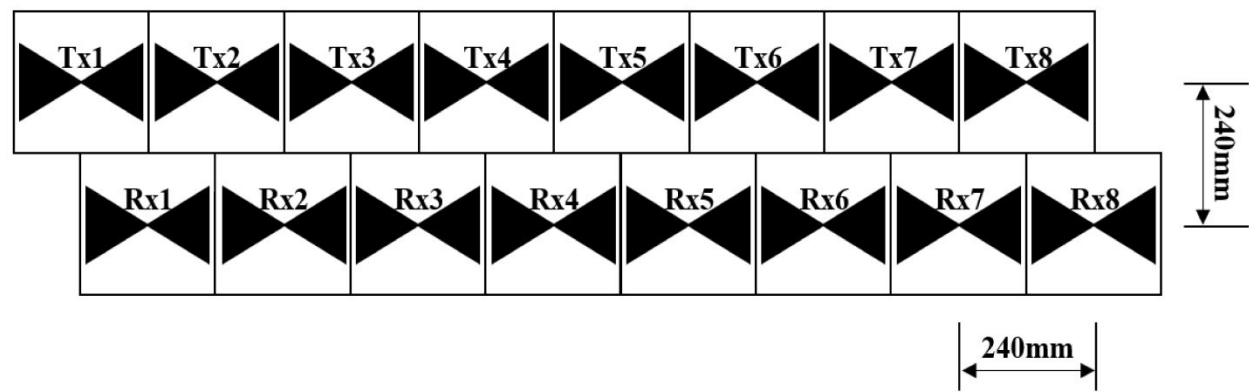


Figure 2. Antenna configuration of the multi-static ground penetrating radar system.

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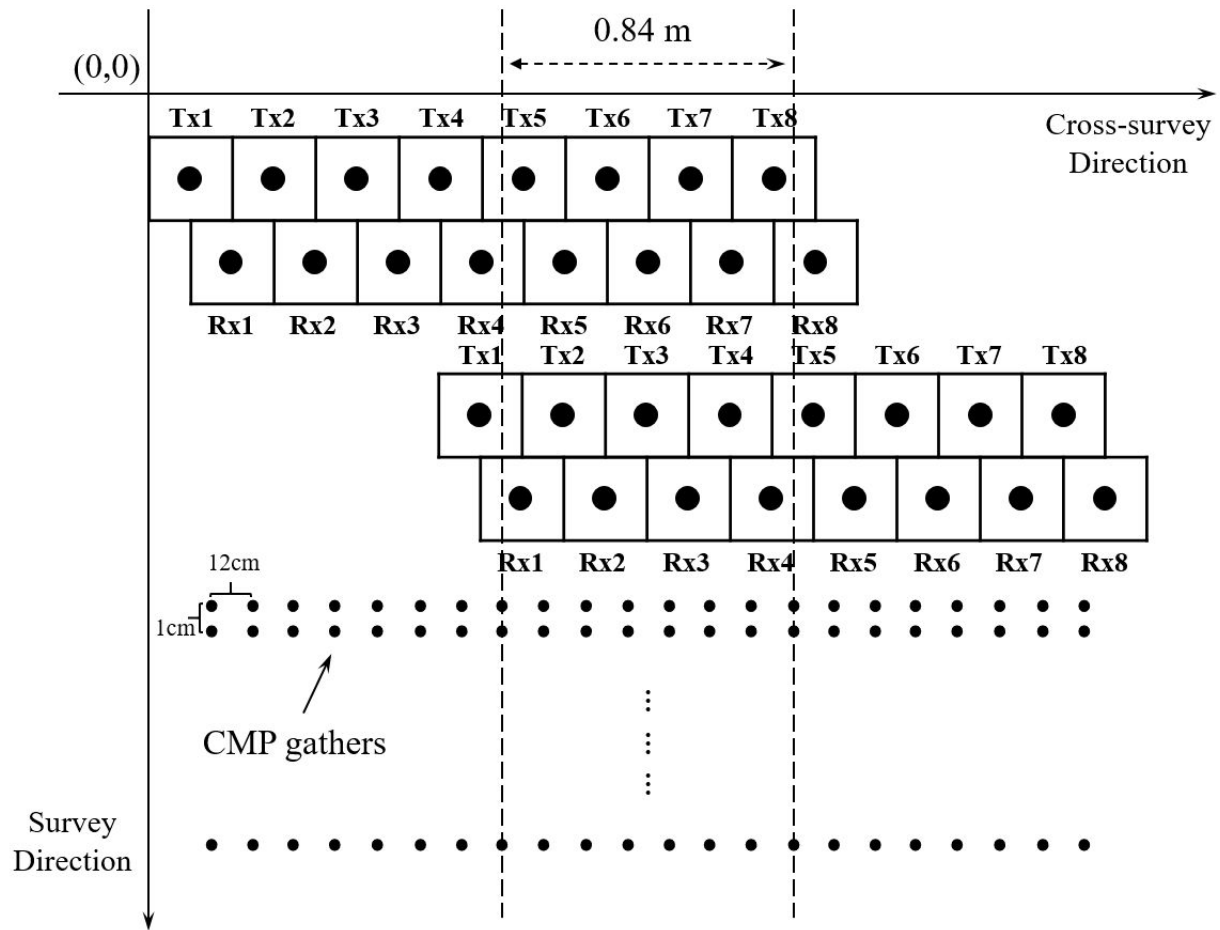


