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THEMATIC ISSUE

Application of seismic velocity tomography in investigation of karst collapse hazards, Guangzhou, China

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Abstract
This paper describes seismic velocity tomography applied to the investigation and assessment of karst collapse hazards to facilitate accurate characterization of geological conditions of karst sinkhole formation. In the survey areas of Xiamao, Guangzhou, China, and Huangchi, Foshan, China, seismic velocity tomography was used to explore the structures of rock and soil associated with karst collapse. The results show that sand intercalated with clay or clay intercalated with soft soil dominates the cover of these two areas. The overburden is 20–33 m thick and underlain by Carboniferous limestone. In the limestone, there are well-developed karst caves and cracks as well as highly fluctuating bedrock surfaces. The seismic velocities are less than 2500 m/s in the cover, 2500–4500 m/s in the karst fracture zones and caves of Xiamao, and 1500–2000 m/s in the Huangchi collapse area. The karst fracture zones, relief of bedrock surfaces, and variations of soil thicknesses revealed by seismic velocity tomography are well constrained and in agreement with those in the drilling borehole profiles. This paper demonstrates that seismic velocity tomography can delineate anomalies of rock and soil with the advantages of speed, intuitive images, and high resolution.

Keywords Seismic velocity tomography · Low-velocity anomaly cover · Karst cave · Fractured zone · Bedrock surface · Karst collapse

Introduction

Karst collapse is a primary geologic hazard in karst terrains. With the rapid development in China, such hazards are occurring more frequently, causing severe economic losses and adverse impacts on the society (Lei and Jiang 1998;Lei et al. 2009; Zong et al. 2007). Because karst collapse often happens unexpectedly owing to various factors, its prevention and management remain major challenges. Thus, clarification of the formation conditions, generation mechanisms, and distribution rules is of great importance for the security of life and property and for promoting sustainable development of the economy.

In general, special geologic conditions are responsible for occurrence of karst collapse. Research indicates that such collapse is likely to happen in areas with many karst caves and soil caves, and loose and thin cover (Cheng and Huang 2002). Therefore, an understanding of the distribution of karst and soil caves and the behavior and thickness of cover is important in early warning and prevention of karst collapse (Sheehan et al. 2005; Šumanovac and Weisser 2001; Cardarelli et al. 2010; Carpenter and Higuera-Diaz 2003). Seismic velocity tomography (also known as computerized tomography) is a fast and economic tool that can accurately explore the form, scale, and location of subsurface karst (Li et al. 2011; Meng and Wang 2008; Sagong et al. 2012; Hultunen and Cramer 2008). This paper first presents the principles and technical requirements of seismic velocity tomography. Then, taking the Xiamao area of Guangzhou,

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China and the Huangchi area of Foshan, China as examples, it describes how to apply the seismic velocity tomography method to investigate and assess karst collapse hazards. The results provide scientific evidence for the evaluation and management of karst collapse in these two areas and contribute to the body of research on karst collapse in China.

Seismic velocity tomography exploration technology

Principle of seismic velocity tomography

The seismic velocity tomography (or computerized tomography) method is also called seismic perspective tomographic imaging technology (Jackson et al. 2001; Cardarelli et al. 2010). It is based on the classical Radon transform or generalized Radon transform and is described as follows. Assume $u(x,y)$ is a sufficiently smooth binary function defined on the x–y plane, which becomes zero outside a sufficiently large domain. L is an arbitrary straight line in this plane. Then, the integration of $u(x,y)$ along the line L is called the Radon positive transform, which is written as (Reference):

$$Ru = \int_L u(x, y)\mathrm{d}s \quad (1)$$

where ds is the element of line length. Usually, u is the image and Ru is the projection of this image.

