Tunnelling and Underground Space Technology 82 (2018) 50–65

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

Numerical modeling for karst cavity sonar detection beneath bored cast in situ pile using 3D staggered grid finite difference method

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ARTICLE INFO

Keywords:
Geo-investigation
Karst
FDTD
Underground construction

ABSTRACT

Karst cavities beneath bored cast in situ piles constitute substantial dangers to the stability and quality of underground construction projects. Therefore, it is important to detect and image these karst cavities before the construction of piles for such projects. New sonar detection methods, which have advantages such as low cost and high efficiency, can ensure the quality of the bedrock for underground construction projects. In this study, a three-dimensional (3D) hole-bedrock-cave model for the sonar detection of karst cavities was developed using the finite difference time domain (FDTD) method. The modeling parameters were calibrated with measured data, and the numerical results were then compared with measured field detection data to validate the reliability of the proposed method. The numerical results revealed the following findings. (1) The waves transmitted to the center of the pile hole bottom can be divided into three types: the waves traveling upward into the slurry that are absorbed by a perfectly matched layer (PML) and can be ignored, the waves traveling horizontally along the hole bottom that constitute the primary interference during the detection process, and the waves traveling downward into the bedrock that represent the effective detection signal. To minimize the negative effects of multiple reflections from the pile hole wall, we deployed a receiver at the midpoint between the transmission point and the hole wall, at which location the signals from the multiple reflections are symmetrical and easy to identify. (2) The reflected signals generated from different depths, sizes and directions of cavities have different travel time features that make it possible to estimate the depth, size and direction of a cavity beneath a pile. (3) The velocities of multiple surface wave reflections can be predicted in the frequency spectrum of a test signal and then used to predict the arrival times of multiple surface wave reflections and identify reflected P-waves. (4) Cavities have a focusing effect on waves when they are completely filled with a low-velocity medium. The energy of a wave reflected from the floor of a karst cavity after focusing is theoretically stronger than that reflected from the roof of a karst cavity. (5) PMLs can effectively absorb waves reflected from artificial boundaries to avoid false interference. High-order FDTD methods can eliminate numerical dispersion and reduce the computational costs. In general, the sonar detection of karst cavities beneath bored piles can be simulated using a 3D high-order staggered grid finite difference method and PMLs. This numerical modeling scheme is reliable and can improve the accuracy and feasibility of practical detection experiments.

1. Introduction

Karst landforms are widely distributed throughout the world. Unfortunately, disasters associated with geological karst environments are considered the most dangerous factors in underground construction projects (Ford and Williams, 2013; Li et al., 2017), particularly since karst terrains constitute special problems that include vulnerable soils and unpredictable ground surface instabilities (Li et al., 2013). For instance, although bored cast in situ piles are commonly applied during underground construction endeavors in karst areas, karst cavities beneath pile bottoms represent potential geological disasters (Elmahdy et al., 2012). Therefore, undetected and untreated karst cavities located under piles are highly dangerous, as they could lead to the leakage of slurry, the burial or collapse of the borehole, the cracking of

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https://doi.org/10.1016/j.tust.2018.07.034
Received 27 March 2018; Received in revised form 11 July 2018; Accepted 29 July 2018

Table 1
Comparison of detecting method for the karst cavity under pile bottom.

Method	Theory	Suitable for detecting karst cavity beneath a pile?	Additional drillings required	Detection extent	Detection precision	Whether it can used with slurry in the hole	Evaluation
Macro-geological analysis	Macroanalysis base on geological data	No	–	–	–	–	The prediction result is macroscopic and cannot be used to make an accurate judgment
High-density apparent resistivity	Determine the conductive differences between the rocks and karst features	No	–	–	–	–	The infill of a karst cavity is complex. It is difficult to determine the corresponding conductivity.
Traditional seismic reflection	Employs an artificial source to detect ground velocity variations	No	–	–	–	–	The bottom of the hole must be kept dry and smooth, which cannot be achieved in a bored pile.
Ground-penetrating radar	Determine the dielectric differences among underground media	No	–	–	–	–	The transmitting and receiving antenna must be placed at the bottom of the pile hole, which is not possible in a bored pile.
Transient electromagneticmethod	Measure the subsequent decay response of induced electric and magnetic fields	No	–	–	–	–	The tests are easily disturbed by metal structures, cables, etc.
Elastic wave CT	Subsurface tomographic imaging method	Yes	Need 2–5 drillings	Between the tested boreholes	More than 0.2 m	No	Two boreholes are needed to apply the CT method. The method cannot recognize karst features outside the profile between two test holes.
Guided wave testing	Use tube waves to obtain information on the strata or lithology	Yes	Need 1 drilling	Approx. 1 m around the borehole	More than 0.3 m	No	The test depends on the advanced drillings at the pile position. The direction of a karst feature cannot be recognized.
Advance drillings	Advance drillings at the pile bottom	Yes	Need 1–5 drillings	Within the drilled borehole	Based on the number of boreholes	No	Too few drillings could easily lead to a false negative. Excessive drillings for each pile make the geotechnical investigation too complex and time-consuming.
Sonar detection	Transmit elastic waves from the pile bottom to detect karst cavities beneath the pile	Yes	No need	Approx. 8 m under the pile	More than 0.1 m	Yes	The method does not need additional drillings, and it can be used in construction. It has the advantages of a low cost and high speed.