Figure 3. Measurement survey coordinate aimed for dense CMP gathers extraction.

Review

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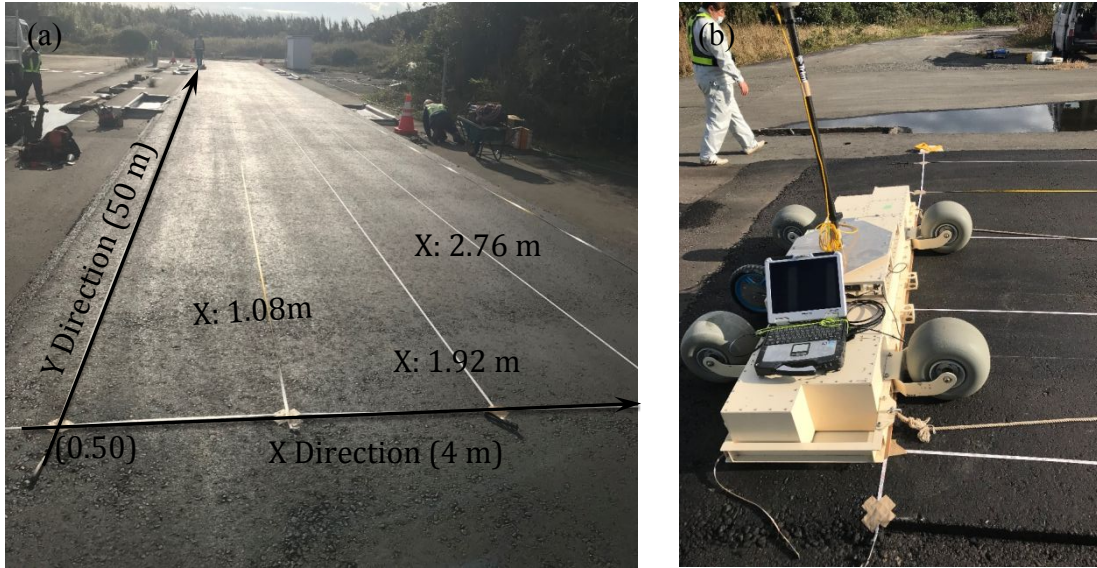


Figure 4. Measurement on the airport pavement model: (a) Entire measurement site and survey coordinate; (b) Operation of the multistatic GPR system on the site.

