Mapping deeply buried karst cavities using controlled-source audio magnetotellurics: A case history of a tunnel investigation in southwest China

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ABSTRACT
Karst cavity mapping is attracting great interest from engineering geologists because of its relation to the dangerous geohazards faced during engineering construction. Ground-based geophysical methods still face challenges in karst mapping, and concealed karst cavities potentially pose threats to tunnel construction in southwest China. Given the significant contrast in electrical resistivity between karst cavities and their host rocks, geoelectrical methods are widely used for mapping these cavities. We have developed a successful case history of mapping karst cavities on a planned railway route using controlled-source audio magnetotellurics (CSAMT). Scalar CSAMT, with frequencies ranging from 0.5 to 8192 Hz, was used for field data acquisition. A full-frequency domain apparent resistivity correction method was used for near-field corrections. Electromagnetic array profiling (EMAP) filtering was used for topographic and static shift corrections, and the Bostick conversion was used for data interpretation. Our study indicated that the results of the Bostick conversion with EMAP filtering were more acceptable than the results of rapid relaxation inversion and nonlinear conjugate gradient inversion in this case. The G Tunnel is a key tunnel along the Gui-Guang high-speed railway in southwest China. Initial geophysical and engineering geologic results suggest that the bedrock of the survey section of the G Tunnel route is sandstone. A CSAMT survey with three inline sections and three crossline sections over the tunnel route was conducted in two phases to verify the rock conditions of the tunnel route. A concealed karst cavity with a low-resistivity anomaly was found on the tunnel route and was verified by the borehole. Data from the CSAMT survey significantly refined our understanding of the subsurface engineering geologic conditions along the tunnel route.

INTRODUCTION
Karst features, which develop around and within carbonate or evaporitic rocks primarily by dissolution, are well-known potential geohazards, and they also show great potential as oil and gas reservoirs (Farrant and Cooper, 2008; Chalikakis et al., 2011; Liu and Liu, 2012). Major advances have been made in karst studies in the past 50 years, and several geophysical methods and assessment techniques have been developed in recent years (Chalikakis et al., 2011). However, karst mapping still needs to be thoroughly explored, and ground-based geophysical methods still face challenges in characterizing heterogeneities in the karst environment (White, 2007; Waele et al., 2009; Chalikakis et al., 2011). Traditional methods of karst location involve remote sensing and borehole observations; however, remote sensing does not work in many cases in which the structural and solution features lack surface expressions.
and are not detectable on aerial photographs, whereas borehole surveys are costly and restricted to the points of observation (Doolittle and Collins, 1998). As a result, surface geophysical methods play a dominant role in karst mapping and location. Chalikakis et al. (2011) provide an overview of the most relevant geophysical research studies published over the preceding 20 years in international journals, which indicates that almost all of the available ground-based geophysical methods have been used for karst mapping, including electrical resistivity tomography, radio magnetotellurics, seismic refraction, seismic reflection, microgravity, magnetics, time-domain electromagnetics (TDEM), ground-penetrating radar, very low-frequency electromagnetics, audio magnetotellurics (AMT), controlled-source AMT (CSAMT), magnetic resonance sounding, the spontaneous potential method, and Slingram electromagnetics. In general, most of these geophysical methods are only suitable for near-surface karst mapping. TDEM has good resolution, but field operations in karst terrain areas have proven to be difficult. High-resolution 3D seismic acquisition techniques have been used for characterizing deeply buried karst cavities serving as carbonate oil and gas reservoirs (Zhao et al., 2010). Most karstification in China developed before the Triassic and is associated with rock that is characterized by high compressive strength and low porosity (Han and Liu, 2004). In addition, there are large amounts of groundwater in southwest China. These conditions are favorable to karst cavity development (Yuan et al., 1996). As a result, all types of karst cavities exist in southwest China. Most of the tunnel route is covered by karst terrains. Faults, which always act as a cause of karst cavities, are also well-developed across or along the tunnel route (Figure 2). The initial geophysical and engineering geologic survey considered the surrounding rock in the section from milestone 35,000 to 37,480 (Figure 3) as intact sandstone. However, a drilling hole before the CSAMT survey and after the initial geophysical and engineering geologic survey at milestone 35,000 to 37,480, a CSAMT section was conducted to investigate the tunnel route. A karst cavity was found by CSAMT and verified by borehole drilling at milestone 35,870 proposed by the result of the CSAMT survey (Figure 3). To map the extent of the found cavity, a second CSAMT survey phase, which had two other inlines and three crosslines, was carried out.

