Sinkhole Effects on Bridges in the World

Mohammad H. Nateqi, Hamed Niroumand

Abstract— Sinkhole is considered as a precarious phenomenon which has occurred in various countries of the world. Sinkhole is thought of a close surface depression appeared on the ground usually in Karst landscapes which is generally triggered by dissolution of underlying susceptible rocks. Due to groundwater circulating, these carbonate rocks are gradually dissolved. As a result of dissolution, some spaces, caverns or even caves will develop underneath. Over a time, these cavities either remain as underground caves or cause unpredictable collapses. Although sinkholes may vary in size and shape, they are commonly formed in circular and cylindrical shapes. Sinkholes can cause major damages to buildings and personal properties. They may also incur damages to structures. The purpose of this paper is to mention destructive effects of sinkholes on the general topography of the area and also all surrounding buildings including bridges. It also provides an overview of bridges destroyed or damaged in Sinkhole catastrophe across different countries.

Keywords— bridges, damages, effects, sinkhole, world

I. Introduction

SINKHOLE is a common scientific term which is generally used to describe either a steep walled hole in the ground or a depression on the ground surface [1], [2]. These spaces beneath the ground surface might be developed by groundwater exploitation [3], dissolution of carbonate and evaporite (susceptible) rocks – usually known as soluble rocks [1] and erosion of overburden soils [4], or Karstification in particular – usually refers to a type of landscape where the underlying bedrock formations are dissolved by water [5]. Each reason has been detailed below:

A. Groundwater Exploitation

The main reason of sinkhole occurrence is anthropogenic use of water and decline of water level due to groundwater pumping and aquifer exploitation [1]. Even though solution of susceptible rocks has influence over the creation of sinkholes, pumping the groundwater increases downward percolation of groundwater from the overlying superficial layers and causes the gradual dissolution of rocks significantly [6]. Sinkholes in the northern plains of Hamadan province, Central plain, present threat for people and human structures because of loss of buoyant support due to Groundwater over-exploitation [7].

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Despite regional geology of the study area, the mechanism of land subsidence and sinkhole occurrence are both supposed to occur because of ground water lowering [7]. Therefore, pumping a well can cause significant water level lowering (see figures 1 and 2) [8].

Fig. 1 Appeared sinkhole induced by decline in groundwater level due to over-exploitation from the thick alluvial cover and the underlying cavernous limestone, formed in Hamekasi, Hamadan. Adapted from [7]

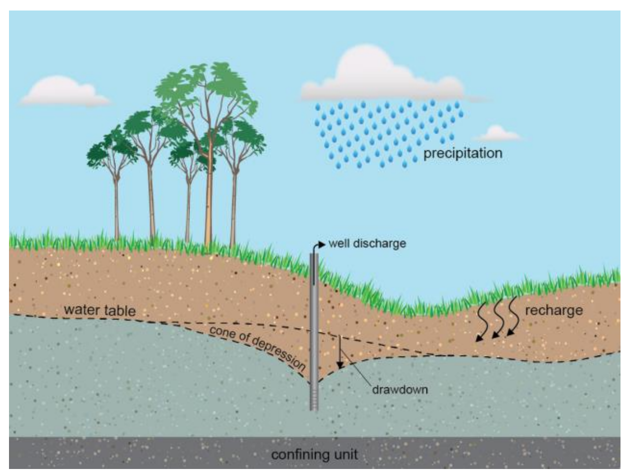

Fig. 2 Discharge of water from wells (groundwater exploitation) causes drawdown and water table lowering and eventually increases probability of sinkhole and Subsidence occurrence. [8]

B. Dissolution of Susceptible Rocks and Erosion of Soils

Studies into soluble bedrocks in most landscapes have shown that the main characteristic of these bedrocks is their potential in being dissolved by groundwater flow [9]. Some sinkholes occur when the bedrock beneath cannot support the ground surface and can naturally be dissolved by groundwater circulating through them [10]. As the bedrock dissolves, cavities or caverns develop underground. Thin soil layers and sediments over these spaces may be overburdened with an intense pressure. However, the aquifer systems are balanced by groundwater fluid pressure; In point of fact, groundwater helps to keep the surface soil in place. As these spaces appear in the bedrock, the possibility of sinkhole occurrence increases and forms in three formations: *Dissolution*, *Cover-subsidence*, and *Cover-collapse*:

Some sinkholes occur where groundwater is in contact with the atmosphere and limestone is exposed at the upper thin layers [10], [11]. This type of sinkhole is commonly called as Dissolution (or Solution) sinkhole (see figure 3). The solution sinkholes are mainly formed in those terrains with poor vegetation [10] and bare limestone [12]. Dissolution of underground limestone has been the main cause for sinkhole occurrence in the United States of America [10], [11]. Devil's Sinkhole State Natural Area (Texas) [13], Cedar Sink (Kentucky) [14], Deep Lake (Southern Florida) [15], Blue Hole (New Mexico) [16], [17], and Big Basin (Kansas) [18] are all obvious examples of dissolution-sinkholes occurrence (see figure 6).