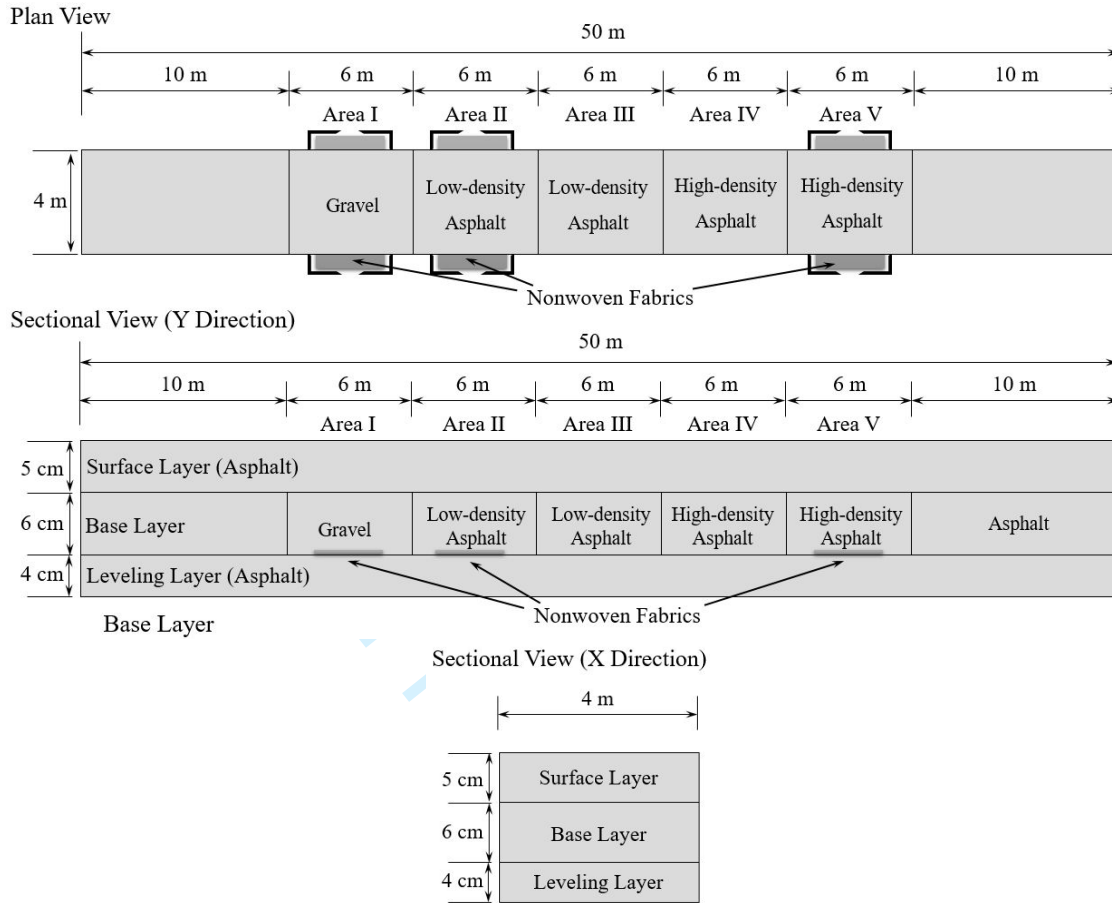
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Peer Review

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Geophysics

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Figure 5. Structure layout of the airport pavement model (plan view and sectional view (X and Y Direction)).

Geophysics

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Figure 6. Airport pavement model; (a) scene of Area I; (b) scene of Area II; (c) scene of Area III; (d) scene of Area IV; (e) scene of Area V; (f) the gravel base layer; (g) the hot asphalt base layer; (h) 20 tons truck drove over the model to imitate the loads imposed by the aircraft.