In cross-borehole seismic velocity tomography, if the velocity variation between medium layers is small, or the wave impedance difference is small, the ray path of the initial waves can be approximated by a straight line. In this case, the distribution function of the velocity (or slowness) of the stratum medium in space is just $u(x,y)$ in Eq. (1), and the multiple ray paths from the source to the receiver constitute the so-called straight line cluster, i.e., L in Eq. (1). Thus, the travel time of the initial waves can be regarded as the classical Radon positive transform of the slowness function of seismic waves in the subsurface medium. An inverse Radon transform allows this slowness function (reciprocal of velocity) to be reconstructed. If the wave impedance contrast of the subsurface medium is relatively large, the ray path of the initial waves is a curve, which cannot be approximated by a straight line. In this sense, the travel time of the initial waves should be viewed as the generalized Radon transform of the slowness of seismic waves. Correspondingly, reconstruction of this slowness requires the generalized Radon inverse transform.

Seismic velocity tomography has various recording modes and imaging algorithms. This work uses direct waves to reconstruct the subsurface velocity distribution in terms of joint iteration. The basic idea of seismic tomography can be described as follows. The study area consists of a finite number of rock units. Each rock unit has distinct attributes and structures, and thus variable seismic wave velocities. Using travel times of seismic rays, the velocity of each unit is inverted, and images of the velocity distribution of the subsurface are obtained. Then, these images are interpreted geologically, yielding the final results of exploration. The basic principle of seismic velocity tomography is shown in Fig. 1.

Case studies

Instruments and their working parameters The data acquisition system used in the field was composed of a Mark 6 seismograph (ABEM Company, Sweden), an Impulse Generator IPG1005 high-voltage supply with main frequency over 1000 Hz, and a BHC-3 with 12-channel receiver (manufactured by Geotomographie GmbH, iGermany).

Data acquisition in the field The recording mode of seismic velocity tomography is the common receiver gather, which is a fan-shaped tomography system with one transmitter and multiple receivers, as shown in Fig. 2 (Angioni et al. 2003; Deceuster et al. 2006; Jackson et al. 2001; Liu et al. 2003; Nath et al. 1996; Park et al. 2014; Sagong et al. 2012). Seismic waves are excited successively at all points of the exciting borehole. After each excitation, direct waves are received simultaneously at all sites of the receiving borehole (keeping hydrophones fixed). The spacing of excitation and receiver sites is 1 m. The sampling interval is 0.1 ms, and the recording length is 4096 in total. When the hydrophones are shifted, at least one measurement point is repeated to ensure consistency of the acquisition times at the repeated points. Integrated waveforms from seismic velocity tomography acquisition are shown in Fig. 3.

Xiamao collapse site The Xiamao collapse occurred close to the Xiamao bus station in Baiyun district of Guangzhou. It lies on the north edge of the Zhujiang Delta alluvial plain with flat terrain. This site collapse damaged many houses, one of which at the center sunk into the subsurface completely. Many buildings became vulnerable, forcing inhabit-