Fig. 3 Dissolution Sinkhole. [19]

In areas where the overburden layers mostly contain non-cohesive granules such as sand, overlying sediments settle into cavities [10], [11], [20]; this process which is usually termed as *Piping* causes *Cover-subsidence* sinkholes [10], [11]. These sinkholes are related to subsidence induced by subsurface Karstification [1]. Formation period of time for cover subsidence sinkholes can vary from hundreds of years, to a couple days depending on the overburden layer thickness (see figure 4).

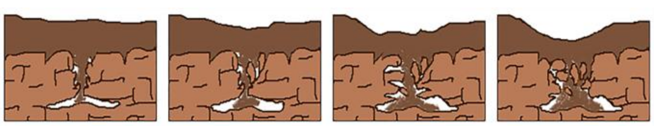

Fig. 4 Cover-Subsidence Sinkhole. [19]

Otherwise, where the overburden layers are cohesive covering sediments (mostly clay), lower layers of sediments start to be eroded and spall into the created cavities [10], [11], [20]. Eventually, the upward growth of the underground space forms a structural arch and might leave only a thin layer of soil which is not enough strong to support its own weight. As shown in figure 5, the arch collapses and causes the most hazardous sinkhole termed as *Cover-collapse* [10], [11], [21].

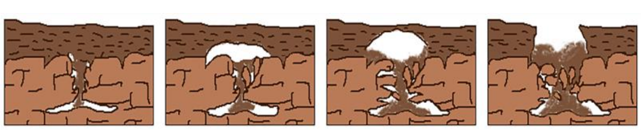

Fig. 5 Cover-Collapse Sinkhole. [19]

Fig. 6 Devil's Sinkhole State Natural Area; located in Northeast of Rocksprings in Edwards County, State of Texas, United States of America; Formed around one million years ago; in the shape of shaft: 50 ft (ca. 15.2 m) wide and 140 ft (ca. 42.7 m) deep; Preserved by Texas Parks and Wildlife Department. Adapted from [11], [13]

Fig. 7 Cover-Subsidence Sinkhole; formed underneath a US27 in Polk County, United States of America. Adapted from [4]

Fig. 8 Danvisky Cover-Collapse Sinkhole; appeared on January 1998, western Ukraine. Adapted from [1]

C. Karstification

Karst is defined as landforms produced through the dissolution of rocks, such as limestone, dolomite, gypsum, and salt. Due to dissolution of bedrock, various features of Karst appear and form as Sinkholes, Caves, Springs, Valleys, and

Sinking Streams. The main characteristics of these landscapes are flow of groundwater through the cavities, caverns, and conduits underneath and the dissolution of bedrock. Providing a stable foundation for the construction of roads, bridges, and buildings on Karst landscapes requires special engineering considerations. Sinkhole collapse, drainage problems, and groundwater contamination are considered as major engineering and environmental threats to Karst landscapes [22]. Karst topography generally plays a large part in increasing the possibility of sinkhole occurrence on bridges and also all those geologic and hydrologic factors which contribute to sinkhole collapse [23].

II. SINKHOLE HAZARD

Sinkhole occurrence has been known as a hazard associated with Karstic areas. Developed sinkholes on Karst landscapes may cause damages to human built structures and also threaten the human life [1], [24]. In spite of the fact that sinkhole hazards are investigated to reduce the risks, damages, and loss of life, the sinkholes are generally considered as a catastrophe for public life and human activities on Karst environments [1].

There is no damage until sinkholes are not identified and appeared on the ground surface. When a sinkhole occurs on upper layers, formed as a progressive subsidence (Cover-Subsidence Sinkhole) or in a sudden way and without any warning (Cover-Collapse Sinkhole), it will probably bring structural and environmental damages [25], [26]. Therefore, the load imposed by whether natural or human induced reasons may cause dangerous sinkholes which trigger severe damages to structures [1]. Both Cover-Subsidence and Cover-Collapse formations may damage roads, bridges, power transmission lines, pipelines, buildings, and farmland, and also lead to massive financial losses related to the repair of the damaged structure or infrastructures, serious traffic delays, disturbance to transportation system [26], disruption to transportation route serviceability, and accidents involving fatalities [27].

