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Land subsidence hazards in Hanoi, Vietnam

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Abstract: The study area is located in the southwest of Hanoi, the capital of Vietnam, encompassing the districts of Quoc Oai, Chuong My, My Duc, and Ung Hoa. This region is densely populated and has experienced frequent collapses and land subsidence over the years. Notably, these phenomena have persisted into 2023. The foundation structures in the southwestern part of Hanoi are categorized into five types, with Quaternary sediments forming the upper layer and limestone constituting the base. The formation of Quaternary sediments over the Dong Giao Formation limestone is closely linked to the transgressive and regressive processes that occurred during the Quaternary period. Based on geological research, geophysical studies, and wellbore analysis, the authors have drawn the following conclusions: 1. The collapses are associated with underground karst activity, and 2. Urbanization and underground exploitation are key factors contributing to the increasing frequency of collapses. These research findings are scientifically significant and serve as a valuable resource for identifying and warning about geohazards in areas with similar geological conditions. They also support efforts toward achieving the Sustainable Development Goals.

Keywords: Collapse, land subsidence, geohazards, karst, Quoc Oai, Chuong My, My Đuc, Hanoi

INTRODUCTION

The capital, Hanoi, is located in the Red River Delta region. This is a region with a complex geological structure. The formations distributed in the study area include the Tan Lac Formation (T1otl); Song Boi Formation (T2-3sb); Đong Giao Formation (T2ađg); Vinh Phuc Formation (Q13vp); Hai Hung Formation (Q21-2hh); and Thái Bình formation (aQ23tb) (Figure 7). The formation of the Red River Delta region is closely tied to periods of transgression and regression. At present, the bedrock in the Red River Delta is largely weathered, with remnants of limestone predominantly found in the western part of Hanoi. This area, which serves as a densely populated hub, is also a key political and economic center. Geological borehole studies reveal that the upper layer consists of Quaternary sediments, while the lower layer comprises limestone containing numerous karstic caves.

Research on geohazards related to karst is of interest to many geologists (Derek & Paul, 2007; VIGMAR, 2008; Le Canh Tuan, 2009, 2019, 2020; Binh & Duc, 2013; Binh, 2015, Binh *et al*., 2021; Petar T. Milanovíc, 2018; Thinh *et al.*, 2022; Phu *et al.*, 2022; Amina & Ali, 2023). The study area is located to the west of Hanoi, in the Chuong My, and Quoc Oai districts, and part of the Ung Hoa District (Figure 1). Research results show that collapse has been occurring for many years. A typical example is the April 6, 2021 collapse in Village 2, Quang Bi commune, Chuong My District, which caused alarm among residents. The collapse phenomenon in Hanoi happened in 2008 in Yen Son commune, Quoc Oai District, Hanoi. Since then, collapses have occasionally occurred in the My Duc district, Chuong My District, and Ung Hoa District. In 2023, collapses have continued in Dong Tien commune, Ung Hoa District. We predict collapse will continue to happen in the future.

The main concern is that these collapses occur in densely populated areas, causing significant anxiety and fear among residents. In affected locations, households have been forced to evacuate. Following the incidents, authorities in Hanoi implemented emergency measures to address the situation.

The collapses in the southwestern region of Hanoi are a serious and dangerous phenomenon, likely linked to underground geological formations. Systematic research is urgently needed to accurately identify the causes of these collapses, providing a foundation for effective prevention and recovery strategies. This research is critical and should be prioritized. Its findings will play a key role in identifying and warning against geohazards, contributing to the sustainable development of Hanoi.

MATERIALS AND METHODS

Methods

To solve the above goals and tasks, we choose the following research methods:

