Combination of ERT and EM methods in the exploration of karst caves and foundation in the Nujiang airport survey of China

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Abstract. Due to controls from karst cave, grike fissure zone, tectonic crushed zone and other defects in rock masses, the airfield runway in the karst region is easy to have collapse and leakage failure, thus resulting in runway deformation and buckling. Therefore, it is of important significance to detect rock defects in airfield runway accurately. In this study, electrical resistivity tomography (ERT) and electromagnetic (EM) were combined to detect stability of karst cave and foundation under the runway of Nujiang airport survey of China. Size, shape and scale of underground karst cave were detected accurately by setting 3 ERT measuring lines. Distribution of karst caves in shallow underground layer was disclosed and validated by drilling data. Electrical structures in deep underground layer were detected by setting 11 EM profiles. Based on 2D EM inversion and 3D modeling, it found that electrical structure in deep underground layers of the runway was dominated by high specific resistance, indicating that there’s relatively complete bed rock mainly composed of limestone. Hence, the foundation showed relatively satisfying overall stability, accompanied with local distribution of low-resistance anomalies which was attributed to crushed mudstone. Research results demonstrated that the combination of ERT and EM is feasible and applicable to detect geological structural stability in karst development and deep positions beneath the runway in karst areas.

1. Introduction

Karst caves are widely distributed in soluble rock regions around the world, and the karst environment is one of the most challenging in terms of groundwater, engineering and environmental issues\cite{1}. Since roads, railways construction may damage the caves, and further cause ground surface potholes or collapse, geophysical investigations are often used to detect and delineate the geometry characteristic of the caves. Up to now, several geophysical methods have been applied in cave studies...
based on there is a strong contrast in physical properties between the cave and the host rock. For example, microgravity[1-3], electrical[2,4-7], electromagnetic[2,5,8-10], seismic methods[6,11-12] have provided possible solutions for determining cave geometry and the surrounding subsurface geological structure.

The planned Nujiang airport is situated about 9 km south of Nujiang County in Yunnan Province, southwest China, and southwest China represents one of the largest continuous karst regions in the world[13]. The bedrock strata of the field are mainly limestone and flint limestone, and the local lot develops the karst cave. Due to the crushing of the rock mass, some of the karst roof has poor stability. The bedrock strata are mainly carboniferous strata (C1X) limestone and (C1P) flint limestone. The landform types are peak pleomorphic features, corrosion -relief mountain topography, karst valley and karst funnels, etc. The surface karst microgeomorphological type are stone bud, the dissolution groove, the funnel, the sink hole, the ground cave, etc. Underground karst types are underground karst caves, corrosion belts and so on. For the stability of the airport foundation, this paper used two surface geophysical methods, namely electrical resistivity tomography (ERT) and electromagnetic (EM) method, to investigate two purposes: one is revealing the cave development and distribution underground, and the other is investigating the deep structural integrity assessment.

2. Geological setting and cave description

The study area locates in the boundary between Gondwanaland and Eurasia. It is an important region to study the collision effect of Yangtze plate and Indian Plate and has very complicated geological structures. The study area is developed with fracture, fold structures and north-south tectonic belt, east-west tectonic belt and arc tectonic belt in the meridional tectonic system (Figure 1). Fracture contains various compression and pressure-torsional features. The airport locates on the Nujiang-Lancangjiang fault structural belt in the Yunnan-Tibet groove folded region. Neotectonics brings serious lifting of the region. Incision of rivers like Nujiang and Lancangjiang form the famous tall and steep mountains and valley terrains. In the region, it is mainly developed with sedimentary rocks. Among them, carboniferous system has the most extensive distribution, followed by Permian system and Triassic system successively. The Jurassic system and Cambrian system only outcropped in small scales. The total sedimentation thickness ranges between 5580~9250m. The outcropped formations from old to new are carbonate sedimentation, neritic facies, Cambrian system, lower palaeozoic erathem; carbonate and argillaceous and silt sedimentations, neritic facies, carboniferous system, upper Paleozoic erathem; silt sedimentations, neritic facies, Permian system; compound sedimentation of sea basin and carbonate sedimentation of platform type, Triassic system, Mesozoic Erathem; continental detrital deposit of fluvial and lacustrine facies, Jurassic system; alluvial deposition, colluvial deposition, pluvial deposition and residual accumulation of quaternary system, Cenozoic erathem.

