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GEOPHYSICS[®]

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

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Manuscript Focus Area:	Engineering and Environmental Geophysics, Ground-Penetrating Radar



1		Geophysics 1
2 3 4	1	ABSTRACT
5 6 7 8	2	The multi-layer nature of airport pavement structures is susceptible to the
9 10 11	3	generation of voids at the bonding parts of the structure, which is also called interlayer
12 13 14 15	4	debonding. Observations have shown that the thickness of the resulting voids is usually
16 17 18	5	at the scale of millimeters, which makes it difficult to inspect. The efficient and accurate
20 21 22	6	characteristics of ground penetrating radar (GPR) make it suitable for large area
23 24 25	7	inspections of airport pavement. In this study, a multi-static GPR system was used to
26 27 28 29	8	inspect the interlayer debonding of a large area of an airport pavement. A special antenna
30 31 32	9	arrangement can obtain common mid-point (CMP) gathers during a common offset
33 34 35 36	10	survey. The presence of interlayer debonding affects the phase of the reflection signals,
37 38 39	11	and the phase disturbance can be quantified by wavelet transform. Therefore, an
40 41 42 43	12	advanced approach that uses the average entropy of the wavelet transform parameters
44 45 46	13	in CMP gathers to detect the interlayer debonding of airport pavement is proposed. The
47 48 49 50	14	results demonstrate that the regions with high entropy correspond to the regions where
51 52 53	15	tiny voids exist. The new approach introduced in this study was then evaluated by a field-
54 55 56 57 58 59 60	16	base experiment at an airport taxiway model. The results show that the proposed

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17 approach can detect interlayer debonding of the pavement model accurately and

18 efficiently. The on-site coring results confirm the performance of the proposed approach.

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1		Geophysics 3
2 3 4	19	INTRODUCTION
5 6 7		
8 9 10 11	20	Maintaining pavement facilities (runway, taxiway) at the airport faces many unique
12 13 14	21	challenges. A significant amount of economic costs and a large number of airport
15 16 17	22	engineering and maintenance personnel are required to provide all-weather facilities for
18 19 20 21	23	the safe operation of the airport. The integrity and flatness of airport pavement facilities
22 23 24	24	plays an important role in the safe operation of aircraft. Even a small defect and the
25 26 27 28	25	resulting debris can cause catastrophic accidents. So, the anomalies must be accurately
29 30 31	26	detected before major damage occurs due to the particular requirements of airport
32 33 34 35	27	pavement facilities. Hence, it is important to develop a low-cost, reliable and effective
36 37 38	28	detection technology to detect anomalies in the concrete structure of the airport, thus
39 40 41 42	29	providing integrity and safety services to aircraft operating at airport road facilities
43 44 45 46	30	(Frederickson and LaPorte, 2002).
47 48 49 50	31	In order to meet the high standard requirements of perfect flatness, toughness,
50 51 52 53	32	and uniformity of airport road facilities, multi-layer designs with different materials are
54 55 56 57 58 59 60	33	usually used for construction (Fwa, 2003). Normally, the multi-layer structure consists of

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3 4 5 6 8

34	3 to 4 layers. They are a surface asphalt layer, base asphalt layer, sub-base layer, and
35	bottom layer from the surface to bottom. Typically, the thickness of each layer is about
36	several centimeters (Zou et al., 2018). However, the multi-layer design of airport
37	pavement has its disadvantages. A small raindrop or snow flake on the surface can be
38	pressed into the pavement structure when an aircraft moves over the pavement. This
39	small amount of water can remain in the small area of the shallow pavement. With
40	changes in pavement surface temperature, the volume of water becomes larger (when
41	the temperature is high, it becomes water vapor; when the temperature is low, it turns to
42	ice), expands and extends as a void on the layer bonding region (usually called interlayer
43	debonding phenomenon). At the same time, the temperature and pressure change
44	generated by the aircraft moving over the pavement can further accelerate this procedure.
45	The integrity of the airport pavement becomes weaker as the interlayer debonding
46	extends further and further, and the pavement surface could be distorted and collapse,
47	thus affecting the safe operation of aircraft. The interlayer debonding plays an important
48	role in the remaining life of airport pavement facilities. Therefore, it is important to detect
40 41 42 43 44 45 46 47 48	changes in pavement surface temperature, the volume of water becomes larger (when the temperature is high, it becomes water vapor; when the temperature is low, it turns to ice), expands and extends as a void on the layer bonding region (usually called interlayer debonding phenomenon). At the same time, the temperature and pressure change generated by the aircraft moving over the pavement can further accelerate this procedure. The integrity of the airport pavement becomes weaker as the interlayer debonding extends further and further, and the pavement surface could be distorted and collapse, thus affecting the safe operation of aircraft. The interlayer debonding plays an important role in the remaining life of airport pavement facilities. Therefore, it is important to detect