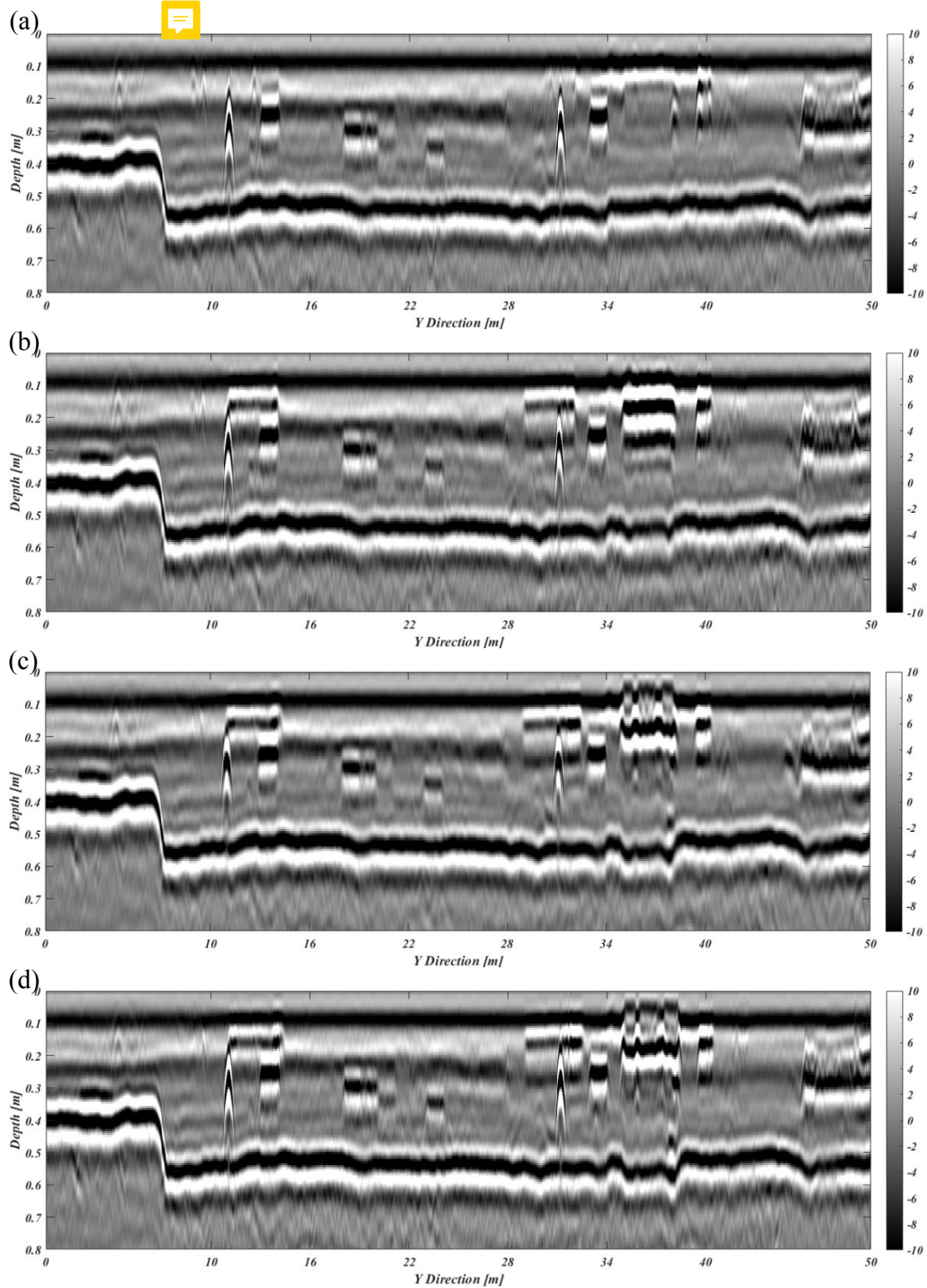


Figure 7. B scans acquired on the survey line X = 1.08m; (a) survey on 30th October; (b) survey on 6th November; (c) survey on 14th November; (d) survey on 30th November.