Carbonate deposition system of neritic facies of Cambrian system is outcropped in the regional formation, which distributes symmetrically at two sides of the Nujiang. It is far away from the airport area. Carbonatite and argillaceous siltstone system of neritic facies of carboniferous system and siltstone system of neritic facies of Permian system distribute extensively in near-field regions (Figure 2). The sea-basin compound sedimentation of Triassic system of Mesozoic erathem and platform-type carbonatite system distribute at two sides of the airfield region. Continental elastic sedimentary rock system of fluvial and lacustrine facies of Jurassic system and alluvial deposition, colluvial deposition, pluvial deposition and residual accumulation of quaternary system, Cenozoic erathem scatter around in the airfield region.
**Figure 1.** Position of the study area and distribution of ERT and EM survey lines. Red full line is ERT survey lines, block solid rounds are EM measuring points and blue hollow circles are drilling positions.

**Figure 2.** Karst development in the study area.

a. Limestone karst pores  
b. Surface karst cave
2.1. Quaternary system (Q)
Quaternary system is mainly composed of colluvial deposition, pluvial deposition and residual deposition. The colluvial deposition mainly distributes in the middle and lower parts of Zhongshan steep cliffs (ridges and slopes), which form avalanche debris cone in local areas. Generally, it is thick in lower part and thin in upper part. Silty clay and macadam (blocks) are the major lithologies. The total thickness generally ranges 1~10m and is higher than 20m in some regions. The pluvial deposition mainly distributes in bottom of karst gully. Silty clay is the main lithology, accompanied with few fragments. The total thickness is generally 1~8m. The residual deposition is mainly in haystack and top of slope. Silty clay is the dominant lithology. Total thickness ranges between 1~3m.

2.2. Carboniferous system (C)
① Woniusi Formation (C₃w): The lithology is composed of purple grey and fray amygdaloidal and dense basalt, amaranth shale and limestone lenticles. They have distributions at two sides of the airfield and mainly outcropped in the south segment of the airfield area. The total thickness is about 740m.
② Dingjiazhai Formation (C₃d): it consists of isabelline mudstone with sands and gravel-containing limestone in the lower part. It has distributions in the airfield and two sides of the airfield area. The total thickness is about 300m.
③ Pumenqian Formation (C₁p): it consists of limestone containing chert nodule, accompanied with few muddy limestones. It has extensive distribution in the airfield area and the total thickness is about 250m.
④ Xiangshan Formation (C₁x): it is composed of limestone, accompanied with marlstone, calcilutite and chert nodule. It mainly distributes in middle mountain ridges in the airfield area and is identified by anticlinal core. The total thickness is about 460m.

3. Methodology

3.1. Electrical resistivity tomography (ERT)
The basic working principle of ERT is generally same with that of conventional resistivity method. It is an electrical resistivity survey based on electrical difference of rock and earth mass. According to distribution law of conduction current in Formations under the effect of applied electric field, it infers that there are geologic bodies with different resistivity. It supplies electricity (current= Iₐb ) to underground region through electrodes A and B, and then measures potential difference between electrodes M and N (Uₘn ), thus calculating the apparent resistivity of the measuring point:

$$\rho_a = k \frac{U_{MN}}{I_{AB}},$$

(1)

Based on calculation and analysis of measured apparent resistivity, resistivity distribution in formations can be gained, thus enabling to divide formations and determine abnormal formations. It integrates electrical profile and electrical sounding and makes 2D geoelectric sectional measurement by using high-density measuring points. ERT is characteristic of large data size, abundant information, high observation accuracy and fast measurement. It is one of the most effective geophysical prospecting methods to search karst cave and structural fracture zone in limestone regions. Resistivity distribution in formations can be gained from calculation, processing and analysis of measured apparent resistivity, thus solving corresponding engineering geological problems.