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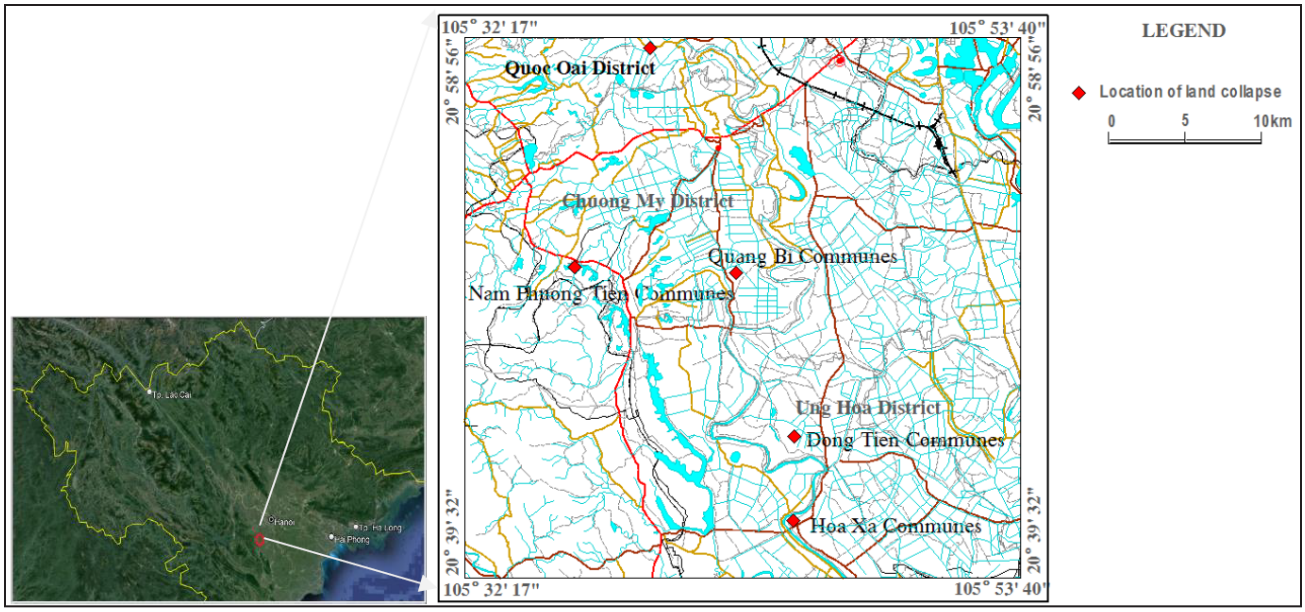


Figure 1: Location of the collapses in the southwest, Hanoi.

Collect and analyze documents

Collect and process all the study area's geological, hydrogeological, and engineering geological documents. Especially research on collapse and borehole documents (VIGMR, 2008; Binh & Duc, 2013; IWRE, 2020; Le Canh Tuan, 2020; Binh *et al*., 2021, Institute for Environment and Resources- Consultancy, Technology Development and Construction in Mining and Geology Company Limited, 2023).

Field investigations

The field investigation method aims to collect data and information about the collapse phenomenon. Tasks include locating collapsed areas and surveying the current status of underground water exploitation and usage (Figure 2). Information that needs to be investigated includes stratigraphic geology, borehole density, borehole depth, exploitation flow, and water level measurements in well bores and boreholes. All of the above information was compiled and analysed to find their relationship with the phenomena of land subsidence and collapse.

Survey and study of wells of surrounding people and areas where land subsidence and collapse have occurred were carried out, including at places where walls have cracked, and wells had no water (Figure 3).

We also investigated and interviewed people in areas where land subsidence and collapse had occurred.

Geophysical methods

Geophysical methods are very suitable for studying deep structures. Based on this, different types of rocks have different electrical resistivities. Weathered rocks and Quaternary sediments often have low electrical resistivity, from a few Ωm to a few hundred Ωm. Solid bedrock has higher electrical resistivity than weathered rock. The

Figure 2: Survey of groundwater exploitation parameters.

Figure 3: Survey and collect information at places where land subsidence occurred.

difference in electrical resistivity of bedrock, karst caves, and unconsolidated sediments is the physical basis for applying the electrical resistivity measurement method. Karst caves often contain water and Quaternary sediments, which are excellent electrical conductors and can be detected by electrical resistance measurement. We designed and carried out geophysical measurement lines where land subsidence and collapse occurred (Figure 4).

We used a geophysical meter called ES-4 made in Vietnam, AB distance between two current electrodes, MNmax = 40 m (Figure 5). Geophysical methods are very effective for the in-depth study of structures. The ES-4 machine is used to determine the underground caves. The ES-4 gauge gives accurate readings to a depth of 250 m.

In the research area, we used a 4 symmetrical poles equipment system with the following distance: AB = 440 m, MN = 40 m, d = 5 m.

In which:

AB - distance between two current electrodes

MN - distance between two potential electrodes

d - is the distance between two measuring points.