1		Geophysics 5
2		
3 4 5	49	interlayer debonding at its early stage and repair it. This is the priority for airport road
6 7 8 9	50	maintenance.
10 11 12 13	51	In recent years, non-destructive testing (NDT) has been widely used in airport
14 15 16 17	52	pavement inspection and maintenance due to the reliable and efficient information that it
18 19 20	53	can provide (Breysse, 2012; Liu et al., 2020). Ground Penetrating Radar (GPR), Infrared
21 22 23 24	54	Thermal Imaging, Acoustic or Ultra-Sounding Detection, and Microwave Remote Sensing
25 26 27	55	are widely used to detect the inner anomalies of concrete infrastructure. The accuracy
28 29 30 21	56	and economy of these technologies fully guarantee the integrity and safety of the
32 33 34	57	pavement infrastructure. At present, the conventional methods of anomaly detection in
35 36 37 38	58	airport pavement facilities are acoustic imaging and infrared irradiation methods. Acoustic
39 40 41	59	imaging needs a large number of experienced engineers and technicians, while infrared
42 43 44 45	60	radiation cannot be applied to large-scale rapid detection due to the strict conditions and
46 47 48	61	limited size for pavement inspection (Zou, et al., 2020). However, due to the existence of
49 50 51 52	62	tiny voids, the small density change in the depth direction can be used for inspection.
52 53 54 55 56 57 58 59 60	63	Based on this idea, both nuclear densitometer and ultrasonic measurements have

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64	achieved accurate results in laboratory experiments. But, these two methods are not
65	suitable for real-life application to large-scale inspection of airport pavement.
66	As an NDT method, GPR can provide optimal resolution of different plications
67	in civil engincering (Alani and Tosti, 2018; Benedetto et al., 2017; Eskelinen and Pellinen,
68	2018; Liu et al., 2020; Saarenketo and Scullion, 2000; Shangguan et al., 2016;
69	Spagnolini, and Rampa, 1999; Lai et al., 2018) due to the ultra-wide frequency band that
70	is used. For the detection of airport pavement facilities by GPR, the challenge mainly
71	comes from how to extract information from the reflection generated by the small
72	anomalies. This is quite different from the data processing for most pavement inspection
73	cases, which focuses on large-scale anomalies in the deep region of the pavement.
74	Meanwhile, the anomalies inside the structural layers of airport pavement are millimeter
75	order in size (Zou, et al., 2020). These thin layers are difficult to directly observe on the
76	GPR profile given the system resolution, as pointed out by Bradford and Deeds (2006)
77	and Hartikainen et al., (2018). Besides, the thin layers in airport pavement facilities are
78	usually shallow (a few centimeters depth); (Zou, et al., 2020). The complex

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1		deophysics
2 3 4 5	79	electromagnetic response generated by the electromagnetic wave at the boundary of air
6 7 8	80	and pavement cannot be separated from the response of small shallow anomalies. How
9 10 11 12	81	to interpret, from a GPR signal with a center frequency of several GHz, the responses
13 14 15 16	82	from such small, shallow anomalies has become a difficult task and a challenge. In
17 18 19	83	addition, in the light of the slight dielectric coefficient difference or the change in velocity
20 21 22 22	84	of the shallow pavement structure due to the presence of tiny voids, GPR measurements
23 24 25 26	85	have made it possible to further identify the anomalies of the airport pavement. However,
27 28 29	86	the small change of dielectric coefficient does not produce an obvious anomaly by the
30 31 32 33 34	87	conventional survey and processing.
35 36 37 38	88	Further expanding on the above idea, considering the size, location of the thin
39 40 41	89	layer, and the system resolution, the small change of dielectric coefficient along the
42 43 44 45	90	horizontal direction can also be used to judge the existence of anomalies in the airport
46 47 48	91	pavement structure. Because this change is extremely small, a reference or level should
49 50 51 52	92	be considered. The reference or level can be the reflection from a certain point or a
52 53 54 55 56 57 58 59 60	93	multichannel response. Based on the above idea, Yi et al. (2018) proposed an approach

1		Geophysics 8
2 3 4 5	94	that analyzes the tiny deviation of the asphalt layer depth and velocity by using the phase
6 7 8	95	deviation of the common mid-point (CMP) gather for airport pavement inspection. Zou et
10 11 12	96	al. (2020) proposed another method that uses the energy deviation of the lateral wave in
13 14 15 16	97	a CMP gather for the airport pavement inspection. Both of these methods are verified by
17 18 19	98	real measurements carried on pavement at Tokyo International Airport (Japan). However,
20 21 22 23	99	due to the difficulty of parameter adjustment, there are some limitations in practical
24 25 26 27	100	application (Yi et al., 2018; Zou et al., 2020) of the above methods.
28 29 30 31	101	In this paper, we investigate a new approach, which is robust, easy to understand,
32 33 34 25	102	and practical in terms of implementation and results. The proposed approach analyzes
36 37 38	103	the average wavelet entropy of the shallow region reflection in a CMP gather. Compared
39 40 41 42	104	to the Fourier transform, the wavelet transform has many advantages for representing the
43 44 45	105	detailed information in a signal. The wavelet transform can deconstruct and reconstruct
46 47 48 49	106	any aperiodic signals accurately. It can analyze the localization of time- or space-
50 51 52	107	frequency by stretching and shifting the signal step by step. The detailed information in
53 54 55 56 57 58 59	108	the signal can be represented by time subdivision at high frequency and frequency