3.2. Electromagnetic (EM)
Electromagnetic sounding uses natural alternating electromagnetic field as the field source. When the alternating electromagnetic field is applied onto the earth surface, if (1) the natural electromagnetic field is vertical incidence of plane wave into the earth and (2) underground media are uniform in a
certain range, electromagnetic wave will attenuate to some extent with the increase of propagation
distance in underground media. The depth when amplitude attenuates to $1/e$ is defined as the skin
depth or penetration depth. Due to influences of skin effect, electromagnetic waves with different
frequencies have different penetration depths. The longer the period is, the higher the penetration
depth will be. Therefore, resistivity distribution of medium at different underground depths can be
obtained by studying earth responses to frequency of natural electromagnetic field (that is, impedance $Z$.
It is generally transformed into apparent resistivity and impedance phase).

To get impedance response features of different frequencies, time-domain denoising, time-
time-frequency transformation and frequency-domain denoising have to be performed to four components
of time series $E_x$, $E_y$, $H_x$ and $H_y$, thus getting the power spectrum. Finally, tensor impedance that
characterizes underground electrical structure can be acquired:

$$
Z_{xx} = \langle E_x, A^* \rangle \langle H_x, B^* \rangle - \langle E_x, B^* \rangle \langle H_x, A^* \rangle / D
$$

$$
Z_{xy} = \langle E_x, B^* \rangle \langle H_x, A^* \rangle - \langle E_x, A^* \rangle \langle H_x, B^* \rangle / D
$$

$$
Z_{yx} = \langle E_y, A^* \rangle \langle H_y, B^* \rangle - \langle E_y, B^* \rangle \langle H_y, A^* \rangle / D
$$

$$
Z_{yy} = \langle E_y, B^* \rangle \langle H_y, A^* \rangle - \langle E_y, A^* \rangle \langle H_y, B^* \rangle / D
$$

where $D = \langle H_x, A^* \rangle \langle H_y, B^* \rangle - \langle H_x, B^* \rangle \langle H_y, A^* \rangle$. Combinations of value ranges of $A$ and $B$
include $(H_x, H_y)$, $(E_x, E_y)$, $(E_x, H_y)$ and $(E_y, H_x)$. $\langle E_x, A^* \rangle$ represents cross-power
spectrum of $E_x$ and $A^*$ after various denoising treatments. Generally, the component $H_x$ shall be
measured to calculate tipper information.

### 3.3. Data acquisition

Karst development in the airfield region can be observed in engineering geological mapping (Figure 2).
There are many phenomena, such as great changes of the overburden thickness of Quaternary system.
Necessary geophysical methods have to be used to explore the development degree. In this
ground prospect, ERT and EM were used. According to abnormal features, interpretation
accuracy is enhanced by increasing short survey lines and combining engineering drilling, aiming to
offset shortages of slow advancing of drilling and high cost. The geophysical prospecting was
accomplished in two times: (1) site survey from April 9th, 2016 to May 5th, 2016. (2) Field survey from
September 14th, 2016 to September 22nd, 2016. Specifically, EM had 11 survey lines which covered
6.625km. Field data acquisition parameters and settings are shown in Table 1. ETR had 3 survey lines
(L1, L2 and L3), covering a total of 10.175km. Field data were acquired by Wenner Array. Field data
acquisition parameters and settings are shown in Table 2. By interpreting geophysical prospecting data,
it is speculated the stability of deep structures in the study area. Overburden thickness data in airfield
regions are provided and the karst development is deduced. Survey lines are arranged by RTK
sampling, which ensures arrangement accuracy of survey lines. The airfield is on a series of north-
south striking mountain heads with high vegetation coverage. There are many forests and wastelands,
high in the middle and low at two ends, showing high topographic relief. The elevation in the region
ranges 2230m-2500m. Therefore, it is very difficult to make field geophysical prospecting.