There are several preventive approaches used to reduce sinkhole damages on transportation infrastructures and structures built in Karstic areas: 1) Reduce the hazards and destructive factors associated with sinkhole development, for instance, pumping and irrigating farmlands; 2) Select an area off subsidence-prone zones beforehand and consider a route for road construction, a tolerable area for transportation infrastructure or a foundation design in a bridge construction; 3) Limit vulnerability of structures and reduce sinkhole hazard by engineering sinkhole-resistant designs [1], [27]. Most research in this field (Sinkhole Hazard Mitigation) has proved that selection and design of bridges built upon Karstic areas relies on special design of foundations and site investigations including geological-geomorphological mapping, geophysical surveys and closely-spaced boreholes [26].

Although scientific communities' achievements has been developed in assessing the Sinkhole Hazard, the amount of sinkhole damages to public life shows an increasing trend resulting from dramatic increase in population and the number of human structures in Karstic regions, sinkhole development due to human activities, increasing demands for water and energy, technical and political decisions without an enough understanding of the Karstification [1].

III. ANALYSIS OF SINKHOLES ON BRIDEGES

Investigating sinkhole occurrence and its consequences is essential in order to take the necessary precautions before any irrecoverable incidents. Characteristics of sinkholes occurred on bridges, usually in Karst terrains and their serious damages on these structures have been assessed below:

1. Ancient Yellow River Fault zone

The development of earth fissures, Karstic cavities and 17 occurred sinkholes are highly associated with rapid depletion of groundwater in Xuzhou urban area, Jiangsu province, China (see figure 9). Actually, the major role in developing of Karst features has been groundwater exploitation from the fractured Karst (limestone stratum) in urban and township areas. Moreover, in 1997, earth fissures occurred in Changjing township and cause damages to 387 houses and buildings, a 9,602.8 m^2 workshop, two bridges, and several sections of roads and underground pipelines [28].

The most ideal solution to the problem of sinkhole damages is to avert sinkhole development by controlling groundwater exploitation [28].

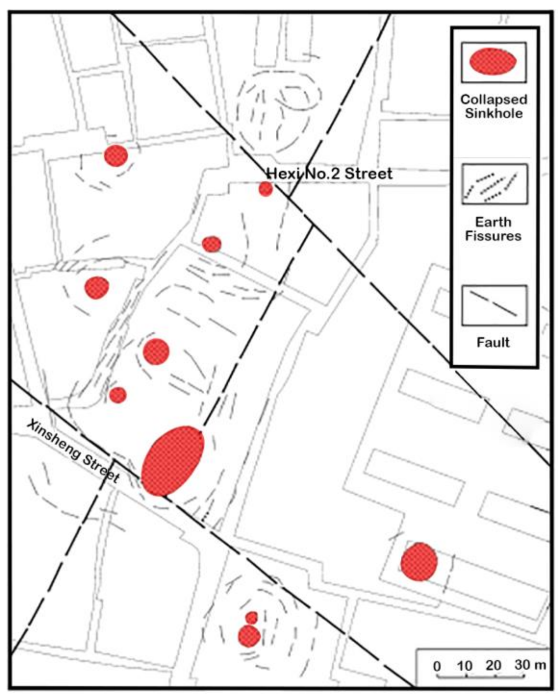

Fig. 9 Karst sinkholes and earth fissures in Xuzhou city. Adapted from [28]

2. Bridges in some provinces of China

Sinkholes in China generally open up on the ground surface due to either natural reasons or human activities, for example tunnel excavation and mine, pumping, reservoir impounding, vibration loading, and waste liquid infiltration. In spite of mentioned classification for sinkholes, they may be classified into four different models: Balance Arch Failure, Hourglass, Subjacent Drilling-Induced Erosion, and Vibration. Balance Arch Failure model has been selected for Cover-Collapse sinkholes and Hourglass model defines those sinkholes which are known as Cover-Subsidence. The third model, Subjacent Drilling-Induced Erosion model is used for sinkholes occurred when the top soil layers are scoured and eroded and The Vibration model is used for describing depressions appear on the ground when the soil layer or the top of the cave is damaged by the vibration of drilling operations. In many regions in China, these sinkholes have occurred during the engineering construction. Some of them have had an influence over bridges (see Table 1) [29].