The study area is located in the center of the Southeast Asia karst region, which is one of the largest karst areas in the world and covers approximately 620,000 km² in this region (Huang and Cai, 2007). The climate in the study area is warm and moist, with average temperatures ranging from 14°C to 16°C (Han and Liu, 2004; Huang and Cai, 2007). The G Tunnel is located in the orogenic belts of the Yangtze Platform and Cathaysian Block (Figure 1); these two blocks came together to form the South China Block.

Mapping the karst cavity is a key task in engineering exploration before tunnel construction in these areas.

Engineering geologists have devoted a large amount of time to mapping karst cavities. Locating these cavities using ground-based methods is an important task in drawing geohazard maps (Chalikakis et al., 2011). Moreover, mapping deeply buried karst cavities stands out as one of the toughest technical challenges in the planning of railway routes because such cavities generally occur in mountainous areas with rough topography and complex geologic settings. Seismic reflection and refraction methods are difficult to apply in the field because the karst topography and cavities inside limestone will distort seismic wave propagation. Therefore, high-frequency electromagnetic methods, including AMT and CSAMT, are widely used for karst mapping because they can be incorporated into high-resolution, portable data acquisition systems with greater exploration depth and lower time consumption (Sandberg and Hohmann, 1982; He et al., 2006; Asch and Sweetkind, 2011).

In this paper, we present the project and geologic background of the G Tunnel. The field operation, data acquisition, and processing, especially the processing of near field, topographic, and static shift effect, are described. Finally, the CSAMT exploration results and the verification of drilling results are discussed. Our exploration refined the engineering geologic understanding of the G Tunnel and helped to optimize the engineering design to avoid a vital failure in its construction.

**BACKGROUND AND GEOLOGIC SETTING**

The G Tunnel lies in the southeastern part of the Guizhou Province in southwest China (Figure 1). It has a total length of 14 km, and it is the main project of the Gui-Guang high-speed railway. Most of the tunnel route is covered by karst terrains. Faults, which always act as a cause of karst cavities, are also well-developed across or along the tunnel route (Figure 2). The initial geophysical and engineering geologic survey considered the surrounding rock in the section from milestone 35,000 to 37,480 (Figure 3) as intact sandstone. However, a drilling hole before the CSAMT survey and after the initial geophysical and engineering geologic survey at milestone 35,620 met limestone and fault breccia. To verify the bedrock conditions from milestone 35,000 to 37,480, a CSAMT section was conducted to investigate the tunnel route. A karst cavity was found by CSAMT and verified by borehole drilling at milestone 35,870 proposed by the result of the CSAMT survey (Figure 3). To map the extent of the found cavity, a second CSAMT survey phase, which had two other inlines and three crosslines, was carried out.

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at approximately 1000–800 Ma during the assembly of the Rodinia supercontinent (Gu et al., 2013). The metasedimentary basement of the southern Yangtze Block is comprised mainly of two low-grade sequences separated by a regional angular unconformity that marks the boundary between the Mesoproterozoic and Neoproterozoic (Zhan and Jin, 2008; Gu et al., 2013). Outcropping strata along the tunnel route include sedimentary sequences from the Cambrian to Devonian; regional outcropping strata include all sedimentary sequences from the Sinian to Triassic. The Devonian and Silurian series are quite well-developed. The major formations along the tunnel route (Figure 2) include the (1) Cambrian (C), which is formed mainly by dolomite, oolitic dolomite, and shale; (2) Ordovician (O), which is formed mainly by calcareous siltstone with a shaly bed and argillaceous nodular limestone with a shaly bed; (3) Silurian (S), which is formed mainly by shale with a sand streak, quartz sandstone, and calcareous sandstone; and (4) Devonian, which is comprised of the Upper Devonian (D3), Middle Devonian (D2), and Lower Devonian (D1), which are formed mainly by limestone, dolomite, and quartz sandstone with a shaly bed. Karst cavities always develop around the boundaries of limestone and sandstone or mudstone. Three folds and three major faults trend across the tunnel route.

