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硕士学位论文

探地雷达道路剥离检测的时频分析方法研究

Time-Frequency Analysis of Air-coupled GPR Data for Identification of Delamination between Pavement Layers

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摘　要

随着国家对交通基础设施的投入加大，全国高速公路的里程数日益增加，随之而来的道路工程问题也日益扩大，造成严重的社会影响和经济损失。探地雷达作为一种高性能的无损检测工具，不仅在工程勘探结果上直观准确，而且操作简便高效，在公路病害无损检测中已经得到广泛应用。然而，受限于探地雷达的工作带宽，在一些数值上需要精确测量的工程问题方面，探地雷达的分辨率仍然无法满足要求。

本文主要关注高速公路沥青面层与混凝土基层之间的剥离问题，利用时频分析工具对不同厚度薄层的雷达反射复合波频谱特性进行研究，从而提供一种道路层间剥离病害情况评估的参考依据。首先建立起沥青道路结构中间隙薄层的数值模型，利用分层介质格林函数（DGF）方法对不同薄层厚度的模型进行数值仿真实验。时域波形的结果表明，四分之一波长是最小可分辨薄层厚度，厚度四分之一波长以下相应的雷达反射信号无法分辨薄层上下界面的反射子波。利用短时傅里叶变换（STFT）对薄层反射信号进行处理，得到薄层反射瞬时频谱与薄层厚度的对应关系。结果表明，薄层反射的峰值频率及其在瞬时频谱中的幅值对薄层厚度的变化十分敏感，当薄层厚度小于四分之一波长，薄层反射的峰值频率比无薄层情况下界面反射的峰值频率要高，而峰值频率在瞬时频谱中的幅值随薄层厚度的增加而增大，通过一系列不同薄层厚度的数值仿真实验，可以总结薄层反射瞬时频谱峰值频率及其幅值随薄层厚度的变化规律，并拟合出峰值频率及其幅值与薄层厚度之间的关系曲线。本文也进行了一系列室内模拟实验，模拟沥青道路中薄层的检测，该时频分析结果得到的薄层反射瞬时频谱与薄层厚度关系，与数值仿真实验的分析结果呈现出同样的规律。道路检测中只要利用同一测量仪器事先进行标定试验，采用本文提出的方法可以提供道路剥离间隙层厚度估计的重要参考。工程上仅需要根据雷达反射信号的峰值频率与界面反射子波峰值频率的对比，观察瞬时频谱主频上升现象可以有效鉴定四分之一波长以下厚度的道路层间剥离是否存在。

关键词：探地雷达（GPR）；道路层间剥离；时频分析

Abstract

With the mileage of the highway increasing, numbers of highway engineering issues arise, which causes serious damage to the social economy. Ground Penetrating Radar (GPR) is one kind of high performance non-destructive testing (NDT) technology. With its precise and efficient performance, GPR is comprehensively used in pavement inspection. However, limited by the bandwidth, the range resolution of GPR is not high enough to resolve some kinds of engineering issues demanding extremely precision measurement.

In this paper, we focus on the air-filled delamination in pavement layers. By investigating the characteristics of the composite reflection from a thin layer using time-frequency analysis, we propose a method to detect the delamination between pavement layers. We firstly simulated GPR data from an asphalt pavement model with an embedded air gap of different thicknesses by the Green's function method. The time domain signals of the data show that quater of wavelength is the limited resolution of the thin layer. We apply time-frequency analysis on the thin layer reflection using short time Fourier transform (STFT) and find out the relation between instantaneous frequency spectrum and the thickness of thin layer. It is demonstrated that the peak frequency of the thin layer reflection and its corresponding magnitude in the spectrum is sensitive to the thickness. When thickness is less than quater of wavelength , the peak frequency is higher than that of the normal interface reflection, and the corresponding magnitude increases with the thickness. We set up a statistics analysis model between the characteristic of the instantaneous frequency spectrum and the thickness of thin layer from a series of experiment data, and a trend curve indicating the relation between the spectrum and the thickness is drawn. We also conduct indoor experiment on imitated pavement model, and the result shows the same trend of the relation between instantaneous frequency spectrum of the reflection and the

