



Standard guide for karst collapse investigation and its technical essential

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Abstract

Karst collapses are one of the six major geological hazards in China and the unique geological hazard in karst regions. Karst collapse is mainly distributed in southwest, south, and central China. According to incomplete statistics, there are 3315 karst collapse disasters recorded in China, which are distributed in 22 provinces (autonomous regions), such as Guangxi, Guizhou, Hunan, Guangdong, and Hubei. Due to extreme weather conditions and increasingly intensive engineering activities, karst collapses have occurred more frequently in recent years. These collapses have seriously affected human daily life, urban planning, and engineering construction. In 2012, under the support of the geological survey project, the project of “karst collapse investigation in key areas” was implemented. In order to standardize and guide karst collapse investigation and evaluation on scale of 1:50,000 in China, we developed the “Standard Guide for Karst Collapse Investigation (1:50,000).” This standard stipulates the objective of investigation, survey area classification and basic work, design document compiling, investigation content, technical methods and primary demands of investigation, comprehensive evaluation, database construction, data compilation and achievement establishment, quality control examination, and achievement acceptance metrics. The standard can be applied to karst collapse investigation on scale of 1:50,000 and can be a reference in the investigation and exploration of karst collapses on other scales.

Keywords Karst collapse · Investigation · Standard · China

Introduction

Karst collapses are a kind of karst dynamic geological effect and phenomenon in which the deformation of rock and soil above karst caves and fissure leads to collapse pits on the surface under natural and human activity conditions. It is a globally distributed geological hazard. According to incomplete statistics, serious karst collapses occurred in sixteen countries, including China, America, South Africa, France, England, Germany, Russia, Poland, Czech Republic,

Yugoslavia, Belgium, Turkey, Canada, Israel, and so on. The extensive and harmful occurrence of karst collapses has already caused general concern of the international community. The multidisciplinary conference “Sinkholes and the engineering and environmental impacts of karst” has already held fourteen times in the USA from 1984 to 2015. The activities had rendered researchers from various countries the chances to exchange experience and discuss the solutions to this kind of geological hazards with each other.

In 1981, Florida Sinkhole Insurance Law was passed by the first session of the Standing Committee at its seventh session of the Florida House of Representatives. The law requires every insurer authorized to transact property insurance in this state must provide coverage for a catastrophic ground cover collapse. In 2005, in order to assist the insurance industry, geologic and geotechnical consultants, government agencies, property owners, and the public with sinkhole investigations, the Florida Geological Survey has published the “Geological and Geotechnical Investigation Procedures for Evaluation of the Causes of Subsidence Damage in Florida” (2005). This publication has provided

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templates for investigating and evaluating of subsidence from several aspects including initial data gathering, geophysical site characterization, floor mapping, subsurface geotechnical testing and geological interpretations, laboratory testing, structural inspection, and final report. Most investigators in Florida follow the recommendations. These guidelines are intended to standardize subsidence investigations initiated to determine the presence of a sinkhole loss as defined in the Florida Statutes. In 2012, “South African National Standard SANS 1936” has been published. The objective of SANS 1936 is to set requirements for the development of dolomite land in order to ensure that people live and work in an environment that is seen by society to be acceptably safe, where loss of assets is within tolerable limits, and where cost-effective and sustainable land usage is achieved. SANS 1936 consists of 4 parts, and the part 2 is “geotechnical investigations and determinations” which provides requirements for feasibility-level geotechnical investigations, design-level investigations, the determination of the inherent hazard class of dolomite land, and inspection and verification during the implementation phase of a project on dolomite land. This standard is suited to geotechnical site investigations. In addition, a set of effective exploration methods has formed in detecting of development conditions of karst collapse, such as “Standard Guide for Selecting Surface Geophysical Methods” (ASTM6429–99) published by American Society of Testing Materials and “Code of practice for site investigations” (BS5930:1999) published by British Standards, they all recommended geophysics methods suitable for detecting covered karst. There also have many guidance for sinkhole investigation, such as the book of “Sinkhole and Subsidence” which was authored by Waltham et al. (2005), and the article of “A review on natural and human-induced geohazards and impacts in karst” (Gutierrez et al. 2014), has systematically described the karst collapse, including classification, naming, mechanism, ground investigation, risk assessment, and prevention and treatment. However, these technical standards or guidelines for karst collapse are aimed at a certain field. There have no standards for a large scope on scale of 1:50,000.