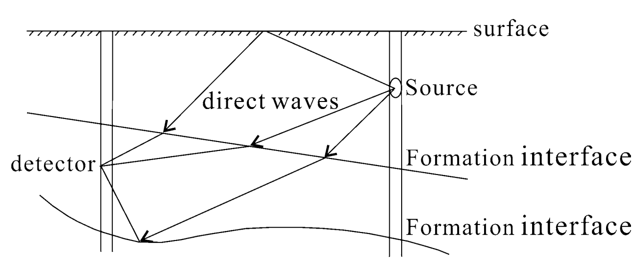

Fig. 1 Principle of cross-borehole seismic velocity tomography

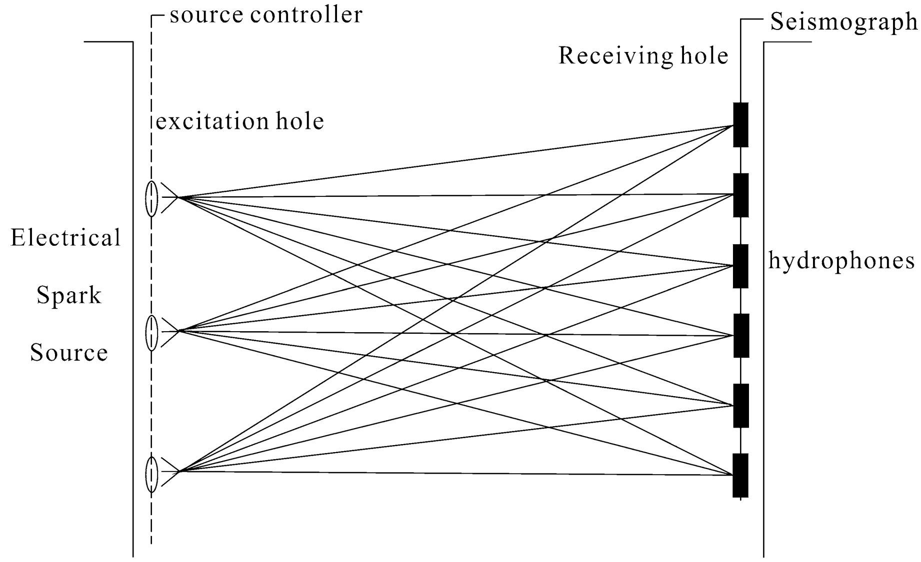

Fig. 2 Sketch showing principle of cross-borehole common receiver gather

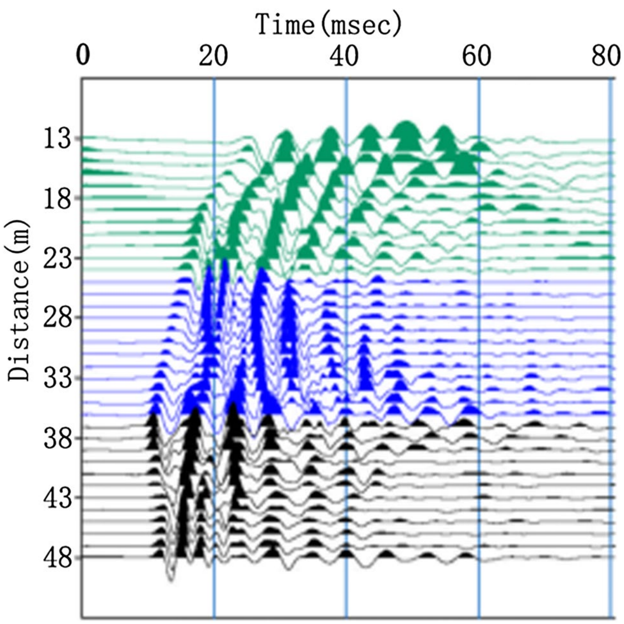

Fig. 3 Integrated waveforms from seismic velocity tomography acquisition

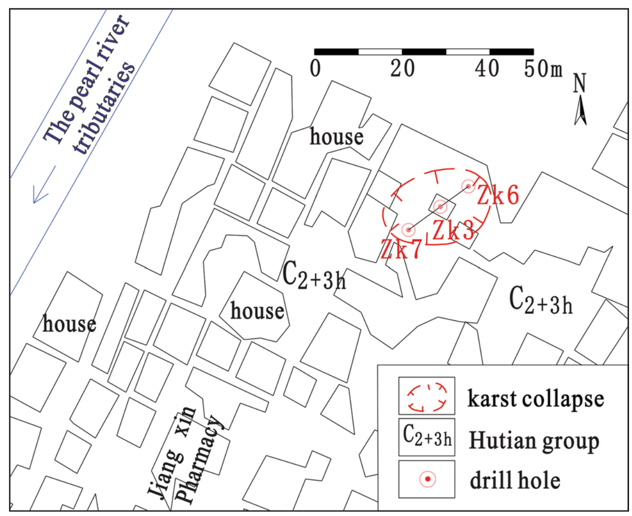

Fig. 4 Sketch map showing Xiamao collapse site

ants to evacuate. The lithology of the site is dominated by gray-white, gray, or red thick limestone with cryptocrystalline structure, intercalated with dolomitic and brecciform limestone of the Hutian Group (C2 + 3 h) of Carboniferous age. It belongs to marine carbonate deposits with a thickness over 150 m. Complicated faults are distributed in this area, and the major faults trend NE and nearly EW in the northeastern and northwestern parts of the study area, respectively. The collapse location is shown in Fig. 4, where groundwater is shallow, about 3.5 m below the surface.