layer thickness. If a calibration test using the same equipment is conducted before the pavement inspection, it is possible to estimate the delamination thickness by the time frequency method proposed in this paper. In practice, it is a valid method to detect whether there is delamination thinner than quater of wavelength just by observing the frequency peak shift of a GPR spectrum towards a higher frequency compared to the interface reflection wavelet spectrum.

Keywords: Ground penetrating radar (GPR); delamination in pavement; time-frequency analysis

参考资料

[1]陈凤晨. 路面雷达在沥青路面检测中的应用研究[D]. 哈尔滨：哈尔滨工业大学,2006,1-2
[2]乔雪峰. 我国高速公路总里程突破13万公里[N]. 人民网, 2016年12月26日
[3]张全升. 高速公路路面和路基病害检测理论与方法研究[D]. 北京：中国地质大学,2007,1-6
[4]谢源. 探地雷达在高速公路病害检测中的应用[J].无损检测,2014, 36(7): 89-92
[5]董荣伟. 地质雷达在高速公路病害检测中的应用分析与研究[J].工程地球物理学报,2009, 6(5): 89-92
[6]谷宪明. 季冻区道路冻胀翻浆机理及防治研究[D]. 长春：吉林大学,2007,1-13
[7]郭寅川. 重交通高等级公路沥青路面层间处治技术研究[D]. 西安：长安大学,2009,1-19
[8]孟美丽. 国内外道路无损检测技术概述[J].山西建筑,2010, 36(33): 278-279
[9]T. Saarenketo, T. Scullion. Road evaluation with ground penetrating radar[J]. Journal of Applied Geophysics, 2000, 43(2-4): 119 – 138
[10]M. Solla, H. Lorenzo, J. Mart í nez-S á nchez, et al. Applications of GPR in Association with Other Non-destructive Testing Methods in Surveying of Transport Infrastructures[J]. Civil Engingeering Applications of Ground Penetrating Rdar, 2015, 327 – 342.
[11]J. Stryk, R.Matula, K. Pospisil.Possibilities of ground penetrating radar usage within acceptance tests of rigid pavements[J]. Journal of Applied Geophysics, 2013, 97: 11 – 26
[12]L. Krysi ń ski and J. Sudyka. GPR abilities in investigation of the pavement transversal cracks[J]. Journal of Applied Geophysics, 2013, 97: 27 – 36
[13]Z. Leng, I. L. Al-Qadi, S. Lahouar. Development and validation for in situ asphalt mixture density prediction models[J]. NDT &E International, 2011, 44(4): 369-375
[14]L. Krysi ń ski, J. Sudyka. Typology of reflections in the assessment of the interlayer bonding condition of the bituminous pavement by the use of an impulse high- frequency ground-penetrating radar[J]. Nondestructive Testing and Evaluation, 2012, 27(3): 219 – 227
[15]杜齐喜. 探地雷达在地雷探测中的应用研究[D]. 长春：吉林大学,2007,8-11
[16]邹海林, 宁书年, 林捷. 小波理论在探地雷达信号处理中的应用[J]. 地球物理学进展, 2004, 19(2): 268-275
[17]曾昭发. 探地雷达方法原理及应用[M]. 北京:科学出版社,2006, 138-164
[18]曹雪山, 郑长江, 蔡亮. 高等级公路沥青路面结构的探地雷达检测技术[J]. 洛阳大学学报, 2002, 17(4): 73-75
[19]A. Loizos, C. Plati. Accuracy of pavement thicknesses estimation using different ground penetrating radar analysis approaches[J]. Ndt & E International, 2007, 40(2):147-157
[20]A. Loizos, C. Plati. Accuracy of Ground Penetrating Radar Horn-Antenna Technique for Sensing Pavement Subsurface[J]. IEEE Sensors Journal, 2007, 7(5):842-850
[21]A. Benedetto, F. Tosti, L. B. Ciampoli, et al. An overview of ground-penetrating radar signal processing techniques for road inspections[J]. Signal Processing, 2016, 132:201-209
[22]V. D. W. Andrey. Characterization of thin layers into concrete with Ground Penetrating Radar[D]. Belgium: University of Liege, 2014
[23]M. B. Widess. HOW THIN IS A THIN BED?[J]. GEOPHYSICS, 1973, 38(6), 1176 – 1180
[24]X. D é robert, C. Fauchard, P. Côte, et al. Step-frequency radar applied on thin road layers[J]. Journal of Applied Geophysics,2001, 47(3 – 4): 317 – 325
[25]S. Zhao, P. Shangguan, I.L. Al-Qadi. Application of regularized deconvolution technique for predicting pavement thin layer thicknesses from ground penetrating radar data[J]. Ndt & E International, 2015, 73:1-7
[26]J. Xia, E.K. Franseen, R.D. Miller. Application of deterministic deconvolution of ground-penetrating radar data in a study of carbonate strata[J]. Journal of Applied Geophysics, 2004, 56: 213-229
[27]N. Economou, A. Vafidis, H. Hamdan, et al. Time-varying deconvolution of GPR data in civil engineering[J]. Nondestructive Testing & Evaluation, 2012, 27(3):285-292