In addition, the authors also used the Ni004 altimeter of the German Democratic Republic to measure altitude and the 2 m Invar staff to measure land subsidence.

Figure 4: The route diagram measures the depth of polarized excitation and the number.

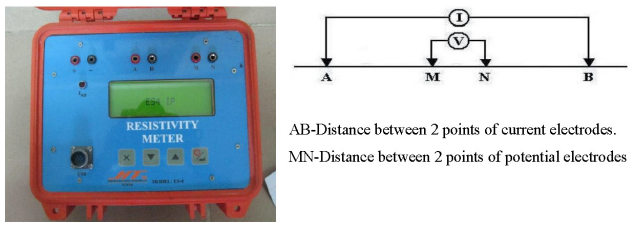


Figure 5: Determination of underground cave by ES4 machine in land subsidence area of Hanoi.

Figure 6: Well-bore geological survey, karst cave identification, and sampling.

Geological drilling studies deep structures

Researching well-bore structures is very important work for interpreting, identifying causes, and proposing remedial measures. At locations where land subsidence occurred, we conducted geological survey drilling, took samples for testing and analysis, and performed water pumping experiments (Figure 6).

Material

Materials examined in the study include:

• Research documents on geology, geomorphology, tectonics, structure, hydrogeology, and geophysics in the southwest region of Hanoi (Toan *et al*., 1994; Lam *et al*., 2019).

• Researched documents on land subsidence of the study area:

1. Research document on land subsidence in Quoc Oai District, Hanoi (Toan *et al*., 1994; Lam *et al*., 2019).
2. Research document on land subsidence in Hoa Xa from the Institute of Water Resources and Environment (IWRE, 2020).
3. Research document on land subsidence in Doan Xa commune, Dong Tien District from the Institute for Environment and Resources - Consultancy, Technology Development and Construction in Mining and Geology Company Limited.

• Data of borehole, the area where collapse and land subsidence occurred and the areas surrounding the collapse, land subsidence area.

• Documents related to the karstifications process, geohazards related to karst.

• Data of field investigations.

RESEARCH RESULTS

Results

Overview of the geology of southwest Hanoi

The study area has a complex geological structure, with long-term geological activities, from about 300 Ma. The results of the 1:50,000 scale map from the geological research are as the following (Toan *et al*., 1994) (Figure 7):