In the Xiamao collapse site, five cross-borehole seismic velocity tomography profiles were completed, and representative profile zk6–zk7 was chosen for analysis (Fig. 5). This site is characterized by intact cover and limestone, karst fracture zones, and karst caves showing considerable velocity differences. The seismic velocities for some rocks and soils are listed in Table 1.

Examination of the colored contours in the seismic velocity profile permits lithology, karst forms, and distribution to be inferred for the target area. As shown in Fig. 5, the upper portion of the cross-borehole profile has smaller velocity (blue) values, while the lower portion has larger velocity (red) values, and between them is medium velocity (green). Dense contours appear in the vicinity of depths 24–30 m, so this is the boundary between high and low velocities, or

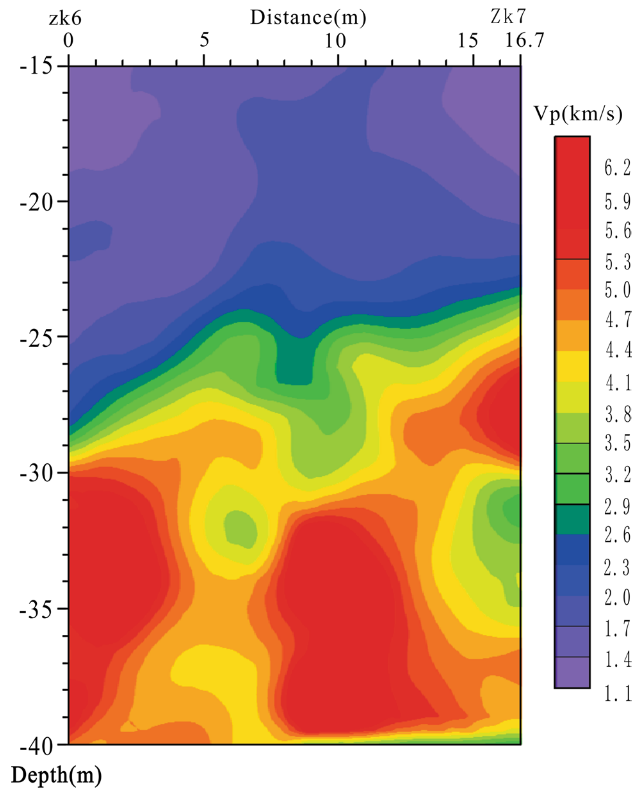

Fig. 5 Seismic velocity model for profile zk6–zk7

between the cover and bedrock with high relief (about 6 m). In the central profile, with depths of 15–25 m, darker colors represent wave velocity values greater than 2300 m/s; these values are obviously larger than on either side, showing a narrow pattern in the upper portion and broad pattern in the lower portion, speculating the range of disturbed soil. Very likely, this portion is an old soil cave that was refilled with detritus during the collapse. On the surface of the bedrock, there is a "U"-shaped low-velocity area (< 3800 m/s) shown by green that is much different from the surrounding intact limestone. This is inferred to be a karst trough on the bedrock. About 7 m away from borehole zk6 and nearby zk7, at depths of 30–40 m, a bead-shaped green and yellow area surrounded by red, with velocity less than 4400 m/s, is speculated to be karst caves. These interpretations are largely consistent with the real cases revealed by the boreholes (Fig. 6). Specifically, two sets of bead-shaped karst caves, one including R1, R2, and R3, and the other including R5 and R6, have been developed in the bedrock area of low velocity. Of these, R1 opens upward and links to sand–soil of the overlying cover, while R5 and R6 connect with R1 through karst fracture zones.