FIELD OPERATION AND DATA ACQUISITION

Electromagnetic inductive methods, including natural field methods and controlled-source methods, provide an excellent means to obtain information about ground electrical conductivities (Lange and Seidel, 2007). They have proven useful in identifying and locating several karst features (Chalikakis et al., 2011) and have been widely used in karst exploration in southwest China. In field operations, AMT and CSAMT can be used for outcropping karst and complex topographies in which TDEM is inconvenient. In most cases, AMT or CSAMT has been used for tunnel route investigations in karst areas. AMT has a high resolution in shallow earth (e.g., less than 200 m) but a smaller depth of exploration, whereas CSAMT has a powerful signal but lower resolution than AMT in shallow earth (He et al., 2006). CSAMT was used to investigate the route of the G Tunnel. The exploration depth of CSAMT with a frequency band of less than 0.5 Hz is greater than 3000 m, and the planned maximum buried depth of the tunnel is 640 m.

We carried out the survey at 596 stations for CSAMT in two phases (Figure 3). In the first phase, line 01 with 125 stations along the railway route was surveyed. In the second phase, data from a total of 471 stations in five survey lines (lines 02–06) were acquired. A set of GDP-32II (Zonge Engineering) multifunction and multichannel receiver was used for data acquisition. The scalar survey mode with one magnetic channel (Hy) and seven electric field channels (Ex 1–7) was used (Figure 3). Eight PbCl (lead chloride)-Pb nonpolarizable electrodes, aligned to cover seven field stations, were used to record the electrical field signal (Figure 3). One station used a pair of electrodes, two adjacent stations used three electrodes, one of which could be used.
for two stations, and seven adjacent stations used eight electrodes, six of which were used for two adjacent stations. A magnetic induction coil was used for magnetic field recording. To avoid the near-field effect, we chose the separation between the transmitter and receiver (T-RS) to be greater than 5 km, which is approximately eight times the maximum burial depth of the tunnel. However, the near-field still affected more than 15% of the total of 29 frequencies, according to the resistivity curves. Two transmitter locations were used during the entire data acquisition. Transmit 01, which had a current-dipole length of 2160 m, was used for lines 01–03, and transmit 02, which had a current-dipole length of 2000 m, was used for lines 04–06 and was designed to be orthogonal to lines 01–03 (Figure 3). In the field operations, the peak current transmitted from the receiver station related to the center the transmit dipole is calculated in the working frequency range. Inductance P, which is dependent on the separations between the receiver and transmitter, and azimuths of the receiver station relative to the center the transmit dipole is calculated in the working frequency range. Inductance P, which is defined as the ratio of T-RS and the skin depth δ, is introduced to calculate the corrected resistivity. A detailed introduction to this method is presented by Luo et al. (1996a). He et al. (2006) discuss the results of this correction method when it is applied to the processing of data on the Qiyueshan Tunnel. Figure 4 shows the results of the near-field correction. Figure 4a shows the apparent resistivity-versus-frequency section of the pre near-field correction. It shows that the apparent resistivity in this section ranges from 10 to 1,676,600 Ωm. The resistivity curve of one station in this section increases with a slope of 45° at frequencies lower than 200 Hz (Figure 4d) in the log-log crossplot. The phase value of the same station was approximately 0° in this frequency range (Figure 4e). Based on the discussion of Asien et al. (2005), large upward biases of the Cagniard resistivity estimates are caused by the near-field (Bartel and Jacobson, 1987; Asien et al., 2005). Figure 4b shows the corresponding section of the post near-field correction, and the apparent resistivity ranges from 10 to 6800 Ωm. Figure 4c shows the relative change in resistivity pre and post correction, which reflect the influence of the near-field. For data at frequencies greater than 200 Hz, the relative changes were approximately zero, meaning that there were almost no near-field effects on the data at those frequencies. For data at frequencies of approximately 100 Hz, the relative changes were less than zero, indicating the effect of a transient field from the source. For data at frequencies less than 50 Hz, the relative changes were positive, indicating that near-field effects were present. From the results of this comparison, it can be seen that the relative changes due to the near-field were greater than 90% at frequencies lower than 4 Hz. It is difficult to use the CSAMT method in areas where deep buried limestone is developed because the karst features are deeply buried and the lower frequencies are most affected by near-field effects. To overcome this problem, it is most useful to enlarge the T-RS as far as possible. Alternatively, a near-field correction can be applied. In the case of a karst cavity with high resistivity, CSAMT, and other EM methods will be challenged. In the case of karst cavities characterized by low resistivities, CSAMT will work well because there are large resistivity contrasts between the limestone and water-saturated karst cavities (He et al., 2011).