In China, the chapter “karst collapse” of the book “Guide to Geological Hazards Investigation” (Liu 2000) provided guidance to the investigation of karst collapse from such aspects as content and demand of exploration, technical requirements, field test, laboratory test, long-term observation, monitoring and early warning, evaluation and prediction, prevention and exploration results compiling, and so on. The chapter was a comprehensive guideline to karst collapse investigation which aimed at standardizing karst collapse prevention and control. The standards that were stipulated are the “Standard for Engineering Geological Investigation in Karst Areas (1:100,000–1:200,000)” (DZ/T0060-1993) and the “Standard for Engineering Geological

Investigation (1:25,000–1:50,000)” (DZ/T009-1994), which are the geological industry standards of China. In addition, the departments of various agencies also have standards involving karst collapse investigation. Some examples are provided below:

- The standards issued by the Railway Ministry of China: “Code for Geology Investigation of Railway Engineering” (TBJ28-91), “Code for Unfavorable Geological Condition Investigation of Railway Engineering” (TB10027-2001), and “Code for Geology Investigation of Railway Engineering” (TB10012-2007).
- The standard issued by the Road Ministry “Code for Highway Engineering Geological Investigation” (JTG C20-2011).
- The standard issued by Power Industry “Technical Code of Karst Engineering Geological Investigation for Hydro-power and Water Resources Project” (DL/T 5338-2006).
- The standard issued by Ministry of Land and Resources “Geological Hazard Assessment of Technical Requirements (for Trial Implementation)” (No. 69 [2004]).

The guidelines, standards, and regulations mentioned above included the definitions, contents, and methods of karst collapse investigation and had acted as guiding references. However, because the pertinence, emphasis, and service objectives are different, each could not totally cover all contents of karst collapse investigation. With rapid development of social economy, karst collapse has occurred frequently in recent years, which is harmful to public lives and property safety and socioeconomic sustainable development. In order to provide the governments with systematic and detailed investigation data on large scales for the prevention and treatment of karst collapse, standard guides for karst collapse investigation and assessment are urgently required so that the karst collapse investigation and evaluation on scale of 1:50,000 can be effectively conducted in the serious karst collapse regions in China. In addition, new technologies and methods which are being effectively used in karst collapse investigation recently need to be updated, such as Geographic Information Technology (GIS) technology, photoelectric sensing technology, testing technology for development criterion, risk assessment, new achievements in field of monitoring and early warning, new equipment employment, optimizing combination and comprehensive comparison, and analysis of various methods of investigation, which should be further standardized.

Moreover, under the support of the geological survey project, the project of “karst collapse investigation in key areas” was implemented in 2012. In order to standardize and guide karst collapse investigation and evaluation on scale of 1:50,000 in China, the Institute of Karst Geology of Chinese Academy of Geological Sciences compiled this “Standard

Guide for Karst Collapse Investigation (1:50,000)” (2016) in reference to the worldwide technological situations. The standard fills the gap lacking technical standard specialized for karst collapse investigation in China and provides with strong technical support in prevention and treatment of the geological hazards.

Basic requirements of investigation

The karst collapse investigation on scale of 1:50,000 is a regional and basic geological investigation on large scales. This work can provide basic data and service for geological hazards control, national economy construction, and ecological environmental protection. Thus, the investigation must be based on detailed field geological observations and measurements. Through the investigation of karst collapse on scale of 1:50,000, the environmental geological conditions for the formation of karst collapses, types, distribution laws, and development characteristics of collapses within the workspace would be systematically identified. And risk assessment and regionalization of karst collapse would be mapped. The work would be carried out with taking karst hydrogeological unit as deployment unit, conducting investigations in terms of map of standard format on scale of 1:50,000 and evaluating at hydrogeological unit or administrative region scales.

Classification based on data at key point and general conditions

Because the karst collapse disasters have major differences in different regions, the investigation should be performed by region and on the principle of emphasizing the key points. A comprehensive surface investigation should be conducted for the collapse prominent regions. On this basis, the most representative and typical karst collapse investigated should be analyzed and researched in details. According to the exposed conditions of karst, three zones are classified in each investigation area. They are general investigation zone, important investigation zone, and typical investigation zone.

The general investigation zone is the area where karst collapse is not easy to happen. They include areas with thick overburden layer exceeding 50 m and deeply buried karst development with the thickness of non-soluble rock exceeding 30 m, bare karst areas, and non-soluble rock areas. The other areas are divided into important investigation zone. And typical investigation zone, where have happened severely collapse events before or have collapse sign, belongs to the important zones. Ground investigation is the main work in general investigation area. Remote sensing interpretation, hydrogeological investigation, and environmental geology investigation are also included. The major

works deployed in important and typical zones investigation are hydrogeological and environmental geology investigation on scale of 1:50,000 and 1:5000, geophysics exploration, hydrogeological drilling, engineering geological drilling, test, experiment, and monitoring.