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1 2		deophysics 9
3 4 5	109	subdivision at a low frequency through the wavelet transform (Kumar, and
6 7 8 9	110	Foufoula-Georgiou, 1997; Sinha et al., 2005). The entropy, which analyzes and
10 11 12	111	compares the probability distribution, can provide a measure of the signal stability.
13 14 15 16	112	The wavelet entropy, which combines wavelet analysis and entropy, can be used as
17 18 19 20	113	a measure of the degree of order/disorder of the signal. Therefore, it can provide
21 22 23	114	useful information about signal dynamical stability. In recent years, wavelet entropy as
24 25 26 27	115	a robust method has been widely applied for fault detection (Rosso et al., 2001; El-
28 29 30 31	116	Zonkoly and Desouki, 2011; Dasgupta et al., 2012).
32 33 34 35	117	Due to presence of a thin void or a micro-damaged zone, the waveform of the
36 37 38 39	118	backward reflection has some slight changes compared to the sound zone. This small
40 41 42	119	change can be illustrated by an entropy change throughout the parameters of the wavelet
43 44 45 46	120	transformation. So, the proposed approach is based on the wavelet entropy difference
47 48 49	121	between the anomalies and sound pavement reflections. The signal processing
50 51 52 53	122	procedure for the proposed approach is also succinct. First, a band-pass filter is applied
54 55 56 57 58 59	123	to the raw frequency domain data and then the Fourier transform was performed to get

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124	time-domain CMP gathers. Next, the trace balance of each CMP gather is applied. Trace
125	balance is a procedure that scale amplitudes to a common root mean square (RMS) level
126	for all traces. Lastly, the mean wavelet entropy of the shallow region reflection is
127	calculated and formed into a 2D entropy map of the entire measurement area. The simple
128	processing procedure makes the real-time pavement inspection much easier perform.
129	Real experiment data obtained from a pavement model have demonstrated the excellent
130	performance of the proposed approach. The processed results also matched with on-site
131	coring results very well.
132	MULTI-STATIC GPR SYSTEM AND PAVEMENT MODEL
132 133	MULTI-STATIC GPR SYSTEM AND PAVEMENT MODEL Multi-static Ground Penetrating Radar System and Survey Strategy
132 133 134	MULTI-STATIC GPR SYSTEM AND PAVEMENT MODEL Multi-static Ground Penetrating Radar System and Survey Strategy With the further increase of GPR application in civil and environmental
132 133 134 135	MULTI-STATIC GPR SYSTEM AND PAVEMENT MODEL Multi-static Ground Penetrating Radar System and Survey Strategy With the further increase of GPR application in civil and environmental engineering, several array radar systems have been developed (Gerhards et al., 2008;
132 133 134 135 136	MULTI-STATIC GPR SYSTEM AND PAVEMENT MODEL Multi-static Ground Penetrating Radar System and Survey Strategy With the further increase of GPR application in civil and environmental engineering, several array radar systems have been developed (Gerhards et al., 2008; Jol, 2008; Xu et al., 2002). To better carry out large-scale measurement, Tohoku
 132 133 134 135 136 137 	MULTI-STATIC GPR SYSTEM AND PAVEMENT MODEL Multi-static Ground Penetrating Radar System and Survey Strategy With the further increase of GPR application in civil and environmental engineering, several array radar systems have been developed (Gerhards et al., 2008; Jol, 2008; Xu et al., 2002). To better carry out large-scale measurement, Tohoku University (Japan) developed an array radar system in 2012 (Liu et al., 2013; Sato et al.,

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1		Geophysics 11
2 3 4 5	138	2016, Yi et al., 2018; Kikuta et al., 2019), shown in Figure 1. The system consists of 8
6 7 8	139	bowtie antennas that form the transmitting array and the receiving array as shown in
10 11 12	140	Figure 2. The receiving array and the transmitting array are staggered with a half antenna
13 14 15 16	141	interval. It is a step frequency continuous wave radar system and the operating frequency
17 18 19	142	varies from 0.05 GHz to 1.5 GHz. The system is a multi-static system which means all
20 21 22 23	143	the combinations of transmitter and receiver antenna are recorded. Overall, 64 channel
24 25 26	144	data can be obtained by a single measurement. It uses a distance-measuring wheel to
27 28 29 30	145	trigger and record the data every 0.01 m interval. The system length is 2 m and can cover
30 31 32 33	146	an area of 2 m at a time. It can be hung on the vehicle and also can be pulled manually.
34 35 36 37	147	The fastest measuring speed can reach 7km / h. Based on the above advantages, the
38 39 40	148	system can cover a large survey area and acquire a dense GPR dataset in a short time.
41 42 43	149	Table 1 shows the main parameters of the multi-static GPR system. By operating this
44 45 46 47 48	150	system, a large-scale GPR survey can be carried out efficiently.
49 50 51	151	In addition to the advantages described above, CMP gathers can b <mark>ee</mark> xtracted from
52 53 54 55 56 57 58 59 60	152	the antenna arrangement of this system at the same time during a common