Data inversion or conversion to depth is a very important link between geophysical data and engineering geology because most interpreted anomalies must be seriously considered during tunnel design. To overcome the bias caused by the source in the transition zone or near-field, where the Cagniard resistivities become unrealistically large, Routh and Oldenburg (1999) present a technique for inverting CSAMT data to recover a 1D conductivity structure. Asien et al. (2005) consider that the Bostick transform yields useful results if applied to curves of all-frequency apparent resistivities recalculated using his new algorithms. When interpreting the G Tunnel data, several data inversion methods, including 2D continuous media inversion, Occam inversion, rapid relaxation inversion (RRI), Bostick (1977) conversion, and nonlinear conjugate gradient (NLCG) inversion based on the algorithm of Rodi and Mackie (2001), have been used to choose the most appropriate data interpretation method. In this paper, results are shown for RRI (Smith and Booker, 1991), the Bostick conversion, and NLCG. Figure 5 compares the results of these different data conversion or inversion methods. Figure 5a shows the result of the Bostick conversion with EMAP filtering; this method is now widely used for the interpretation of AMT and CSAMT data because it agrees well with borehole results in many cases in China. Figure 5b shows the 2D
inversion result of RRI; in general, it is similar to the result in Figure 5a. Figure 5c shows the 2D inversion result of NLG; it is much rougher than the results in Figure 5a and 5b. For RRI, the data are weighted by their associated errors, 2.2% for resistivity and 2.9% for phase; the initial depth of the top layer was 20 m, and the mixed factor for the penalizing trade-off between the horizontal and ver-

Figure 4. Comparison of the resistivity $R$ section. The (a) pre- and (b) postnear-field correction. The relative change $(R_{\text{pre}} - R_{\text{post}})/R_{\text{pre}}$, reflecting the effect of the near-field, is shown in (c). (d) The raw data and their corrected results of a case station in which the raw resistivity curve with a slope of 45° at frequencies lower than 200 Hz in the log-log crossplot. (c) The phase and the corrected result of the same station. The FFDAR method is used for near-field correction. Raw data are from milestone 35,000 to 36,000 of line 03. The separation between the middle of current dipole and the receiver station ranges from 5160 to 5580 m.
tanical structures was 0.7. The number of least-squares iterations was 30. There were eight robust Huber weights that function to down weight outliers (Huber, 1973). We used 5% for the percentages of error in NLCG for resistivity and phase, the regularization factor was 3.0, and the number of iterations was 12. The result of the Bostick conversion clearly showed the conductivity anomaly associated with the buried karst feature and agreed most closely with the borehole results in this case. A major reason is that in this case the low-resistivity anomaly is covered by the high anomaly and covered by the low-resistivity layer; we used a conversion method that helps to keep the utmost direct information from the observed CSAMT result. We chose this method for the interpretation of the data from the six lines.