Collapse site at Huangqi Second Middle School Huangqi Second Middle School is located on the west side of Guangzhou, between Qingyong and Chenxi villages in Foshan, in the transition between low hills and plains of the Zhujiang Delta. The survey area lies in an alluvial plain with flat terrain. Its primary strata are from the lower Carboniferous Dengzi Group (C_{1s}), consisting of dark gray and gray-black limestone, dolomitic limestone, and bioclastic limestone with local carbonaceous shale and sandstone. Thin films are filled along suture planes of the limestone. Overall, the landform of this area is a trough trending NE, with local funnels of ancient karst, where groundwater is as shallow as 4 m below the surface. The survey area lies at the southern part of the southeast flank of the Guanghua complex syncline, where many folds and faults are developed. Field investigations suggest that the collapse trend is consistent with the strike of faults.

Due to the ground collapse, the Huangqi Second Middle School had to be closed. In the subsequent investigation, drilling and seismic velocity tomography exploration were carried out. The location of the collapse is shown in Fig. 7.

Six seismic velocity tomography profiles were measured across the collapse, and representative profile zk2–zk3 was chosen for analysis (Fig. 8). Here, the velocities of soil beds, karst caves, and fracture zones are less than that of intact limestones, which are illustrated by low-velocity areas on the images, differing much from the area of intact limestones. The velocities of soil beds at the site are listed in Table 2.

From the pattern of colored contours on the profile (Fig. 8), a boundary between low and high velocities, marked by dense contours, is present at depths of 25–27 m, which is also the interface between cover and bedrock. Blue characterizes the portion above this boundary, meaning a low-velocity area. The whole bedrock surface has a gentle relief. Close to zk3, the low-velocity layer becomes thicker, presumably implying the existence of karst troughs. Below the bedrock surface, at

Table 1 Velocities of selected rocks and soils at the Xiamao site

Medium	Cross-hole velocity (km/s)	Features of drilling core
Competent limestone	≥ 5.0	Intact, long, or short column, without karst cave
Fissured limestone	4.5–5.0	Short column or fragment, with fissures and cracks, locally small voids (less than 10 cm)
Fractured rocks caves	2.5–4.5	Big or bead-shaped caves, mostly mud filled
Soil	≤ 2.5	Above bedrock surface, saturated, likely with local isolate weathered relics of rock mass