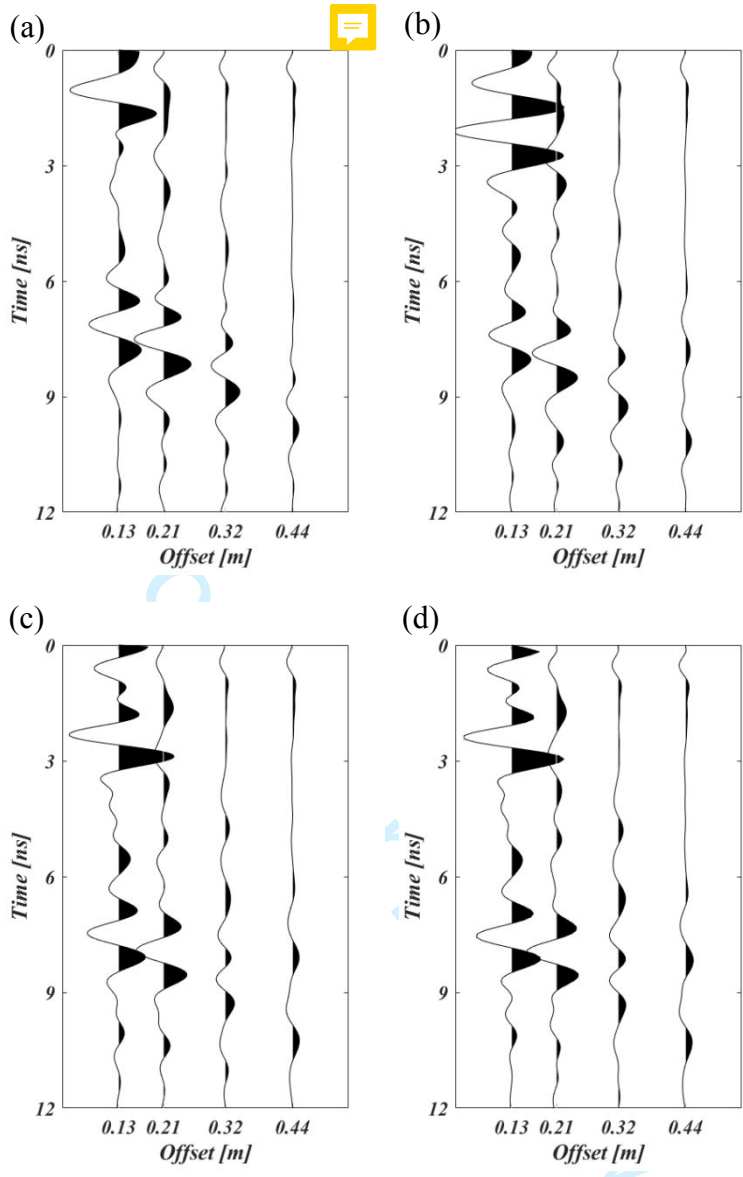


Figure 8. CMP gathers acquired at the point X = 1.08m and Y= 13m; (a) survey on 30th October; (b) survey on 6th November; (c) survey on 14th November; (d) survey on 30th November.

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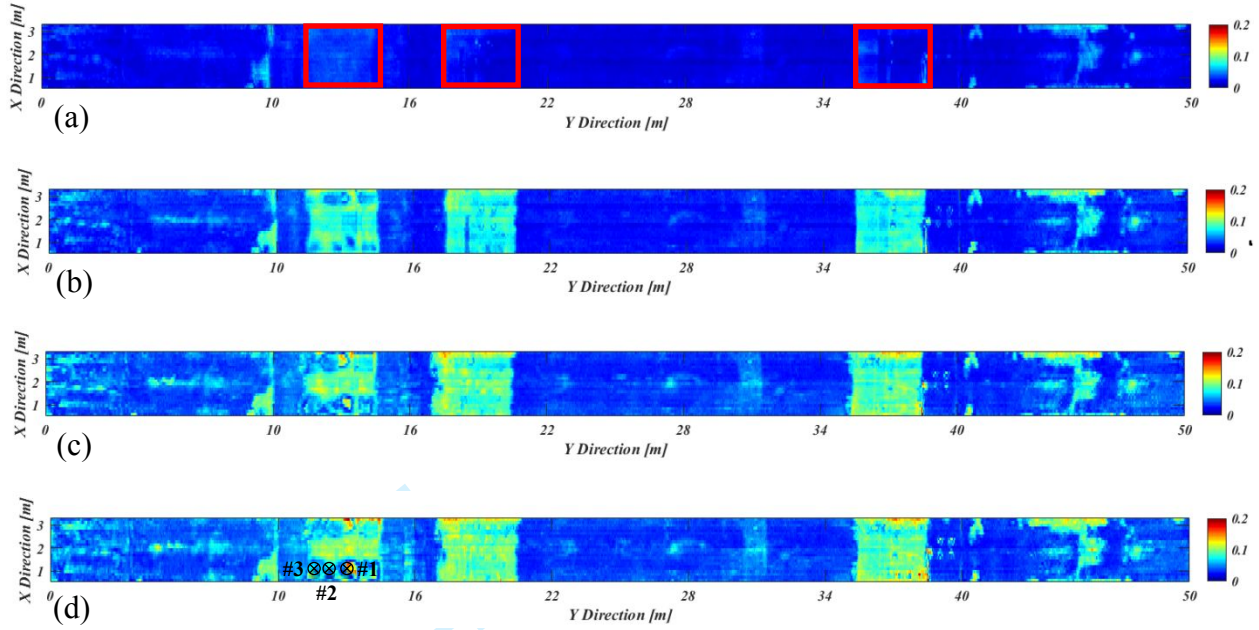


Figure 9. Mean wavelet entropy maps of the entire model: (a) entropy map of the survey on October 30th; (b) entropy map of the survey on November 6th; (c) entropy map of the survey on November 14th; (d) entropy map of the survey on November 30th.