Recognizing the effects of terrain topography and static shifts proves to be difficult in practice when processing CSAMT data. Macnae et al. (1998) discuss static-shift removal and present a method of applying an inductive source telluric field of CSAMT to remove the static shift. Fu et al. (2013) present a terrain correction method by recalculating the horizontal electrical field component from an actual electric-field measurement along a slope. For the G Tunnel, electromagnetic array profiling (EMAP) filtering (Bostick, 1986; Torres-Verdín and Bostick, 1992) was used for the topographic and static-shift corrections. EMAP uses a low-pass filter to diminish or remove the topographic and static shift effects in the spatial or wavenumber domains. The foundation of EMAP is based on the conception that the apparent resistivity at a certain frequency caused by the geologic structure varies smoothly along a continuous survey path in which the electric dipoles are positioned end-to-end (Torres-Verdín and Bostick, 1992), and only topographic and static shifts will cause a rough change. In addition, the resistivity change caused by topographic and static shifts mainly features as a high-frequency component in the resistivity profile. The effects of topographic and static shifts along the survey line could be filtered by a low-pass filter (Torres-Verdín and Bostick, 1992; Luo et al., 1996b). A filter constant c, which plays the role of a window-width expansion factor of the applied Hanning window, is used in the filter adaptation process to control the roll-off characteristics. There are many ways to choose the filter constant c, but the smallest value within an acceptable tolerance level is the most desirable. A detailed description and discussion are presented in Torres-Verdín and Bostick (1992). In the codes we used, the filter constant c was set in the range of 0–999, where zero indicates that no high-frequency component in the spatial domain will be filtered and 999 indicates that all the lateral changes along the survey line will be smoothed flat. Static-shift removal was conducted after near-field correction based on the FFDAR method to avoid failure in the transition and near zones because of the unrealistically large upward biases of the Cagniard resistivity estimates (Asten et al., 2005). Figure 6 shows a comparison of the EMAP filtering with different filter constants c of 0.0 (Figure 6a), 0.2 (Figure 6b), 0.5 (Figure 6c), and 5.0 (Figure 6d). Without EMAP filtering (Figure 6a, c = 0.0), all of the detailed information was preserved, but the model was rough, and it was hard to discriminate the anomalies caused by geology. With a filter constant c of 5.0 (Figure 6d, c = 5.0), the model filters almost all the detailed anomalies, and it shows apparent distortion; the main anomalies, such as the high-resistivity anomaly in the middle portion of the section, have been removed. The results with filter constants c of 0.2 and 0.5 (Figure 6b and 6c) retained the general modality of the section, and most of the detailed anomalies have been saved. Based on our experience in processing the present data, a filter constant c of 0.2–0.5 should always be selected.

RESULTS AND DISCUSSION

Modeling results

To analyze the resistivity anomaly characteristics caused by low-resistivity anomalies, such as a water-saturated karst cavity, we used 2D modeling to examine the expected difference of the surface apparent resistivity between the measured and numerical forward results. The geoelectrical model we used was based on the Bostick
conversion result with an EMAP filter of 0.4 in the middle portion of the CSAMT survey of line 01 as shown in Figure 7a. Figure 7b shows the CSAMT observed result with near-field correction. Figure 7c shows the model simplified from the model shown in Figure 7a; it consists of a conductive layer of clay and shale with a resistivity of 80 and 100 \( \Omega \) m, a relatively conductive layer of sand-mudstone with a resistivity of 160 \( \Omega \) m, and several resistive layers of limestone with resistivities ranging from 300 to 6000 \( \Omega \) m.

Figure 6. Comparison of the resistivity \( R \) section with EMAP filter constant \( c \) of (a) 0.0, (b) 0.2, (c) 0.5, and (d) 5.0 of line 02. The filter constant \( c \) is a window-width expansion factor of the applied Hanning window and has a relationship to the wavelength. Without EMAP filtering (constant \( c \) of 0.0 in [a]), all of the detailed information was preserved. With a filter constant \( c \) of (d) 5.0, the model filters almost all the detailed anomalies. The results with filter constants \( c \) of (b) 0.2 and (c) 0.5 retained the general modality of the section, and most of the detailed anomalies have been saved.