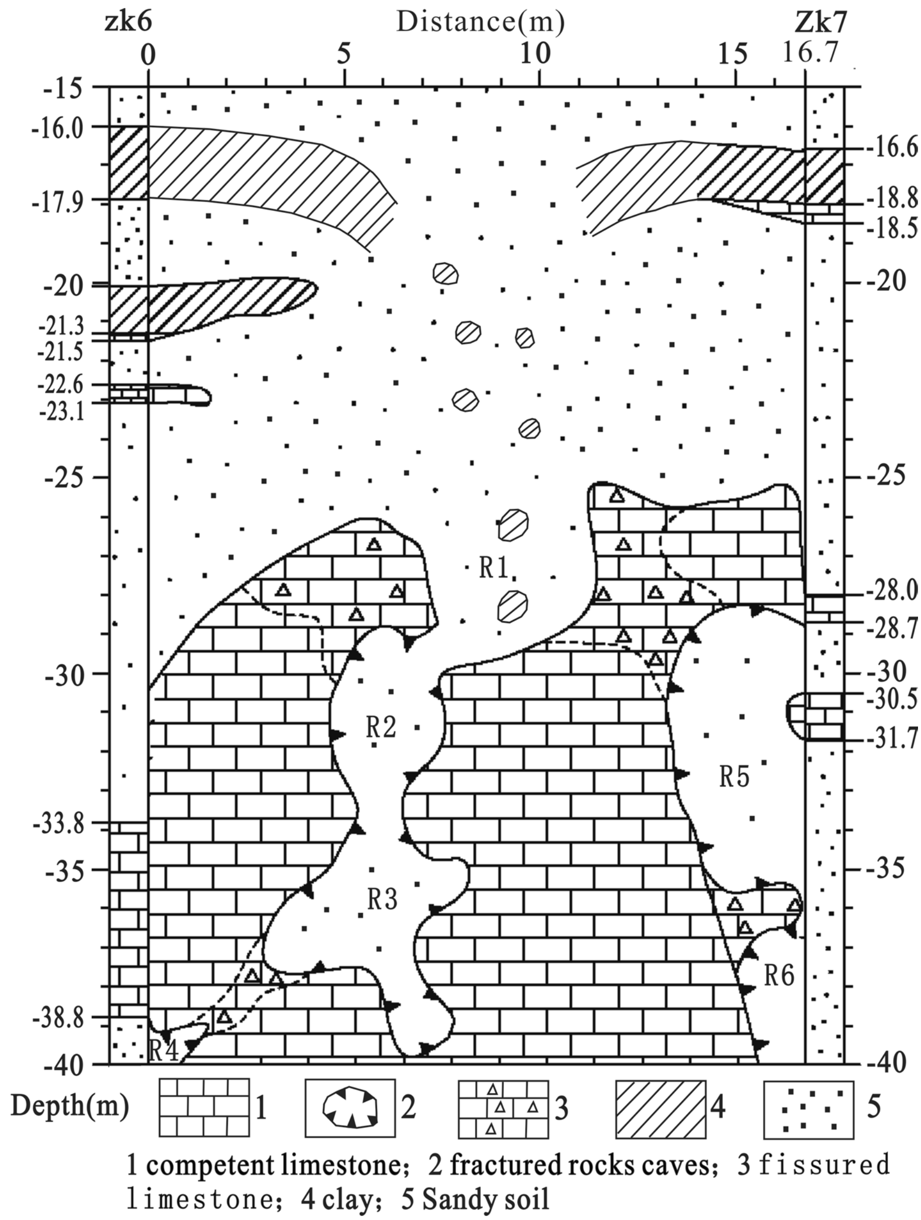

Fig. 6 Interpreted geological profile zk6–zk7

depths of 29–39 m near zk3, there is a low-velocity (blue) area of < 2500 m/s, likely caused by karst caves. Within the cover, a low-velocity (light-blue) area of < 1200 m/s is interpreted to be soft soil, as confirmed by drilling. It is mainly distributed on the surface (3–6 meters) of bedrock, and it is more than 15 meters in thickness in the middle of the section (Fig. 9).

Comparison of drilling data indicates that the low-velocity anomaly areas (< 2500 m/s) coincide well with the locations of the karst caves R7, R8, and R9 in boreholes. Thus, the wave velocity of 2500 m/s can be defined as the limit of the distribution of karst caves.

Conclusions

This paper presents a seismic velocity tomography exploration of two karst collapse sites located in the Xiamao area of Guangzhou and Huangchi area of Foshan. The