[28]S. Zhao, I.L. Al-Qadi. Development of regularization methods on simulated ground-penetrating radar signals to predict thin asphalt overlay thickness[J]. Signal Processing, 2017, 132: 261-271
[29]C.L. Bastard, V. Baltazart, Y. Wang, et al. Thin-Pavement Thickness Estimation Using GPR With High-Resolution and Superresolution Methods[J]. IEEE Transactions on Geoscience & Remote Sensing, 2007, 45(8):2511-2519
[30]X. W. Zhang, Y. Z. Gao, G. Y. Fang. Application of Hilbert spectrum analysis in ground penetrating radar thin layer recognition[J]. Chinese Journal of Applied Geophysics, 2013, 56(8): 2790 – 2798
[31]A. Benedetto. Water content evaluation in unsaturated soil using GPR signal analysis in the frequency domain[J]. Journal of Applied Geophysics, 2010, 71(1):26-35
[32]F. Tosti, A. Benedetto, L.B. Ciampoli, et al. GPR analysis of clayey soil behaviour in unsaturated conditions for pavement engineering and geoscience applications[J]. Near Surface Geophysics, 2016, 14(2): 127-144

[33]S. Guha, S.E. Kruse, E.E. Wright, et al. Spectral analysis of ground penetrating radar response to thin sedimentary layers[J]. Geophysical Research Letters, 2005, 32(23)
[34]S. Guha, S. Kruse, P. Wang. Joint time-frequency analysis of GPR data over layered sequences[J]. The Leading Edge, 2008, 27(11): 1454-1460
[35]F. T. Ulaby, D. G. Long, W. J. Blackwell, et al. Microwave radar and radiometric remote sensing[M]. The University of Michigan Press, 2015
[36]M. Sato, Z. Deng. GPR Reflection Signal from a Thin Layer[C]. The 134th SEGJ CONFERENCE, Tokyo, 2016, 47-50
[37]H.M. Jol. Ground Penetrating Radar: Theory and Applications[M]. The Netherlands: Elsevier B.V., 2009, 1-16
[38]李大心. 探地雷达方法与应用[M]. 北京: 地质出版社, 1994
[39]刘四新,曾昭发. 频散介质中地质雷达波传播的数值模拟[J].地球物理学报,2007, 50(1): 320-326
[40]胡来平,刘占军. 电磁学计算方法的比较[J].现代电子技术,2003, 153(10): 75-78
[41]K. S. Yee. Numerical solution of initial boundary value problems involving maxwell's equations in isotropic media[J]. IEEE Transactions on Antennas & Propagation, 1966, 14(3):302-307.
[42]J. Irving,R. Knight. Numerical modeling of ground-penetrating radar in 2-D using MATLAB[J].Computers & Geoscience,2006, 32: 1247-1258
[43]冯彦谦, 王银, 刘四新. 基于FDTD的探地雷达数值仿真与成像研究[J].铁道工程学报,2009, 129(6): 17-20
[44]Q. H. Liu. Computational Electromagnetics[M]. USA: Duke ECE 577 Classnotes, 2016, 139-154