Figure 7. Models and modeling results for the karst cavity and the host rocks based on the conversion results from the middle portion of CSAMT survey line 01 (a) with EMAP filter of 0.4. (b) The CSAMT observed result with near-field correction, (c) the geoelectric model based on the conversion results shown in (a and d) is the forward-modeling result of model (c). (d) The modeling result is similar in shape to the (b) measured result, but the average resistivity of the measured result was obviously higher than that of the modeling result, and the shape of the lower resistivity anomaly is different between the measured and modeling results.
In addition, a conductive karst cavity with a resistivity of $30–100 \, \Omega \cdot m$ was assumed to be present in the middle portion of the model close to the resistant body. The modeling algorithm uses the numerical forward modeling algorithm described by Mackie et al. (1988). Figure 7d shows the forward-modeling result of the model shown in Figure 7c. It is similar in shape to the measured result (Figure 7b). However, the measured resistivity was obviously higher than the modeling result, and the shape of the lower resistivity anomaly is different from the modeling results. In general, the modeling result provides us information for understanding the presence and effects of the karst cavity, but the forward-modeling data from the conceptual model of the subsurface were not expected to match the actual survey data.

Another modeling exercise was performed to simulate the expected surface apparent resistivity anomaly caused by a deep buried water-saturated karst cavity. The geoelectrical model we used was extracted from the conversion result of line 01. As shown in Figure 8a and 8b, the model was comprised of a conductive layer of clay and shale with a resistivity of $100 \, \Omega \cdot m$, a conductive layer of sand-mudstone of $200 \, \Omega \cdot m$, and several resistant layers of limestone with resistivities ranging from 400 to $5000 \, \Omega \cdot m$. A presumptive conductive karst cavity of $20 \, \Omega \cdot m$ was used in the model in Figure 8a. Figure 8c and 8d shows the inversion result of the modeling data. The inversion algorithm we used was the NLCG algorithm for 2D MT inversion of Rodi and Mackie (2001). Apart from some differences in depth from 200 to 300 m at distance of approximately 1000 m, the results of the two models indicate similar geoelectrical structures. The relative resistivity variation between the two models was quantified using the following relative change:

$$\delta = 1 - \frac{\rho_a}{\rho_b},$$

where $\delta$ is the relative change and $\rho_a$ and $\rho_b$ are the resistivities of the models shown in Figure 8a and 8b, respectively. The result is shown in Figure 8e. The variations of the stations distant from the karst cavity were less than 0.05% or 5%. The relative variations based on equation 1 were greater than 20% at the stations where the karst cavity was set. The modeling results indicate that a
low-resistivity karst cavity in a resistant limestone background could cause relative resistivity variations ranging from 20% to 45%.

**Interpretation**

Figure 9b shows the CSAMT conversion result for line 01 (the location of which is shown in Figure 3), which was conducted in phase I. A remarkable characteristic of the section (line) is that there is a distinct low-resistivity anomaly in the marked area. Another significant characteristic is that the upper geoelectric layer feature has lower resistivity than the deeper layers. The average resistivity of this section is approximately 1000 Ωm. There are two remarkable resistivity highs in this section; one is in the middle of the section close to the low-resistivity anomaly, with a resistivity of 1000–6000 Ωm. The results for lines 02 and 03 are shown in Figure 9b and 9c, both of which exhibit a low-resistivity anomaly in the marked area. The anomalies in the three inline sections are located at almost the same milestone station. The shapes of the low-resistivity anomaly are somewhat different in the three lines. Similar to line 01, there is a remarkable resistivity high in the middle of these two sections. Figure 9d shows the result of the crossline section (line 06). Unlike the result of the inline sections, the average resistivity of the crossline section is less than 200 Ωm, and most of the section has relatively low resistivity. There is a low-resistivity anomaly near the cross station with the inline sections, but the contrast between the anomaly and its surroundings in the inline sections is much more remarkable than those in the crossline. Figure 10 shows a slice contour of resistivity at an elevation of 700 m using the data from the three inlines and three crosslines. There is a significant low-resistivity belt in the middle of the map (delineated by the black lines). It indicates that the low-resistivity belt, which reflects the buried karst cavity, travels along the direction of lines 04–06 and across lines 01–03. This enables an interpretation for why line 06 has a lower average resistivity and features that are quite different than those of lines 01–03.