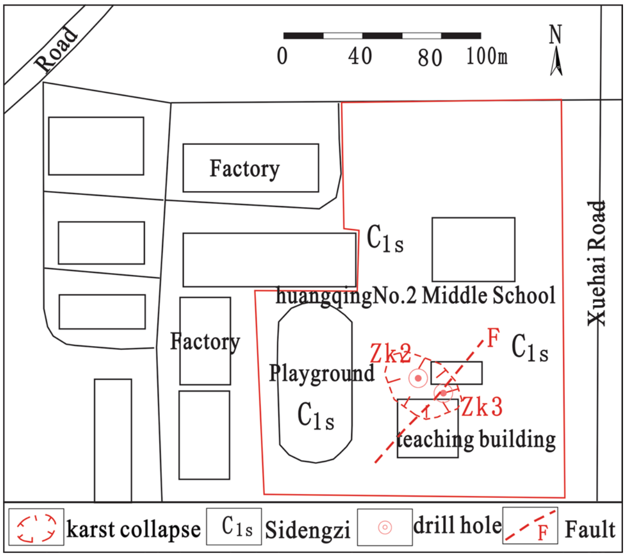

Fig. 7 Sketch showing collapse site at Huangqi Second Middle School

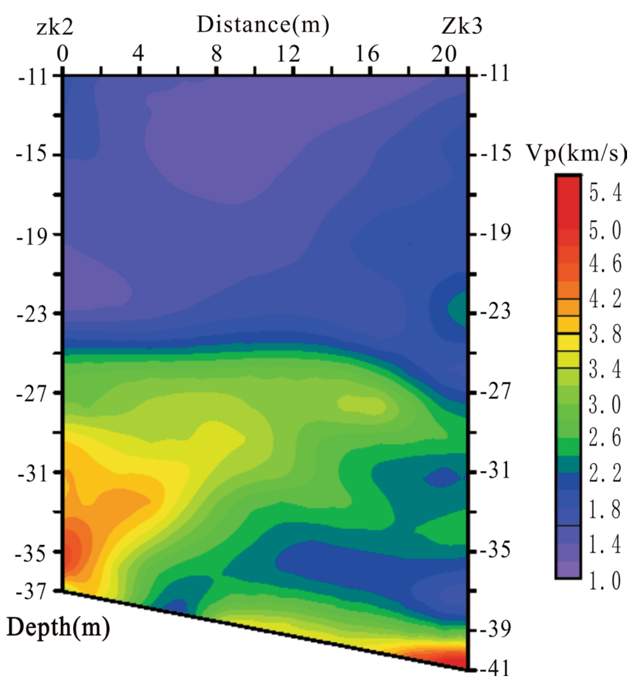

Fig. 8 Seismic velocity model for profile zk2–zk3

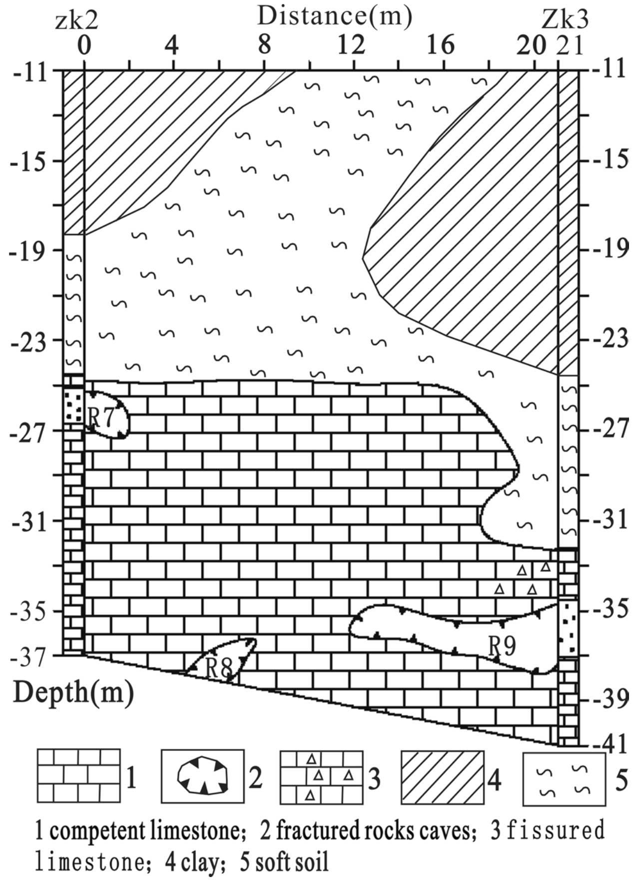

Fig. 9 Interpreted geological profile zk2–zk3

results show that seismic velocity tomography is an effective high-resolution tool that permits fast and accurate characterization of the rock and soil beds, disturbed soil, bedrock relief, fracture zones, and spatial distribution of karst features such as karst caves, revealing the real geology of the target sites, which provides reliable geological basis for geological hazard assessment of karst collapse.