| Table 1. Field setup for EM. | Table 2. Field setup for ERT. |
|-----------------------------|-------------------------------|
| **Equipment**               | **Equipment**                |
| Stratagem (Geometrics, INC, USA) | WDJD-3(Chongqing Benteng Digital Control Technical Institute, China) |
| Frequency range | 3333.33-20 Hz |
| Frequency no. | 33 |
| Survey mode | Scalar |
| Electrode distance | 25 m |
| Record channel | 2 magnetic channels and 2 electric channels |
| Record time | 20 min |
| No. of channels | 60 |
| Max supply voltage | 360 V |
| Max supply current | 2 A |
| Electrode distance | 10 m |
| Array length | 590 m |
4. Geophysical results and discussion

In this study, geophysical data were interpreted based on laboratory data processing, field actual situations and geological data. Due to high investigation depth of EM and high resolution of ERT in shallow surface, EM and ERT were combined to detect surface karst and evaluate deep geological structural stability in the study area. ERT was used to detect geological structure in the depth range of 0-80m, while EM was used to detect deeper structural model.

4.1. Electromagnetic (EM)

The measured apparent resistivity and impedance phase curve not only reflect changes of underground electrical properties with depth at measuring point, but also reflect inhomogeneity of electrical structure at measuring points and surrounding areas. It can be seen from apparent resistivity section that measure line 2-2'-13-13’ have one evident feature: low resistivity in high-frequency section and high resistivity in low-frequency section, indicating that resistivity is low in shallow ground but is high in deep underground. Impedance phases of all 11 survey lines have similar features. There’s high absolute value of phase in high-frequency section, but low absolute value of phase in low-frequency section.

In data processing, “breakdown point” on sounding curve are eliminated firstly from follow-up inversion, thus getting smooth sounding curve in the frequency range of 15.8-33kHz. The 2D module of EMAGE was used for terrain inversion, during which surface elevation data of surface were recorded by RTK device. And deep 2D electrical structural models of all 11 survey lines are shown in Figure 3.

In the deep electrical structural models, electrical structure of measure line 2-2'-13-13’ can be divided into two obvious layers on the whole. The shallow part (30-50m) has low resistivity and deep part has high resistivity. According to drilling data, high-resistivity electrical structures of most deep sections are attributed to C1x or C1p with integral rock mass. These reflect the high stability of deep geological structures.

Some sections have low resistivity abnormalism in some areas: 6-6’ section (scope: 0-200m and depth: 350m), 11-11’ section (scope: 300-600m and depth: 0-100), and 12-12’ section (scope:0-80m). According to drilling data (Figure 4), crushed C3d is the dominant composition in this region, accompanied with development of fracture development. The geological section map of 6-6’ profile is shown in Figure 4, and the low resistivity block at scope 0-200m of the profile in Figure 3 is mainly because of the weathered mudstone and developed with fractures, which is loose and hydrated.

3D map of the EH4 electromagnetic section in the study area was formed by GoCAD (Figure 5). More intuitive and 3D electrical structural models are gained.

4.2. Electrical resistivity tomography (ERT)

For data processing, ERT transmits measurement data in the device to computer by the transmission software, eliminates abnormal points by Sweden RES2DINV ERT inversion software, merges data, makes inversion and finally draws the apparent resistivity contour map directly. In specific inverse algorithm, data processing is accomplished by the terrain-carrying least square method which is based on smoothness-constrained least-squares and uses Quasi-Newton best technology as the criterion.

Generally, apparent resistivity is high, but it is low (<200Ω·m) in surface 0-10m(Figure 6). The surface is the overburden layer and is mainly composed of Colluvial deposition and residual deposition. Gravelly soil is the major lithology. Bed rock takes the dominant role in layers below the overburden layer. The major lithology is C1p, accompanied with flint-carrying limestone, muddy limestone and oolith limestone.
Figure 3. 2D electrical structural models in EM along sections. The blue dotted line represents elevation of airport runway.