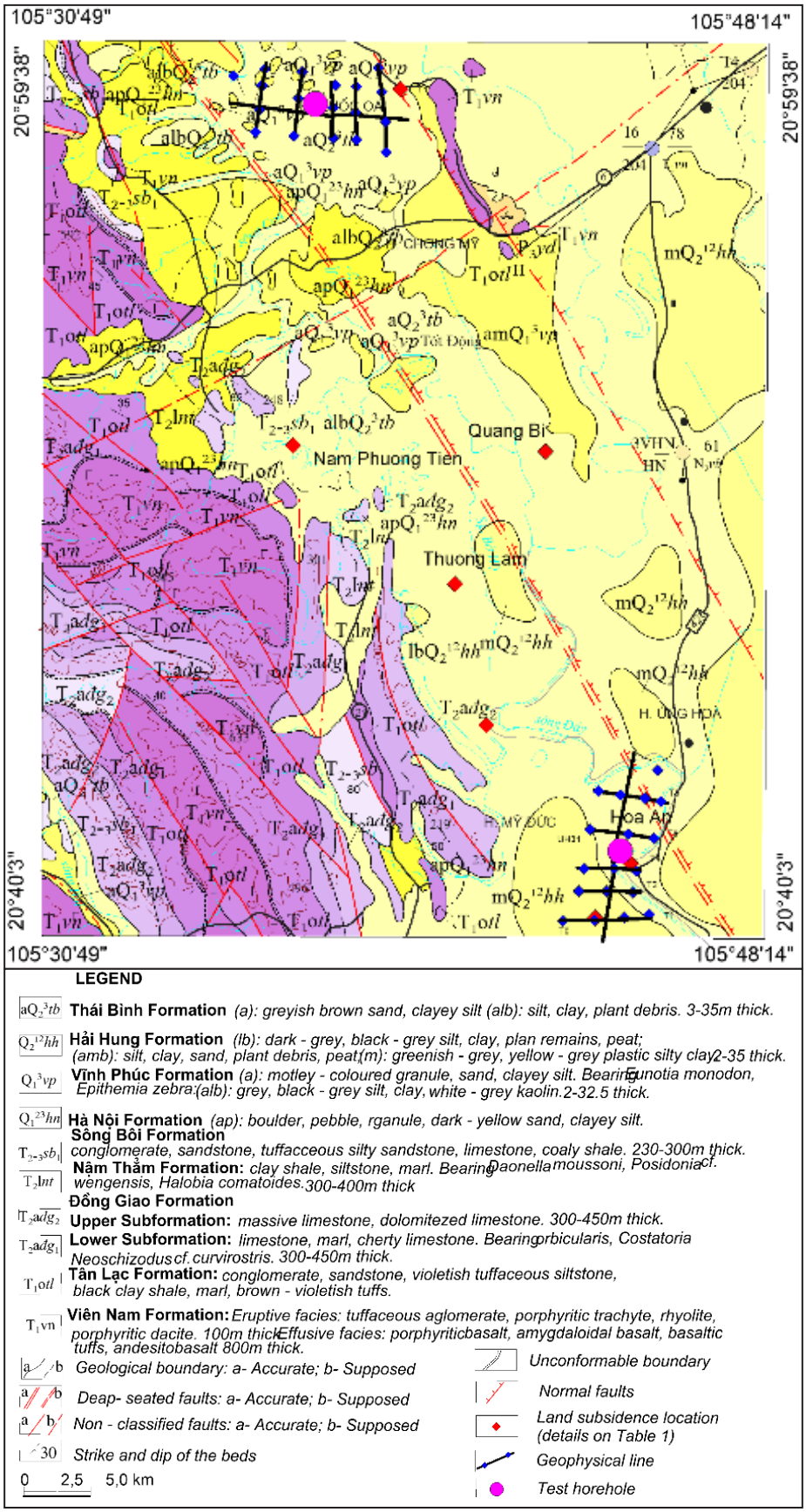


Figure 7: Geological map and location of land subsidence.

Thai Binh Formation (aQ23tb)

Fluvial sediments (aQ23tb): distributed along rivers and streams. The main composition is sand, silt, clay, gray, thickness from 5 to 35.5 m.

Lake faces-marshy faces sediments (albQ23tb): distributed in Van Tri, Uy No (Dong Anh District), and My Duc areas. The composition is silt and clay mixed with many plant debris, some places have peat lenses in the lower part of the section.

Hai Hưng Formation (Q21-2hh):

Lake faces- marshy faces sediments (lbQ21-2hh): formed before the Flandrian transgression. These sediments are distributed in Ba Vi, Yen Lang, Binh Xuyen, Hiep Hoa Yen Phong, and some other places (Son Dong and Hoai Duc districts). The formation is composed of dark gray, black-gray clay and silt-bearing plant debris and lenses of peat. The total thickness of the formation reaches 13.5 m. The peat has excellent reserves (0.5–3.6 m thick) and excellent quality.

Fluvio-marine-marshy sediments (ambQ21-2hh): distributed limitedly in Chau Giang, Thanh Oai, and Thuong Tin areas, they are not on the surface, only found in boreholes. Composition is silt and clay mixed with fine-grained sand, black-gray sandy mud, peat, bearing wood remains, and Early-Middle Holocene. This formation underlies conformably marine blueish clay of also Holocene age.

Marine sediments (mQ21-2 hh): distributed rather largely in Thanh Oai, Thuong Tin, and My Duc, and within boreholes from Son Đong-Nhon toward the south and southeast of the Hanoi Map sheet. They are composed mainly of blueish-gray, yellowish-gray plastic, fine-grained clay, and silty clay, about 6 m thick.

Vinh Phuc Formation (Q13vp)

Fluvial sediments (aQ13bvp): These sediments are distributed in Vinh Yen, Hiep Hoa, Me Linh, Soc Son, Dong Anh, Thach That, Viet Tri, etc. They create terraces on an elevation of 6–20 m. In addition, they have been met within boreholes at a depth of 20–40 m. The composition is sand, silt, and clay, 6.2–38 m thick.

Fluvio-lacustrine-marshy sediments (albQ13bvp): These sediments are distributed in the Soc Son and Vinh Yen areas. Ingredients include gray silt and clay, black-gray clay, white-gray kaolin, 5–32.5 m thick. Their age is Pleistocene.