Table 2 Velocities of selected rocks and soils at the Huangqi Second Middle School site

Medium	Cross-hole velocity (km/s)	Features of drilling core
Competent limestone	≥ 4.0	Complete core, long or short column shape, no karst cave
Fissured limestone	2.5–4.0	Short column or fragment, with fissures and cracks, locally small voids (less than ten cm)
Fractured rocks caves	1.5–2.5	Big or bead-shaped caves, mostly mud filled
Soil	≤ 2.0	Above bedrock surface, saturated, likely with local isolate weathered relics of rock mass

References

Angioni T, Rechtien RD, Cardimona SJ, Luna R (2003) Crosshole seismic tomography and borehole logging for engineering site characterization in Sikeston, MO, USA. Tectonophysics 368(1):119–137

Cardarelli E, Cercato M, Cerreto A, Di Filippo G (2010) Electrical resistivity and seismic refraction tomography to detect buried cavities. Geophys Prospect 58(4):685–695

Carpenter PJ, Higuera-Diaz IC, Thompson MD, Atre S, Mandell W (2003) Accuracy of seismic refraction tomography codes at karst sites. In: Symposium on the application of geophysics to engineering and environmental problems, pp 832–840

Cheng X, Huang RQ (2002) Geological conceptive models of karst collapse. Hydrogeol Eng Geol 29(6):30–34

Deceuster J, Delgranche J, Kaufmann O (2006) 2D cross-borehole resistivity tomographies below foundations as a tool to design proper remedial actions in covered karst. J Appl Geophys 60(1):68–86

Hiltunen DR, Cramer BJ (2008) application of seismic refraction tomography in karst terrane. J Geotechn Geoenviron Eng 134(7):938–948

Jackson PD, Gunn DA, Flint RC, McCann DM, Bent M, Howes D (2001) Cross-hole seismic measurements for detection of disturbed ground beneath existing structures. NDT&E Int 34(2):155–162

Lei MT, Jiang XZ (1998) Research on the present situation and developing tendency of karst collapse and techniques for its supporting. Chin J Geol Hazard Control 9(3):1–6

Lei JS, Yang JS, Xiao WQ, Liu CJ (2009) Analysis of forming conditions and main influential factors of karst collapse in Guanzhou. Geol Explor 45(4):488–492

Li HG, Xu YM, Guan FJ, Cui ZG (2011) Discussion on applications of seismic wave CT technology for survey pile location of some passenger dedicated line in karst area. Railway Investig Surv 37(1):61–64

Liu HG, Xu HG, Song WR (2003) Crosshole ultrasonic tomography and its application to karst investigation. Earthq Sci 16(4):441–448

Meng XB, Wang Y (2008) Application of CT technique for earthquake in investigation of karst along Ha'erbin-Dalian passenger dedicated line. Railway Investig Surv 34(6):56–60

Nath SK, Pani A, Sengupta S (1996) Forward modelling in crosshole seismic tomography using reciprocity. Comput Struct 61(5):805–817

Park MK, Park S, Yi MJ, Kim C, Son JS, Kim JH, Abraham AA (2014) Application of electrical resistivity tomography (ERT) technique to detect underground cavities in a karst area of South Korea. Environ Earth Sci 71(6):2797–2806

Sagong M, Park CS, Lee B, Chun BS (2012) Cross-hole seismic technique for assessing in situ rock mass conditions around a tunnel. Int J Rock Mech Min Sci 53:86–93

Sheehan JR, Doll WE, Watson DB, Mandell WA (2005) Application of seismic refraction tomography to karst cavities. US Geological Survey Karst Interest Group Proceedings, Rapid City, South Dakota, pp 29–38

Šumanovac F, Weisser M (2001) Evaluation of resistivity and seismic methods for hydrogeological mapping in karst terrains. J Appl Geophys 47(1):13–28

Zong N, Fu KL, Ma JJ (2007) The main problems and counter measure of karst in enlarge capacity engineering on Guizhou–Guangxi railway. Subgrade Eng 2:152–154