Integrating data collected at points, transects, and areas during the investigation

1. Area data collection: Investigate regional hydrology and engineering geology conditions and present situation of karst collapse of the entire survey area through the arrangement of relatively uniform observation or exploration points.
2. Transect data collection: Focus on the karst collapse susceptible areas such as karst zone, underground water, tectonic zone, stratigraphic contact zone, and linear projects where human engineering activity is intense through laying out the track route and exploratory transect.
3. Point data collection: Make typical analysis on typical karst collapse through comprehensive exploration.

Making full use of new technologies

The most updated technologies such as 3S technology, geophysical prospecting, in situ test, tracing, and automatic monitoring technology should be applied to improve the work efficiency, quality, and investigation level.

Combining investigation and research

Karst collapse investigation is not only to complete investigation components as required innovation is firmly encouraged. New technical methods and work experience of karst collapse investigation should be explored. Features of karstification, distribution rules, and formative mechanisms should be researched. Susceptibility zonation, prevention planning, and monitoring and early warning should be carried out. These efforts make the investigation achieve better service to disaster prevention and mitigation.

Investigation components

Investigation components include existing situation of karst collapse, regional geological and hydrological conditions, engineering geological conditions of overburden layer, and inducing factors of karst collapse. These data form the basis of the essential conditions required to analyze geological models and dynamic patterns of karst collapse development.

Existing situation of karst collapse

Current situations of karst collapse including characteristics, hazards, and control should be investigated. The characteristics include geographic location, time, influence scope, disaster and disposition, the numbers, shape, scale, spatial position, distribution direction, internal characteristic of collapse pit, and the stage and current stability of karst collapse. Hazards and control include damage caused by collapse, influence of geological environment, and the prevention status of monitoring, and engineering treatment.

Regional geology and hydrogeology

Topography and geomorphology, stratigraphic lithology, geological structure, and hydrogeological conditions should be investigated. Particular attentions should be paid to dynamic conditions of karst collapse, which include relationships between groundwater and bedrock surface, primary runoff zones of karst groundwater and supply, runoff and drainage of surface and groundwater.

Geotechnical properties of overburden layer

The characteristics of overburden layer not only have important effects on the karst collapse, but also are the main controlling factors. Because the impact on the collapse depends on the geotechnical properties of the overburden the genetic type, structure, thickness, physical and mechanical properties of the overburden layer should be investigated.

Inducing factors of karst collapse

Inducing factors of karst collapse include natural and human factors. Natural factors are related to drought and flood, heavy rain, and earthquake. Human factors include underground water exploitation, mine water drainage, and other human activities which could seriously influence the karst groundwater.

Investigation techniques and methods

Data collection and compilation

The following data about should be collected and compiled to study mechanisms and inducing factors of karst collapses: meteorology, hydrology, topography and geomorphology, stratigraphy and structure, earthquake, hydrogeology, engineering geology, remote sensing, geophysical exploration, drilling, disasters that have occurred, engineering and economic activities, social and economic situation, and development plan.

Remote sensing

Topography, karst collapse distribution, and engineering activities in the investigation area are typically interpreted by remote sensing. Remote sensing should be used prior to field investigation and run through entire project. Remote sensing will be a part of design compilation, fieldwork arrangement, indoor materials arrangement, and report compilation.

Geological survey

Before geological survey, typical stratigraphic section should be measured and stratigraphic column and comprehensive profile should be compiled. The profile scale is no less than 1:5,000. Alternatively, we can check the existing stratigraphic column and subdivide it according to actual need of the division of geological mapping unit.

Investigation route should be arranged according to the principles of combing traverse method with tracing method and combing visit with actual measurement. Traverse route should be perpendicular to the strike direction of strata and tectonic lines, and the direction of the landscape changes dramatically. All kinds of geological boundary, landscape boundary, and water sites along the investigation route should have control points. Continuous observation and detailed record should be made along the way. Control points should focus on karst collapse point, landscape boundary, geological boundary, tectonic line, key bed, phase change belt of lithology and lithofacies, well, spring, surface water, important engineering activity points, and other typical outcrops.

Geophysical exploration

Geophysical exploration method and layout area should be confirmed according to the distribution, development level and burial condition of underground karst, and the Quaternary soil structure. The exploration should be deployed mostly around important investigation zone and typical investigation zone.

Geophysical exploration should be closely combined with drilling. Geophysical exploration is generally performed prior to drilling so that the prospecting line and borehole location should be arranged according to the exploration results. During the drilling, in order to delineate the anomalies geophysical exploration can also be used if necessary. In order to ensure the quality of interpretations, two methods should be deployed at the same geophysical profile. The results of geophysical exploration need to be validated by drilling, and profile layout can also be used in a crossway for checking.