1		Geophysics 12
2 3 4 5	153	measurement. Of course, this cannot be achieved by the common parallel survey, and so
6 7 8	154	an improved survey strategy is needed. By separating the transmitting and receiving
9 10 11 12	155	antenna by a relatively small distance simultaneously, a series of reflections from the
13 14 15	156	middle point can be obtained. The reflections can be formed as a CMP gather. As shown
16 17 18 19	157	in Figure 3, a CMP gather can be extracted by judicious choice of traces from the 64
20 21 22	158	channel data. A point located in the middle of the system can have 8 CMP traces, while
23 24 25 26	159	the edge point only has 1 trace. Set each parallel survey line interval as 0.84 m and this
27 28 29 20	160	way can guarantee that each center point has at least <mark>4</mark> CMP trace. Therefore, the dense
31 32 33	161	CMP gathers with a 0.12 m interval along the cross-survey direction, and a 0.01 m interval
34 35 36 27	162	along the survey direction can be extracted with at least 2 parallel surveys. In this paper,
38 39 40	163	4 traces with antenna offsets 0.13 m, 0.21 m, 0.32 m, and 0.44 m were used for all the
41 42 43	164	CMP gathers. Although 4 traces in a CMP gather is sparse compared to traditional CMP
44 45 46 47	165	acquisition, the CMP gathers extracted by this multi-static GPR system still could be used
48 49 50	166	for further signal processing.
51 52 53 54 55 56 57 58 59 60	167	Survey Site and Pavement Structures

2		
3 4 5	168	In order to provide adequate support for the frequent operation of aircraft, it is
6 7 8	169	important to construct a sufficiently strong, stable and smooth airport pavement. First, the
9 10 11 12	170	pavement structure must be of adequate thickness and strength to withstand the loads
13 14 15	171	imposed by the aircraft. Secondly, it must have good wear resistance under frequent
16 17 18 19	172	operation, and will not produce small debris to affect the safety of the aircraft. Finally, it
20 21 22 23	173	must also be able to withstand the effects of extreme weather to ensure the safe operation
24 25 26	174	of the aircraft. To find the pavement that meets the above requirements, many factors
27 28 29 20	175	such as design, construction, and material combinations need to be coordinated to find
30 31 32 33 34	176	the best combination.
35 36 37 38	177	In order to find the best material combination and to monitor its performance under
39 40 41	178	high loads, a pavement model was built in the Port and Airport Research Institute located
42 43 44 45	179	in Nobi, Kanagawa, Japan, as shown in Figure 4 (a). The size of this model is 4 m in width
46 47 48	180	and 50 m in length. It is a multi-layer structure consisting of a surface layer, a base layer,
49 50 51 52	181	and a leveling layer. The structural strength was provided primarily by the surface and the
53 54 55 56 57 58 59 60	182	base layers. They can reduce the load stress produced by the aircraft to a degree that is

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1		Geophysics
2 3 4 5	183	adequately
6 7 8	184	kinds of ma
9 10 11 12	185	The middle
13 14 15	186	leveling la
17 18 19	187	respectively
20 21 22	188	located in
23 24 25 26	189	asphalt, hig
27 28 29	190	the side of
30 31 32 33	191	thickness o
34 35 36	192	V, nonwove
37 38 39 40	193	and contin
41 42 43	194	imitates th
44 45 46 47	195	pavement.
48 49 50	196	process of
51 52 53 54	197	After the m
55 56 57 58	198	imitate the
59 60		

3	adequately sustained by the subgrade. This model was divided into 7 parts with different
4	kinds of material combinations, as shown in Figure 5. Two side areas are 10 m in length.
5	The middle of this model was divided into 5 zones all 6 m in length. The surface layer and
5	leveling layers are asphalt layers with 0.05 m thickness and 0.04 m thickness,
7	respectively. Figure 6 (a)-(e) show the side view of Area I to Area V. The base layers
3	located in Area I to Area V are gravel (Figure 6 (f)), low-density asphalt, low-density
9	asphalt, high-density asphalt, and high-density asphalt, respectively. The base layers on
)	the side of this model are also high-density asphalt, as shown in Figure 6 (g). The
1	thickness of the base layer is 0.06 m. Under the base layers of Area I, Area II and Area
2	V, nonwoven fabrics were buried. Water tanks were built on the outside of these areas
3	and continuous water injection was performed during the monitoring. Such a design
1	imitates the natural procedure of the interlayer debonding phenomenon of airport
5	pavement. The non-woven fabric can bring water into the layer bonding part to imitate the
5	process of pressing raindrops or snow into the pavement when an aircraft moves over it.
7	After the model was built, a 20-ton truck (Figure 6 (h)) repeatedly ran over the model to
3	imitate the loads imposed by the aircraft for 30 days until November 30th, 2017. Four