Fluvio-marine sediments (amQ13bvp): These sediments are distributed in Quoc Oai, My Duc, Ung Hoa, Mai Lam, and Tu Son. The composition is gray clay and silt mixed with a little sand, 2.5–19.6 m thick.

Ha Noi Formation (Q12-3hn)

Fluvio-proluvial sediments (apQ12-3ahn): distributed in the form of terrace II in Xuan Mai, Thach That, Hoa Lac, Viet Tri, Da Phuc, Kim Anh, and Hiep Hoa areas. In the plain, they have been met within deep boreholes.

The composition includes boulders, pebbles from quartz, chert, sandstone, gritstone, effusives, and some volcanic debris from 2.5 to 6 m thick.

Dong Giao Formation (T2ađg)

Lower subformation (T2ađg1): black-gray, thin- to medium-bedded (10–40 cm), fine-grained, easy to be separated by the bedding surface, clayey limestone and limestone which grades gradually into cherty limestone, 300-450 m thick.

Upper subformation (T2ađg2): conformably lying upon the lower subformation, it is composed of ash-gray, light-gray thick-bedded, locally bearing chert, marbleized or dolomitized limestone that grades gradually into white-gray, fine-grained, thick-bedded or massive limestone; 300–450 m thick.

The total thickness of the formation reaches 600–900 m.

Song Boi Formation (T2-3 sb)

Lower Subformation (T2-3 sb1): basal conglomerate, sandstone, silty sandstone, tuffaceous siltstone, siltstone, locally violetish medium-bedded sandstone, lenses of limestone (sometimes 30–40 m thick) or grading upward to stripped clay shale, interbeds of coaly shale; thickness: 230–300 m.

Upper Subformation (T2-3 sb2): light gray sandstone, silty sandstone interbedded with black clay shale, violetish siltstone grading upward to black clay shale, siltstone, sandstone, locally some interbeds of black-gray limestone, 250–300 m thick.

The total thickness of the formation reaches 480–600 m.

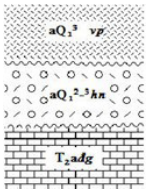
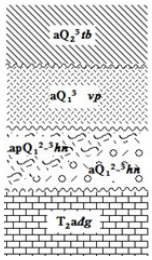
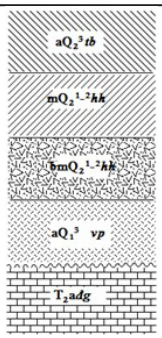
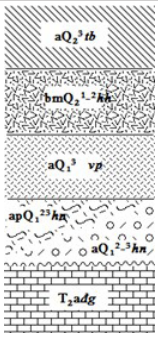
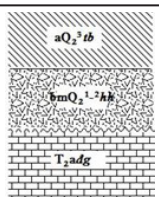
Tan Lac Formation (T1otl): conglomerate interbedded with chocolate, yellowish-gray sandstone, tuffaceous siltstone. Pebbles of conglomerate consist of basalt, quartz, sandstone, siltstone, limestone, and clay shale grading upward into gray marl, black clay shale, and gray siltstone, the cement is composed of mafic effusiveness. The total thickness of the formation reaches 890 m.

T1vn: composed of greenish-gray, dark gray porphyritic basalt, amygdaloidal basalt, and their tuffs. Phenocrysts in basalts usually consist of sericitized plagioclase and a little actinolitized pyroxene. The groundmass consists of a crypto- or microcrystalline association including glass, plagioclase, biotite, actinolite, epidote, and sericite. The ratio between phenocrysts and groundmass varies very largely. Thickness (about 800 m).

Characteristics of engineering geology

Based on the research of 58 boreholes in Quoc Oai, 28 boreholes in Hoa Xa, 47 boreholes in Quang Be, and 34 boreholes in Nam Phuong Tien and Thuong Lam, combined with existing studies (Binh & Duc, 2013; Binh, 2015; Binh *et al*., 2021), we analyzed and divided the southwest region of Hanoi into 5 types of foundation structures (Table 1). The types of foundation structures that formed are a strong interaction of karstification, neotectonic activities, and transgressions and regressions.

Table 1: 5 types of foundation structures in the study area.