In order to obtain geophysical parameters, method test and physical property test should be carried out before the

geophysical exploration. The method test of geophysical exploration should be arranged at the profile along which boreholes data are available.

Geophysical survey lines should be perpendicular to the major axis of variation of geological properties, such as tectonic line, groundwater flow direction, and karst development direction.

The purpose and applicability of the main geophysical exploration methods for karst collapse can be found in Table 1.

Drilling

On the basis of full use of the drilled borehole data, borehole position and drilling footage should be arranged to obtain property, structure, and thickness of the overburden, development characteristics of covered karst and the demand on engineering test on rock and soil, monitoring and working accuracy. Boreholes should serve multi-purpose if necessary. For example, borehole geophysical prospecting and monitoring can be employed in one borehole.

Boreholes are arranged along the prospecting line which is perpendicular to the direction of topography and tectonic line and control different landform unit, rock-soil mass type, and karst developing area. The prospecting line in intensive section of karst collapse should be arranged along the primary direction of collapse, such as extension direction of the cone of depression and direction perpendicular to the shoreline near the river and lake. Short transverse profiles should be added to improve control precision if necessary.

Hydrogeological drilling should consider the requirement of verifying the hydrogeological structures, obtaining hydrogeological parameters, and validating the interpretation results of geophysical exploration. And engineering geological drilling should focus on identifying engineering properties of the overburden and lithology of the underlying bedrock.

In order to satisfy the requirement of groundwater level measurement and borehole geophysical exploration, PVC pipeline should be installed in each borehole with water level and geophysical hole, and initial hole should be protected properly.

Exploring trench and shallow bored well

Appropriate work of exploring trench and shallow bored well should be assigned to typical karst collapses or potential danger points in order to fully understand the Quaternary soil properties and construction and obtain undisturbed samples.

Test and experiment

Tests and experiments that should be arranged in the investigation of karst collapse are listed in Table 2.

Monitoring dynamic conditions of karst collapses

Because the variation of water (air) pressure in underground karst conduits is the main dynamic factor for most karst collapse, the dynamic conditions of groundwater should be monitored during the period of investigation. Monitoring site should be arranged in karst developed area, strong runoff zone, or the area where the engineering activity is intense in the important investigation zone. Each monitoring site should monitor Quaternary pore water level (if available) and water (air) pressure in underground karst conduits. Monitoring duration should be no less than 1 hydrological year, and sampling interval should be less than 20 min.

Susceptibility assessment of karst collapses

On the basis of the investigation data (1:50,000) collected on karst collapses, the susceptibility assessment of karst collapse should combine the qualitative and quantitative methods. Morphological characteristics and distribution patterns of karst collapse should be analyzed. Development phases of karst collapses should be ensured. Intensity, development rate, and frequency of the karst collapses should be evaluated. Formation conditions and main control factors of karst collapses should be confirmed. Inducing factors, their dynamic changes, and their relationship to karst collapses should be assessed. The composition and distribution characteristics of karst water system, replenishment, runoff and discharging conditions, and dynamic variation characteristics of water level and discharge should be analyzed.

The susceptibility of karst collapse is assessed by taking four factors (but not limited to) into account:

- Development level of underground karst.
- Overburden properties.
- Dynamic condition of groundwater.
- Densities of the collapses.

The effect of a single factor on the susceptibility of karst collapses is determined by analyzing the interaction of rock, soil, and water which affect the formation of collapses.