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1		Geophysics 15
2 3 4 5	199	GPR surveys were conducted from the initial build to the end of the 30 days load test.
6 7 8 9	200	The first measurement was performed just after the model was built. The second test was
10 11 12	201	performed after 7 days of loading and injection of water. The third measurement was
13 14 15 16	202	taken 10 days after the second measurement. And the last measurement was completed
17 18 19 20	203	by the end of the evaluation.
22 23 24	204	Three survey lines were designed at 1.08 m, 1.92 m, and 2.76 m in the X-direction.
25 26 27	205	In this way, a large number of CMPs can be collected from 0.6 m to 3.24 m with 0.12 m
28 29 30 31	206	intervals in the X direction and every 0.01 m in the Y direction. Overall, more than 100
32 33 34 35	207	thousand CMP gathers were available for further analysis in this survey area.
30 37 38 39 40	208	SIGNAL PROCESSING
41 42 43	209	The processing procedure for the proposed approach consists of three sequential
45 46 47	210	stages. Pre-processing algorithms include band-pass filtering and trace balancing of each
48 49 50	211	CMP gather to increase the overall signal to noise ratio. Subsequently, the wavelet
52 53 54 55 56 57 58 59 60	212	transform was performed in the shallow region reflection. In this paper, the asphalt

1		Geophysics 16
2 3 4 5	213	dielectric coefficient is presumed to be 4 and the wavelet analysis was performed using
6 7 8	214	a response signal from 0 to 4 ns. The 4 ns lapse signal is adequate to contain all the
9 10 11 12	215	reflecting layers compared to the 0.15 m thick pavement model. In the last stage, the
13 14 15 16	216	entropy value was calculated on the basis of the wavelet coefficients and thus the mean
17 18 19	217	entropy values of each CMP could be obtained. Finally, a 2D mean wavelet entropy map
20 21 22 23	218	of the entire measurement field is produced for interlayer debonding detection.
23 24		
25 26 27	219	The stability of the reflection signal phase is the main point of the proposed
28 29 30 31	220	approach. Ideally, the reflection of the GPR is a direct function of the coefficient of
32 33 34	221	reflection. But many factors will affect the stability of the reflection at the target boundary.
35 36 37 38	222	It will make the inspection of anomalies difficult. However, some considerations and
39 40 41	223	assumptions can be assumed to mitigate this impact by considering the airport asphalt
42 43 44 45	224	pavement properties.
46 47 48 49	225	The basic assumption of this proposed approach is that the material itself does not
50 51 52 53	226	change the reflection phase with the offset. The first assumption is the transmission loss
54 55 56 57 58 59 60	227	of the asphalt can be assumed as a constant with offset (Shang and Umana, 1999;

1		Geophysics 17
2 3 4 5	228	Jaselskis et al., 2003). Another assumption is that the asphalt is a frequency-independent
6 7 8 9	229	material for the operating bandwidth of the GPR system (Lai et al., 2011). It is a basic and
10 11 12	230	reasonable assumption of the proposed approach because it could significantly affect the
13 14 15 16 17	231	phase information of different offset reflections.
18 19 20 21 22	232	
23 24 25 26	233	Mean Wavelet Entropy
27 28 29 30	234	Compare to Fourier analysis, wavelet analysis can process a signal with different
31 32 33	235	scales and resolutions. A large window can be applied in wavelet analysis which results
34 35 36 37	236	in the global features. Similarly, analyzing a signal with a small window can pick out
38 39 40 41	237	localized features. Based on these characteristics, wavelet analysis has been
41 42 43 44	238	successfully applied in many applications, such as image analysis, transient signal
45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60	239	analysis, and other signal processing applications.