Foundation structure type	Stratigraphical section according to borehole	Petrographic composition
Type 1		Clay, clay loam is lateritized, patchy, yellow-brown, and yellow-gray.
		Clay, clay mixed with grit, pebbles, gravel, and sand.
		Gray limestone, fractured, strongly broken, with many karst caves
Type 2		Clay, sandy clay loam gray, yellow-brown, small sand grains gray-brown, and yellow-gray.
		Clay, clay loam is lateritized, patchy, yellow-brown, and yellow-gray.
		Clay, clay mixed with grit, pebbles, gravel, and sand.
		Gray limestone, fractured, and strongly broken, with many karst caves.
Type 3		Clay, sandy clay loam gray, yellow-brown, small sand grains gray-brown, and yellow-gray.
		Clay is blue-gray, smooth, and sticky clay.
		Silty clay, sandy clay loam gray, mixed with organic matter, and dark gray sand.
		Clay, clay loam is lateritized, patchy, yellow-brown, and yellow-gray.
		Gray limestone, fractured, and strongly broken, with many karst caves
Type 4		Clay, sandy clay loam gray, yellow-brown, small sand grains gray-brown, and yellow-gray.
		Silty clay, sandy clay loam gray, mixed with organic matter, and dark gray sand.
		Clay, clay loam is lateralized, patchy, yellow-brown, and yellow gray.
		Clay, clay mixed with grit, pebbles, gravel, and sand.
		Gray limestone, fractured, and strongly broken, with many karst caves.
Type 5		Clay, sandy clay loam gray, yellow-brown, small sand grains gray-brown, and yellow-gray.
		Silty clay, sandy clay loam gray, mixed with organic matter, and dark gray sand.
		Gray limestone, fractured, and strongly broken, with many karst caves.

Geophysics measurement results combined with verification drilling

In the area where subsidence occurred, we designed resistance survey lines (Figure 4). Geophysical measurement results are linked with wellbore data to explain the cause of land subsidence (Figure 8).

During the borehole process, we carefully monitor the soil and rock composition from top to bottom, stratigraphically describe it, take samples, and record field logs carefully. The boreholes are linked to geophysical measurements to interpret the results.

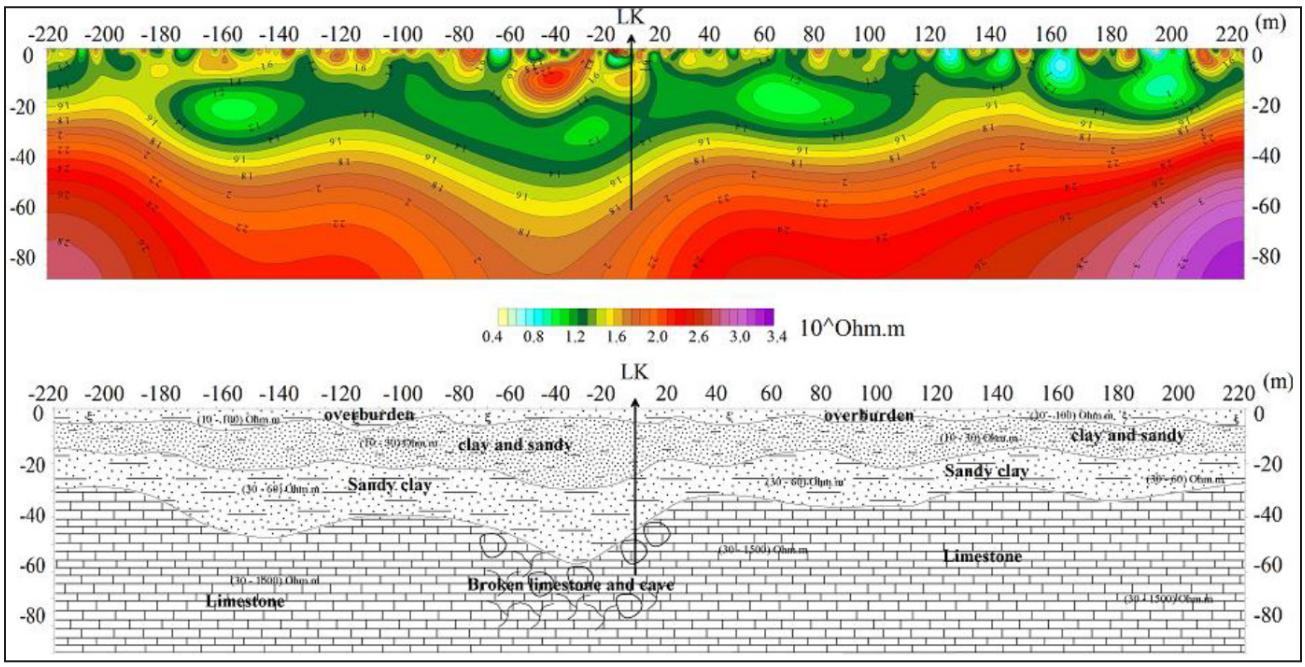


Figure 8: Structural interpretation of places where land subsidence occurred using geophysical and well-bore methods.