Table 1 Geophysical exploration methods for karst collapse

Exploration purpose	Geophysical exploration methods	Application conditions
Overburden structure and thickness	Geological radar method, seismic refraction method, high-density resistivity method, seismic reflection method	Under general conditions: (1) Depth-determining Set D = detection depth (m) When $D < 10$ m: geological radar method, seismic refraction method, Rayleigh wave method
Deep and undulation of bedrock	High-density resistivity method, Rayleigh wave method, seismic refraction method, seismic reflection method, geological radar method, transient electromagnetic method, audio or controllable source audio magnetotelluric method	When $10 < D < 30$ m: seismic refraction method, Rayleigh wave method, high density electrical sounding method, seismic reflection method
Soil cave, soft soil, collapse	Geological radar method, seismic refraction method, high precision gravimetric method, Rayleigh wave method, high-density resistivity method, radioactivity method	When $30 < D < 50$ m: high density electrical sounding method, seismic reflection method
Karst cave and fissure	In-well geophysical method, high-density resistivity method	When $D > 50$ m: high-density resistivity method, transient electromagnetic method, natural electric field method, In-well geophysical method, high-density resistivity method, transient electromagnetic method, audio or controllable source audio magnetotelluric method
Underground river and Karst reservoir leakage	Charging method, natural electric field method, In-well geophysical method, high-density resistivity method, transient electromagnetic method, audio or controllable source audio magnetotelluric method	(2) Other positioning methods High density joint section method, charging method, natural electric field method, high precision gravimetric method, radioactivity method, microdynamic method
Groundwater flow velocity and flow direction	Charging method, natural electric field method	(3) Qualitative methods Water abundance: polarization method, microdynamic method
Ancient river road	High-density resistivity method, seismic reflection method, transient electromagnetic method, audio or controllable source audio magnetotelluric method	(4) High precision positioning In-well geophysical method: borehole radar, cross-hole electromagnetic wave method, cross-hole acoustic wave method, cross-hole resistivity imaging, etc.
Weathering zone	Seismic refraction method, high-density resistivity method, Rayleigh wave method	
Karst and non-karst contact surface and water rich zone	High-density resistivity method, transient electromagnetic method, audio or controllable source audio magnetotelluric method, polarization method, microdynamic method	
Fault, fractured zone, karst development zone and water rich	High-density resistivity method, seismic refraction method, transient electromagnetic method, controllable source audio magnetotelluric method, radioactivity method, microdynamic method, induced polarization method	
Rock mass loose zone, rock integrity, dynamic elastic mechanics parameters	Seismic refraction method, acoustic logging	

Table 2 Test and experiment

Test and experiment	Description	
In situ test	For natural soil, the common methods of in situ tests are static cone penetration test, dynamic penetration tests, standard penetration tests, and vane shear tests. In situ tests are generally conducted in combination with drilling	
Tracer test	In order to determine the distribution, velocity, direction, and cave conduit system underneath collapse, tracer tests should be arranged if necessary	
Pumping and injecting test	In order to find out the permeability and water abundance of aquifer and acquire hydrology parameters, pumping tests could be arranged if necessary. And injecting test could be arranged if pumping test conditions don't exist	
Laboratory test	Geotechnical test	The ordinary geotechnical indexes conclude water content, density, and specific weight of soil particles, grain composition, water ratio limit, shear strength, wetting-induced disintegration characteristic and expansion rate, and so on
	Seepage deformation test	Critical hydraulic gradient of seepage deformation occurs under the effect of groundwater is measured to confirm the development criterion of karst collapse
	Rock experiment	Chemical analyst should be done for carbonate rocks. The content of CaO, MgO, SiO ₂ , and R ₂ O ₃ and other constituents should be measured. Specific solubility and specific corrodibility could be measured if necessary
	Chemical analysis	Simple analysis of water samples is essential to determine the water chemical properties and groundwater type. Specialized analysis to the corrosion capacity could be done if necessary

Results

Maps

A series of maps in standard formats should be compiled. The maps consist primary data map, synthetic hydrogeological map, Quaternary soil structure and isopach map, karst collapse distribution map, zoning map for karst collapse susceptibility, and zoning map for karst development level. Additional maps are produced according to the actual conditions. The map specifications should be compiled using plaintext editor.

Databases

The databases include original information database and comprehensive achievement database. The metadata which reflects the quality of data should be constructed in the same step.

The original information database includes collected data, field investigation data, drilling data, geophysical data and achievements, sample testing data and report, and other related data.

Comprehensive achievement database includes achievements of the statistical analysis to the investigation, spatial data of the result maps and other project-specific databases.

Reports

The maps and specifications should be compiled after each sheet (quadrangle) investigation is completed. The

comprehensive reports should be compiled after the investigation to all sheets of the entire karst unit is finished.

Conclusions

This standard stipulates the objective of investigation, survey area classification and basic work, design document compiling, investigation content, technical methods and primary demands of investigation, comprehensive evaluation, database construction, data compilation and achievement establishment, quality control examination, and achievement acceptance metrics.

The basic principles of the Standard Guide for Karst Collapse Investigation (1:50,000) are as follows:

- Focusing on key point data and taking into account the general conditions.
- Stressing the distribution of geological disasters.
- Emphasizing on the investigation of regional geological conditions.
- Emphasizing on the investigation of the formative mechanism of disasters.
- Combining various survey methods such as remote sensing, geological survey, exploration, test, and experiment.
- Making full use of new technologies such as 3S technology, geophysical prospecting, in situ test, tracing, and automatic monitoring technology.

The standard can be applied to karst collapse investigation on scale of 1:50,000 and can a reference in the investigation and exploration of karst collapse on other scales.

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