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1 2		Geophysics
2 3 4 5	240	Wavelet is a kind <mark>of smooth and fast fading wave</mark> , which has good localization both
6 7 8	241	in frequency and time. The wavelet family $\Theta_{a,b}$ is a set of basic functions, which are
9 10 11 12	242	generated by the expansion and translation of a unique mother wavelet $\Theta(t)$:
13 14 15 16 17 18	243	$\Theta_{a,b}(t) = a ^{-\frac{1}{2}} \Theta\left(\frac{t-b}{a}\right) \tag{1}$
19		
20 21	244	where t is the time, a indicates the scale parameter, and b indicates the translation
22 23		
24	245	parameter. The duration of the wavelet increases with the increase of the scale parameter
25 26		
27 28	246	a. Therefore, wavelet analysis has a unique analysis model, which uses different scales
29		
30 31	247	and variable time to analyze the signal.
32 33		
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35 36	248	The continuous wavelet transform (CWT) of a signal $s(t)$ is defined as the
37 38		
39	249	correlation between ${ m a}$ and ${ m b}$ parameters with the family wavelet $\Theta_{a,b}$
40 41		
42 43		$\frac{1}{t-h}$
44	250	$Coef(a,b;s(t)) = \int_{-\infty}^{\infty} s(t) \frac{1}{a} \Theta\left(\frac{t-b}{a}\right) dt $ ⁽²⁾
45 46		
47 48		
48 49	251	Not only will the selected wavelet affect the coefficients of a CWT, but so will the
50 51		
52	252	values of scale and position. The CWT coefficients $Coef(a,b)$ can be obtained by
55 54		
55 56	253	continuously changing the values of scale parameter \mathbf{a} and translation parameter \mathbf{b} .
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Discrete wavelet transform (DWT) provides a non-redundant representation of the signal, and its values constitute the coefficients in the wavelet transform. Wavelet coefficients can provide complete information of signals. Moreover, the local energy can be directly estimated at different scales through the wavelet coefficients. The DWT of a discrete signal s(n) can be derived from CWT and expressed as $Coef(m,u;s(n)) = \sum_{n=1}^{N} s(n) \frac{1}{a} \Theta\left(\frac{u - nb_0 a_0^m}{a_0^m}\right) =$ (4) where a_0^m indicates the discrete scale parameter and $nb_0a_0^m$ indicates the discrete translation parameter m indicates the scale parameter n indicates the translation parameter of the wavelet transform. Then, the wavelet energy of the analyzed signal can be calculated throughout the wavelet coefficients and expressed as: $Energy_m = \sum_k |Coef(m,u)|^2$ (5) Finally, the total wavelet energy can be obtained as:

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$$Energy_{total} = \sum_m Energy_m$$
(6)268Then, the relative wavelet energy can be expressed as:(7)269 $RE_m = \frac{Energy_m}{Energy_m}$ (7)270From the above equations, the relative wavelet energy RE_m can be considered as271a time-scale density and satisfies the following relationship:272 $\sum_m RE_m = 1$ (8)273This provides a suitable tool for detecting and characterizing the time and274frequency attributes of signals.275According to the relative wavelet energy and the Shannon entropy theory (Zhang)276et al., 2015), the wavelet entropy is defined and expressed as:277 $S_{WE}(p) = -\sum_m RE_m \cdot \ln (RE_m)$ (9)278A reflected signal coming from the defects or anomalies in the pavement region279can be taken as a combination of two signals. One signal is the reflection comeing from

1		Geophysics 21
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3 4 5	280	the sound pavement. The other signal is a difference signal between the signals that
6 7 8	281	come from the defective and sound pavement. This type of reflection will have its form of
9 10 11 12	282	wavelet representation and will have an important contribution to all frequency bands. As
13 14 15 16	283	a result, the relative wavelet energy of all resolution levels will be almost equal, and the
17 18 19	284	wavelet entropy will exceed the maximum value. In addition, this signal can also break
20 21 22 23	285	the stability of each CMP trace.
24		
25 26 27	286	In this study, the wavelet analysis of shallow region reflection was performed by
28 29 30 31	287	equation (4) and the wavelet coefficients were obtained. Then the relative wavelet energy
32 33 34	288	was obtained by equations (5) to (7). Next, the wavelet entropy of each CMP trace was
35 36 37 38	289	calculated by equation (9). Finally, the mean wavelet entropy of a CMP gather can be
39 40 41	290	obtained according to each CMP trace entropy value.
42 43 44 45	291	RESULTS AND DISCUSSIONS
46 47		
48 49 50	292	Field Measurement Results
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1		Geophysics 22
2 3 4 5	293	In this study, the test was carried from October 30 th to November 30 th , 2017. Four
6 7 8	294	GPR surveys were conducted from the initial build to the 30 days load test and water
9 10 11 12	295	injection. The first measurement was conducted on October 30 th . The second
13 14 15	296	measurement was conducted on November 6 th . The third measurement was conducted
17 18 19 20	297	on November 14 th . And the last measurement was conducted on November 30 th .
21		
22 23	298	Three survey lines along the Y direction were designed to cover the entire area of
24 25 26 27	299	the model during each measurement. In order to make each measurement start at the
28 29 30 31	300	same position, several markers were nailed in the survey area. The three survey lines
32 33 34	301	covered the area of 0.24 m to 3.6 m along the X direction. In this way, 23 CMP gathers
35 36 37 38	302	were obtained from 0.6 m to 3.24 m with 0.12 m intervals in the cross-survey direction (X
38 39 40 41	303	direction), and 5001 CMP gathers were obtained from 0 m to 50 m with 0.01 m intervals
42 43 44 45	304	in the survey direction (Y direction). Overall, more than 100 thousand CMP gathers were
46 47 48	305	acquired in the entire area. The B scans acquired at X=1.08 m of each survey are shown
49 50 51 52	306	in Figure 7 (a), (b), (c), and (d), respectively. The reflection from the bottom of the level
52 53 54 55 56 57 58 59 60	307	layer can be seen at approximately 0.2 m. The clear reflection around 0.5 m is the