[45]K.A. Michalski. Multilayered media Green's functions in integral equation formulations[J]. IEEE Transactions on Antennas and Propagation, 1997, 45(3): 508-519
[46]徐利明, 聂在平, 王军. 半空间电场型并矢格林函数及其数值计算[J].电子科技大学学报,2004, 33(5): 485-488
[47]方大纲. 分层介质中并矢格林函数的一般表示形式[J].华东工程学院学报,1984, 1: 55-62
[48]冯宁宁. 分层介质电_磁流场_位谱域并矢格林函数的统一形式[J].电波科学学报,1998, 13(4): 335-340
[49]K.A. Michalski. Extrapolation methods for Sommerfeld integral tails[J], IEEE Transactions on Antennas and Propagation, 1997, 45(3): 1405-1418

[50]M. Pieraccini, G. Luzi, L. Noferini, et al. Joint time-frequency analysis for investigation of layered masonry structures using penetrating radar[J]. IEEE Transactions on Geoscience and Remote Sensing, 2004, 42(2), 309 – 317
[51]N. Economou, A., Vafidis. Spectral balancing GPR data using time variant band-width in t-f domain[J]. Geophysics, 2010, 75(3):19-27

[52]A. Majkowski, M. Kołodziej, R. J. Rak. Joint Time-Frequency And Wavelet Analysis - An Introduction[J]. Metrology & Measurement Systems, 2014, 21(4):741-758
[53]I.L. Al-Qadi, S. Lahouar. Measuring layer thicknesses with GPR – Theory to practice[J]. Construction and building materials, 2005, 19(10): 763-772
[54]J. Garcia, K. Hansen. HMA pavement mix type selection guide[M]. National Asphalt Pavement Association, 2001
[55]李如敏. 半刚性基层沥青路面裂缝成因分析及处治对策[J]. 现代交通技术, 2007, 4(4):10-12
[56]M. Heitzman, K. Maser, N.H. Tran, et al. Nondestructive Testing to Identify Delaminations Between HMA Layers[M]. Transportation Research Board, 2013
[57]H. Liu, M. Sato. Determination of the phase center position and delay of a Vivaldi antenna[J]. IEICE Electronics Express, 2013, 10(21): 20130573-20130573
[58]K.Z. Jadoon, S. Lambot, E.C. Slob, et al. Analysis of horn antenna transfer functions and phase-center position for modeling off-ground GPR[J]. IEEE Transactions on Geoscience and Remote Sensing, 2011, 49(5): 1649-1662
[59]M.K. Karkkainen. Subcell FDTD modeling of electrically thin dispersive layers[J]. IEEE transactions on microwave theory and techniques, 2003, 51(6): 1774-1780
[60]H. Liu, X. Xie, J. Cui, et al. Groundwater Level Monitoring for Hydraulic Characterization of an Unconfined Aquifer by Common Mid-point Measurements using GPR[J]. Journal of Environmental and Engineering Geophysics, 2014, 19(4): 259-268
[61]H. Liu, M. Sato. In situ measurement of pavement thickness and dielectric permittivity by GPR using an antenna array[J]. NDT&E International, 2014, 64: 65 – 71