Peer Review

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Geophysics

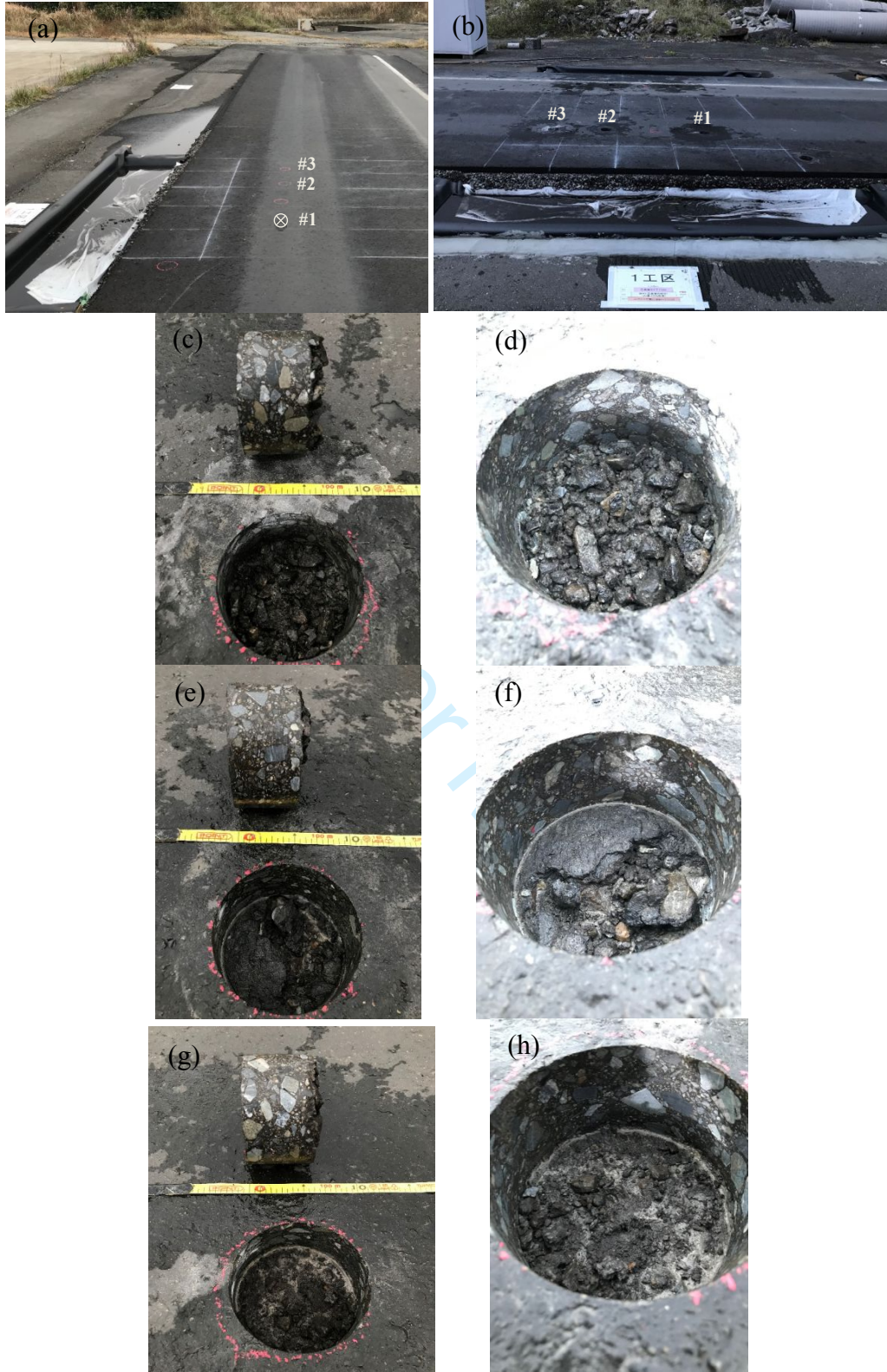


Figure 10. Coring on the pavement model in Area I: (a) #1, #2 and #3 indicated the coring position; (b) scenario after coring; (c) coring sample of #1; (d) coring section of #1; (e) coring sample of #2; (f) coring section of #2; (g) coring sample of #3; (h) coring section of #3.

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parameters	values
system type	step frequency continues wave
antenna type	bowtie antenna
frequency range	0.05 GHz to 1.5 GHz
acquisition points	256
maximum movement speed	2 m/s
system width	2 m
acquisition interval	0.01 m/trace
penetration depth	larger than 2m
sweeping time	around 0.1 s

Table 1: System Parameters of the multi-static ground penetrating radar system.

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For Peer Review

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