**Geologic analysis**

The detection of karst cavities is the key aim of the present CSAMT tunnel investigation survey in southwest China. The key to the karst geologic interpretation of the CSAMT data of the G Tunnel is the understanding of the resistivity anomaly. It was not accepted that the unveiled low anomaly reflected a karst cavity because the initial investigation estimated the bedrock to be sandstone and there were no drilling data when the first CSAMT line was finished. A drilling borehole 1000 m from the lower resistivity anomaly met limestone later. This provided a new opportunity for interpreting the anomaly as the signal of a deeply buried karst cavity. The anomaly was located directly on the tunnel path and posed a major risk to railway construction. A borehole was proposed to verify the CSAMT results. The drilling met the karst cavity unveiled by CSAMT. Figure 11 shows a comparison of the drilling results and CSAMT anomaly. As can be seen, the center of the anomaly coincides with the cavity encountered by the drill.
The modeling results indicate that a karst cavity of 90\% at frequencies lower than 4.00 Hz based on the FFDAR change in apparent resistivity due to the near-field is greater than extent and distribution. In the case of the G Tunnel, the relative route verified that the existence of the cavity was used to map its with two inline sections and three crossline sections along the tunnel route.

The anomaly was located directly on the tunnel path and posed a major risk to railway construction. A borehole was proposed to verify the anomaly, and it revealed a four-layer karst cavity with a total height of 20.5 m (shown in the blue rectangle) in the center of the CSAMT anomaly.

A four-layer karst cavity with a total height of 20.5 m, and it has a smaller size than the low-resistivity anomaly because the resistivity anomaly is comprised of the effects of the cavity, surrounding breccias, and cracked host rocks. After drilling, lines 02–06 were carried out in phase II, and the results also indicated that there is a low-resistivity anomaly at the marked area in Figure 9. The anomalies in the three inline sections are located at almost the same site. The results of phase II provided further evidence for the existence of the karst cavity. The extent and distribution of the cavity around the tunnel route were mapped (Figure 10). Deep karst cavities are always featured as low-resistivity anomalies in southwest China. They are always developed under the water table and are filled with water or sediments. In addition, karst cavities are always developed with faults where the surrounding rock is damaged and has very low resistivity relative to the intact limestone. The CSAMT survey results satisfied the engineering geologists and refined their understanding of the engineering conditions along the G Tunnel route.

CONCLUSION

We conducted a case study using CSAMT to detect a deeply buried karst cavity on a railway tunnel route in southwest China. A four-layer karst cavity with a depth of approximately 400 m and a total height of 20.5 m was successfully unveiled by CSAMT and encountered by the proposed drilling. The karst cavity has low resistivities that are less than 100 $\Omega$m and are 5 to 10 times lower than the surrounding host rocks. A second-phase CSAMT survey with two inline sections and three crossline sections along the tunnel route verified that the existence of the cavity was used to map its extent and distribution. In the case of the G Tunnel, the relative change in apparent resistivity due to the near-field is greater than 90\% at frequencies lower than 4.00 Hz based on the FFDAR method. The modeling results indicate that a karst cavity of 20 $\Omega$m at a depth of 400 m could cause a surface apparent resistivity difference of 20\%–45\%. Our study shows that EMAP filtering is a practical method for topographic and static-shift corrections when an appropriate filter constant $c$ is chosen. In the case of the G Tunnel, the Bostick conversion with EMAP filtering provided a more accurate interpretation than did RRI or NLCG inversion. The data from the CSAMT survey have significantly refined our understanding of the subsurface engineering geologic conditions along the tunnel route.

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REFERENCES


Asten, M. W., M. Vicary, H. Rutter, and J. P. Cull, 2005, An all-frequency resistivity-depth and static-correction technique for CSAMT data, with applications to mineralised targets under glacial cover (Western Tasmania) and basalt cover (Victorian goldfields): Exploration Geophysics, 36, 287–293, doi: 10.1071/EG050287.


Mapping karst cavities using CSAMT