DISCUSSION

Geohazards related to karst regions are of great interest to many authors. Some notable studies (VIGMR, 2008; Derek & Paul, 2007; Binh, 2015; Binh *et al*., 2021; Petar T. Milanovíc, 2018; Le Canh Tuan, 2019, 2020; Phu *et al*., 2022; Thinh *et al*., 2022; Amina & Ali, 2023) suggested that a phenomenon often occurs in karst areas.

The karst area southwest of Hanoi's capital is related to the limestone of the Dong Giao Formation (T2ađg). This is a region that has undergone a long and complex history of geological development. Before the Quaternary period, the study area was a mountainous area, formed by limestone and terrigenous rock deposits. Also during this time, endogenic and exogenic geological processes combined with karstification occurred, causing the Hanoi area to experience strong subsidence (Tapponnier *et al*., 1986). The cavities within the limestone blocks in the southwest of the capital, Hanoi, are due to the karstification process, carried out by the dissolution of limestone:

$$CaMg(CO_3)_2 + 2CO_2 + 2H_2O \leftrightarrow Ca^{2+} + Mg^{2+} + 4HCO_3^- \quad (1)$$

Equation (1) is simulated by Derek & Paul (2007) and Petar T. Milanovic (2018) in Figure 9.

The process of dissolving limestone according to reaction (1) has formed karst caves. In the Quaternary period, the Hanoi Delta was formed. Together with river activities, five types of soil structures have been created as in Table 1 (Binh, 2015; Binh *et al*., 2021).

From 2008 to the present, in the southwest of Hanoi, land subsidence has occurred many times. Table 2 provides some typical landslides.

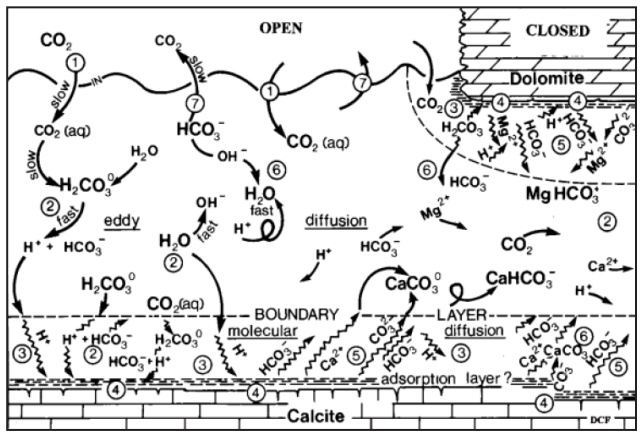


Figure 9: The process of dissolving rocks of karst landform (Derek & Paul, 2007; Petar T. Milanovic, 2018).

In November 2008, when a borehole took water for domestic use at km16, provincial road 419, Quoc Oai town, land subsidence occurred, destroying 2 houses; the danger radius was from 30 m to 40 m (Figure 10). This geohazard incident caused serious damage to property and infrastructure, greatly affecting the lives of some households in the area. It also caused a lot of confusion among people and local authorities (VIGMR, 2008). This land subsidence process is related to foundation structures type 1.

On April 2, 2011, land subsidence occurred in Xuy Xa commune, My Duc District. The land subsidence destroyed a section of a road; the subsidence area was about 100 m^2, and the subsidence was about 0.7 m deep, causing the structure to collapse. This land subsidence process is related to foundation structures type 5.

Table 2: Location of land subsidence areas in Hanoi from 2008 to 2023.