1		Geophysics 23
2 3 4 5	308	boundary of the old pavement structure. All the reflections from the level layer are mixed
6 7 8	309	with the antenna coupling. From Figure <mark>7 (b) to (d),</mark> the effect of water injection can be
9 10 11 12	310	observed around 13 m, 31 m, and 37 m in the Y direction. However, it is hard to judge
13 14 15 16 17	311	any anomalies inside the model structure through the B scans.
18 19 20	312	Figure 8 shows the CMP gather at a point in Area I along the survey line X equal
21 22 23 24	313	to 1.08m for each of the four surveys. There is a strong difference between the first
25 26 27	314	indication of arrival before and after the injection of water. But the difference with the
28 29 30 31	315	loading test is hard to compare. The dielectric coefficient of asphalt is around 4. In this
32 33 34	316	paper, we select 0.15m/ns as the propagation velocity of the pavement model.
35 36 37 38	317	Considering the velocity of the pavement material, the reflection signals from 0 to 4 ns
39 40 41	318	were used for further processing. After the entire collection of CMP gathers were
42 43 44 45	319	processed by the proposed method, the mean wavelet entropy distribution of the entire
46 47 48	320	area was acquired, as shown in Figure 9. Figure 9 (a) shows that the mean wavelet
49 50 51 52	321	entropy value is around 0 in the entire area. But the contour of buried nonwoven fabrics
53 54 55 56 57 58 59	322	(red square in Figure 9 (a)) still can be observed and matched with Figure 5 very well. In

1		Geophysics 24
2 3 4 5 6 7 8	323	Figure 9 (b), after several days of water injection and load test, it can clearly see that the
	324	average wavelet entropy increases significantly in the area that contained the buried
9 10 11 12	325	nonwoven fabrics. But this change in Area I, II, and V is not smooth, which means that
13 14 15	326	the change of wavelet entropy is mainly caused by water injection. In other words, the
16 17 18 19	327	existence of this thin layer of water induces a greater change in the process of shallow
20 21 22	328	reflection than the thin layer of air. The average wavelet entropy of the whole experimental
23 24 25 26	329	area is changing with the progress of the experiment, as shown in Figure 9 (c) and (d).
27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 53 6 7 8 9 40 41 42 43 44 55 56 57 58 59	330	Overall, the relationship of entropy value is Area I>Area V>Area II>Area IV>Area III. The
	331	average wavelet entropy of the area of the nonwoven fabric is around 0.1 with the
	332	progress of the experiment. We believe that the pavement structure should not
	333	experience large damage during the load test. But, some regions show high entropy value
	334	at the end of this test, especially a high entropy value is appearing in Area I where the
	335	base layer is constructed by gravel. This means that the base layer constructed by gravel
	336	is the weakest structure compared to the other materials. The entropy value of the region
	337	located around 1 m in the X direction and 13 m in the Y direction is greater than 0.2, two
	338	times higher than the normal nonwoven fabrics region. At this point, we can conclude that

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339	the phenomenon of interlayer debonding has occurred in that region. From the results
340	from where no nonwoven fabrics were buried, the high entropy regions during this test
341	are around the anomalous regions in the beginning. The anomalous regions in Figure 9
342	(a) means these regions are not well constructed or the material used is non-uniform.
343	That is to say, the quality of construction and the heterogeneity of the material used both
344	have a significant effect on its service life.
345	Validation by Coring
346	In order to obtain more details during this test, on-site coring was performed
347	following the acquisition of multi-static GPR data. Three core samples were drilled in Area
348	I, where the gravel was used as the base layer. The circles with a cross marker in Figure
349	9 (d) and Figure 10 (a) indicate the location for coring. Figure 10 (b) shows the scenario
350	after coring. Figure10 (c), (e) and (g) show the coring sample of #1, #2 and #3, respectively,
351	and Figure 10 (d), (f) and (h) show the coring section of #1, #2 and #3, respectively. It can
352	be seen that the sampling of coring from #1 is uneven and some debris remains on the
353	surface of the section. But the coring sampling from #2 and #3 are relatively integral and