Figure 4. Geological section map of 6-6’ profile.
4.2.1. Line L1. There’s moderate high apparent resistivity at the horizontal distance of 0-450m of L1, which generally values 500-3000Ω·m. Relative integral limestone is the dominant lithology. Apparent resistivity is relatively low in local areas. At the horizontal distance of 250-300m and deep positions (depth>10m), the apparent resistivity is relatively low (200-500Ω·m). It is speculated that rock mass in this regions is crushed and there’s mature fracture development.

Apparent resistivity at the horizontal distance of 450-670m is low (<500Ω·m). It is speculated as limestone with high degree of crushing and fracture development. Two closed abnormal belts with low resistivity in center and high in surrounding areas were formed at horizontal distance=470-500m, depth = 10-35m and horizontal distance=625-650m, depth=15-35m. These two positions are developed with karst and filled with clays and other low-resistivity materials. According to drilling data of this region, zk16 and zk21 are set close two abnormal positions. The column drilling data of zk16 demonstrated smashed rock masses and fracture development at 3-20m. There are many karst holes and corrosion phenomenon on fissure surface. According to column drilling data of zk21, there are smashed rock masses and fracture development at 13.1-24m, where the region of 16.5-19.0m is the karst cave filled with clay minerals. There’s local corrosion development. The interpretation of geophysical prospecting results agrees well with drilling data.

At the horizontal distance of 670-1450m, the apparent resistivity is low at upper regions and high at lower regions. Apparent resistivity in the layer of 0-30m is smaller than 200Ω·m. It is speculated that this layer is the overburden layer and mudstone. Apparent resistivity at deeper layers is higher than 500Ω·m. It is inferred that these layers are mainly composed of limestone. These conform to lithological data of zk26 and zk36 in the region. At the horizontal distance of 1000-1025m, apparent resistivity is relatively high at upper and lower regions, which are guessed limestone. Resistivity in the middle layer (10-20m) is relatively low and this layer is the karst development region. It is filled with low-resistivity substances like clay. According to column drilling data of zk31 in this region, layers below 8m are limestone and karst cave is observed at 12.0-15.0m. There’s semi-filling of clay minerals. Interpretation of geophysical prospecting results agrees well with drilling data.

Apparent resistivity at the horizontal distance of 1450-1600m is relatively low (100-800Ω·m). This position is mainly composed of smashed limestone and high fracture development.

Apparent resistivity at the horizontal distance of 1600-2870m is relatively high (>1000Ω·m). This position mainly contains relatively integral limestone. Apparent resistivity at the horizontal distance of 1800-1825m is relatively low (100-800Ω·m). This section has smashed rock masses and high fracture development.

Apparent resistivity at the horizontal distance of 2870-3650m is moderate-low on the whole (100-2000Ω·m), showing violent changes. Lithology is dominated by smashed limestone and there’s high fracture development.
4.2.2. **Line L2.** Apparent resistivity in the section of 0-2850m (horizontal distance) is relatively high. Most are higher than 800Ω·m and limestone is the dominant lithology. Rock mass in the region is relatively complete. Local apparent resistivity is relatively low. For example, apparent resistivity in the section of horizontal distance =480-580m, depth >50m and the section of horizontal distance =1400-1460m, depth >50m is lower than 500Ω·m. These positions contain smashed rock masses and high fracture development, accompanied with low-resistivity closed abnormal belt in some regions. The apparent resistivity in the section of horizontal distance =1400-1460m, depth=1-40m is lower than 300Ω·m, while apparent resistivity in surrounding regions is high. This section is the karst development zone filled with low-resistivity materials like clay. According to zk10 column drilling data in this region, fracture is highly developed in the depth of 1-37m and there are karst holes on fracture surface. Apparent resistivity in the section of horizontal distance = 410-440m, depth=5-30m is lower than 300Ω·m, but it is higher in surrounding areas. This section is the karst development region filled with low-resistivity materials like clay. According to zk15 column drilling data in this region, there’s extensive fracture development in 3-20.7m and karst development in 5-12m. Apparent resistivity in the section of horizontal distance = 570-580m and 640-660, depth=10-30m is lower than 300Ω·m, but it is higher in surrounding areas. This section is the karst development region filled with low-resistivity materials like clay. According to zk20 column drilling data in this region, there’s extensive fracture development, karst hole and karren in 5-26m. Apparent resistivity in the section of horizontal distance =1340-1390m, depth=30-50m is higher than 4000Ω·m, but it is lower in surrounding areas, forming a high-resistivity closed abnormal belt. This is speculated the karst cave. According to zk50 column drilling data in this region, there are karst caves in depths of 33.5-35.0m and 44.8-48.2m. No fillings are observed.