No	Year	Location	Area of influence
1	2008	km16, provincial road 419, Quoc Oai town	Destroying 2 houses, the danger radius was from 30 m to 40 m.
2	2011	Xuy Xa commune, My Duc District	The subsidence area was about 100 m^2, the subsidence was about 0.7 m deep.
3	2020	Thuong Lam commune, My Duc District	The land subsidence hole was 18.5 x 6.5 m in size.
4	2021	Quang Bi commune, Chuong My District	The diameter of the sinkhole was about 60 m.
5	2023	Dong Tien commune, Ung Hoa District, and Dong Quang commune, Quoc Oai District	The diameter of the sinkhole was about 50 m.

Figure 10: Land subsidence in Quoc Oai in 2008.

In 2016 and 2019, land subsidence occurred in An Tien commune, My Duc District. In April 2020, land subsidence occurred in Nam Phuong Tien commune. This land subsidence process is related to foundation structures type 5.

In May 2020, when a borehole took water for domestic use in Thuong Lam commune, My Duc District, land subsidence occurred, the land subsidence hole was 18.5 x 6.5 m in size. This land subsidence process is related to foundation structures type 5.

In April 2021, land subsidence occurred in Quang Bi commune, Chuong My District; the diameter of the sinkhole was about 60 m. This land subsidence process is related to foundation structures type 3.

In July 2023, land subsidence occurred in Dong Tien commune, Ung Hoa District, and Dong Quang commune, Quoc Oai District. This land subsidence process is related to foundation structures type 5.

In certain areas, land subsidence is caused by well drilling and water extraction from karst caves. In other locations, it occurs suddenly without any apparent human influence. Research findings have confirmed that collapses and land subsidence are closely associated with karst caves located beneath Quaternary sediments. What is particularly concerning is that these subsidence sites are situated in residential areas and key economic centers. Consequently, human activities have amplified the geohazard risks in the southwestern region of Hanoi. The karst formations of the study area develop in the NW-SE direction. This is Triassic limestone (T2ađg) with a very high karstification, with many karst caves. In addition, the tectonic activities from faulting that caused fractures to limestone were strong. The phenomenon of collapse and land subsidence in the study area is due to the activity of underground karst.

Based on the geological data (Toan *et al*., 1994), combined with geophysical measurements and borehole documents, the authors have determined the following geological structure in the southwest of Hanoi city:

- From 0 to 35 m is Quaternary sediments
- From a depth of 35 m down is the Dong Giao limestone formation with high karstification, with many karst caves.
- Drilling results have determined that the depth of the karst cave causing collapse and land subsidence ranges from 40.0 to 42.5 m.

The depth of karst caves depends on the thickness of the overburden and the distribution of karst formations in each region.

Based on research documents on geohazards in karst areas in Vietnam (VIGMR, 2008; Binh *et al*., 2013, 2021; IWRE, 2020; Le Canh Tuan, 2020), we give three causes of collapse and land subsidence in the southwest of Hanoi i.e., due to the weight of the Quaternary sedimentary overburden above the limestone, due to underground water drilling, and building the infrastructure. The solution is to drill, and bring sand-cement solution and bentonite down to the collapse and land subsidence for reinforcement. Because the collapses and land subsidence in the study area range from a few meters to 20–50 m in diameter, we use a sand-cement-bentonite solution sprayed at high pressure, causing the strength of the ground to increase. The depth of treatment is from 39.0 m to 45.0 m, the holes are 1.5 to 2 m apart, the thickness of the concrete is 15 m, and the radius of the concrete is 20 m from the location of the borehole.

CONCLUSIONS

The study area is located in the southwest of Hanoi, where the surface is covered by Quaternary sediments ranging from 36 to 52 meters in thickness, classified into five distinct types. Beneath these sediments lies the limestone of the Dong Giao Formation (T2ađg), which contains numerous karst caves. Most instances of land subsidence in the area are linked to human activities, such as water extraction

from karst caves. This subsidence has caused significant damage, including house collapses and cracked walls, due to the activity of underground karst within the Dong Giao Formation. The depth of the karst caves responsible for these incidents ranges from 40.0 to 42.5 meters. While temporary solutions have been implemented to address the problem, Hanoi urgently requires systematic research to develop long-term strategies and support its sustainable development.

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AUTHORS CONTRIBUTION

All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by NCG, LCT, TTL and NQM. The first draft of the manuscript was written by NCG and LCT, and all authors commented on previous versions of the manuscript. Supervision, conceptualisation, writing-review, and editing by LCT. All authors read and approved the final manuscript.

COMPETING INTERESTS

The authors declare that they have no competing interests

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