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1		Geophysics 26
2 3 4 5	354	the coring section surface is smooth. As a consequence, defects or anomalies occurred
6 7 8	355	in the region around #1 during the 30-day test. As seen from Figure 9 (d), coring #1 is
9 10 11 12	356	located in the high entropy region, while coring #2 and #3 are located in the relatively low
13 14 15 16	357	entropy region. The results of the coring showed that the proposed method showed
17 18 19	358	reliable and excellent efficiency in detecting the defect or anomalies of the airport
20 21 22 23	359	pavement.
24 25		
26 27	360	CONCLUSION
28		
29 30 31 32 33 34 35 36	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
36 37 38 39	363	voids that occurred at the bonding region in the shallow parts of airport pavement. The
39 40 41 42	364	existence of thin water-filled or air-filled voids can be considered an inhomogeneous layer
43 44 45 46	365	in the structure that influences the phase stability of the reflection signals in a CMP gather.
47 48 49	366	It can be expected that this form of anomaly within the layered structure can be inspected
50 51 52 53	367	by a tiny signal phase difference. During the experiment, a multi-static GPR system was
54 55 56 57 58 59 60	368	used to complete the large-scale airport pavement inspection. The antenna configuration

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2 3 4 5	369	of the system and a designed survey strategy made it possible to obtain dense CMP
6 7 8	370	datasets during a common survey simultaneously. Moreover, a wavelet transform was
9 10 11 12	371	applied to these dense CMPs to evaluate the phase details of the shallow reflection.
13 14 15 16	372	Furthermore, the mean entropy value of each CMP was used to determine the stability of
17 18 19	373	the reflection phase among surveys throughout different periods. The proposed approach
20 21 22	374	to inspecting anomalous regions in an asphalt layer has been illustrated by numerous
23 24 25 26	375	field experiments with an airport pavement model. The on-site coring results also indicate
27 28 29	376	the precision of the proposed approach. The proposed approach is easier to understand
30 31 32 33	377	and the measurement process is much simpler, allowing to implement it in real-time
34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 950 51 52 53 54 55 57 58 960	378	inspection.

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12	481	4	Measurement on the airport pavement model: (a) Entire measurement site and survey	
14 15	482		coordinate; (b) Operation of the multistatic GPR system on the site.	
16 17 18	483 484 485	5	Structure layout of the airport pavement model (plan view and sectional view (X and Y Direction)). Airport pavement model; (a) scene of Area I; (b) scene of Area II; (c) scene of Area III; (d)
19 20	486		scene of Area IV; (e) scene of Area V; (f) the gravel base layer; (g) the hot asphalt base	
21 22	487		layer; (h)20 tons truck drove over the model to imitate the load imposed by the aircraft.	
23	488	7	B scans acquired on the survey line $X = 1.08m$; (a) survey on 30th October; (b) survey on	n
24 25	489		6th November; (d) survey on 14th November; (d) survey on 30th November.	
26 27	490	8	CMP gathers acquired at the point $X = 1.08m$ and $Y = 13m$; (a) survey on 30th October; (b)
28 29	491		survey on 6th November; (d) survey on 14th November; (d) survey on 30th November.	
30 31	492	9	Mean wavelet entropy maps of the entire model: (a) entropy map of the survey on Octobe	۶r
32	493		30th; (b) entropy map of the survey on November 6th; (c) entropy map of the survey on	
33 34	494		November 14th;(d) entropy map of the survey on November 30th.	
35 36	495	10) Coring on the pavement model in Area I: (a) $\#1$, $\#2$ and $\#3$ indicated the coring position;	
37	496		(b) scenario after coring; (c) coring sample of $\#1$; (d) coring section of $\#1$; (e) coring	
30 39	497		sample of $#2$; (f) coring section of $#2$; (g) coring sample of $#3$; (h) coring section of $#3$.	
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Figure 1. Multi-static ground penetrating radar system.







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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7		Area I Area II Area III Area IV Area V
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9		4 m Gravel Low-density Low-density High-density High-density
10		Asphalt Asphalt Asphalt Asphalt
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12 13		Sectional View (Y Direction)
14		50 m
15		10 m 6 m 6 m 6 m 10 m
16		Area I Area II Area III Area IV Area V
17		5 cm Surface Layer (Asphalt)
18		
19		6 cm Base Layer Gravel Gravel Asphalt Asphalt Asphalt Asphalt Asphalt Asphalt Asphalt
20 21		4 cm Leveling Layer (Asphalt)
22	540	Nonwoven Fabrics
23	512	Base Layer
24		Sectional View (A Direction)
25		<
26		
27 28		5 cm Surface Layer
29		6 cm Base Layer
30		4 cm Leveling Lever
31	513	
32	514 515	Figure 5. Structure layout of the airport navement model (plan view and sectional view (X and Y Direction))
33	515	righte 5. Scructure by out of the disport pavement model (plan view and sectional view (x and i birection))
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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 8. CMP gathers acquired at the point X = 1.08m and Y = 13m; (a) survey on 30th October; (b) survey on 6th November; (d) 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.

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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.

	Geophysics		
		parameters	values
		system type antenna type	step frequency continues wave bowtie antenna
		frequency range	0.05 GHz to 1.5 GHz
		acquisition points	256
C		maximum movement speed	2 m/s
1		system width	2 m
2		penetration depth	larger than 2m
4		sweeping time	around 0.1 s
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₅ 557 7 558	Tabl	e 1: System Parameters of the mu	ulti-static ground penetrating radar syste
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