Apparent resistivity in the section of 2850-3600m (horizontal distance) is generally low (<500Ω·m). It is inferred that mudstone is the major lithology, which is consistent with drilling data.

4.2.3. **Line L3.** On L3 section, apparent resistivity in the section of 0-3050m (horizontal distance) is relatively high and limestone is the dominant lithology. Apparent resistivity in the section of 0-1680m (horizontal distance) and 2860-3050m (horizontal distance) change greatly from hundreds to thousands of Ω·m. This section contains smashed rock masses and extensive fracture development. Apparent resistivity in the section of 1680-2860m (horizontal distance) is relatively high (>1000Ω·m), indicating high integrity of rock masses in the region. Closed low-resistivity abnormal zones can be seen in some regions. Apparent resistivity in the section of horizontal distance=740-760m, depth=10-30m, section of horizontal distance= 900-920m, depth=15-35m, and section of horizontal distance= 1320-1380m, depth=40-70m is lower than 300Ω·m, but it is high in surrounding areas. These sections are karst development zones filled with low-resistance materials like clay. The corresponding zk20 column drilling data in this region reveal that there are fragmented rock core in 13.1-85m and karst development in local areas. Apparent resistivity in the section of horizontal distance=570-590m, depth=20-40m and the section of horizontal distance=1120-1140m, depth=5-15m is higher than 4000Ω·m, but it is low in surrounding areas, forming closed high-resistivity abnormal zones. These zones are guessed karst caves. According to zk34 column drilling data in this region, there are cast caves in depths of 7.2-8.8m, but there are no fillings. Based on above analysis, the enclosed low-resistivity abnormal zone is the karst development zone filled with low-resistivity substances like clay, while the enclosed high-resistivity abnormal zone is karst caves without fillings.

Apparent resistivity in the section of 3050-3750m (horizontal distance) is generally lower than 500Ω·m. It is speculated that mudstone is the dominant lithology, which agree with drilling lithological data.
5. Conclusions

In this study, high resolution of ERT in superficial layer and large investigation depth of EM are combined to investigate karst development and foundation stability in Nujiang Airport.

EM can acquire deeper resistivity model in the study area by using the natural electromagnetic field source and makes 2D inversion by setting 11 EM survey lines, getting resistivity structures along section. Moreover, 3D electrical structural modeling is accomplished. According to deep electrical structures, apparent resistivity is mainly high, accompanied with local distribution of low resistivity. Combining with drilling data analysis, high-resistivity region is mainly composed of limestone. The electrical structure shows low development degree of karst in deep regions and there’s high overall stability of deep geological structure. Local low-resistivity regions are mainly composed of smashed mudstones and are developed with fractures. Abnormal regions deserve corresponding enforcement processing, thus enhancing foundation stability.

Based on the principle of DC electric method, ERT can gain relatively fine electrical structure in shallow positions. It gains electrical structural features in shallow positions (<100m) in the airfield runway by three ERT survey lines. It finds that the enclosed high-resistivity abnormal zone in electrical structural model might be representation of karst caves without fillings, while low-resistivity abnormal zone might be karst development zones filling with low-resistivity materials like clay. These conclusions have been proved by drilling data.

The underground electrical structure of airfield runway which is gained by ERT and EM reflects that deep geological structure is manifested by integral limestone and has high stability, whereas local abnormal zones are formed by smashed mudstone and needs enhancement. Some shallow regions are developed with karst and have to be excavated and filled in order to increase foundation stability.

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