TABLE I
SINKHOLES OCCURRED ON BRIGES IN SOME PROVINCES OF CHINA [29]

Province	Location	Shape	Depth	Year	Model
Guangdong	Pearl River	Circular	10 m	2002	SM 1
	Maan Zhaoqing	Circular	10 m	2005	
Zhejiang	Qingyangdian	Circular	5 m	2007	
Guangdong	Beijiang	Elliptical	2 m	2001	SM 2
	Xinhua	Funnel	5.5 m	2001	
Shandong	Shushui Linyi	Circular	6 m	2007	
Shanxi	Meihuadian	Elliptical	5-6 m	2001	
Guangdong	Yaobu Yingde	Circular	10-15 m	2005	SM 3

SM 1 = Hourglass Model
SM 2 = Subjacent Drilling-Induced Erosion Model
SM 3 = Vibration Model

The groundwater pumping has been identified as a crucial factor which must be managed in the Karst regions in China. Besides, geologic features play the main role of sinkhole development in these regions, particularly in the provinces mentioned in table 2. Owing to the fact that sinkholes spread rapidly in the susceptible areas, the pumping and irrigation must be controlled and, in some cases, stopped [29].

TABLE II
GEOLOGIC FEATURES OF EACH MODEL [29]

Model	Geologic Formation	Soil Type
SM 1	Highly Karstified limestone with interbedded dolomite	Sand, Silty Clay
SM 2	Highly Karstified limestone with interbedded dolomite limestone	Silty Clay, Clay, Sandy Gravel
SM 3	Highly Karstified limestone	Silty Clay, Clay, Sandy Gravel

3. Guang-Qing freeway reconstruction in Qingyuan, China

The Guang-Qing freeway project was started with the aim of reconstructing and extension of the freeway located in Guangdong province, China. The project was located in Karstic areas whose main characteristic is cavities underground. Vibration during engineering activities and exposing underneath cavities influence the Karst groundwater system, disrupt the equilibrium, and finally may trigger sinkhole collapses. Sinkholes endanger existing bridges and nearby buildings, threaten the public life, and cause property loss. Such factors as heavy rainfall impact soil and even groundwater conditions, cause sinkhole development on the freeway project, and damage piles, curbs and road on the bridge (see table 3) [30].

TABLE III
SINKHOLES IN THE GUANG-QING FREEWAY PROJECT [30]

Location	Date	Length	Width	Depth
XiliuRiver Bridge	Nov. 2009	6 m	5.3 m	2.5 m
	Mar. 2010	22 m	20 m	4 m
	Jun. 2012	5.5 m	2.8 m	3.5 m

During reconstruction of structures, it is important to devise an engineering way for each part of a problem, Training of technical personnel, and adequate planning can be practical and increase safety, reliability, and cost-effectiveness of construction projects in Karstic areas. For instance, use of steel casing and riprap filling were selected during the pile construction in order to prevent subsidence and sinkhole development. As mentioned, one of the main reasons is heavy rainfall which has had influence on sinkhole development. Thus, a repairing technique must be used to prevent water runoff from entering the cavities. One technique is filling the cavities with materials to plug voids [30].

Fig. 10 Sinkhole Collapses on the project. Adapted from [30]

4. Pennsylvania, United States of America

When a sinkhole appears on building sites, there is time for people to evacuate from their homes. In fact, the failure of buildings is progressive. Structures such as highway bridges, in contrast, are most susceptible to sudden failures due to their public safety aspect and foundation support. As a result of sinkhole occurrence on bridges, there is a probability of serious accidents and loss of life [31].

PA RT. 33 is a three-span bridge over Bushkill Creek about 15 km north of Easton, Pennsylvania. The bridge was located in a highly active sinkhole area. Thus, sinkholes developed during the bridge construction project. Eastern Pennsylvania has many Karstic areas which are underlain by limestone [32].

In general, the foundation of a bridge is considered as another part which is sensitive to sinkholes created under bridge structures, on the Karst regions. Bridge foundations require particular considerations and a higher factor of safety in order to stabilize and prevent sinkhole activities on bridges. Therefore, cement pressure grouting can be used to manage and decrease the sinkhole risks [31].

By observing abutments during the life of the bridge structure in the so-called project, a single span precast concrete beam structure was designed to eliminate the center piers located in the creek in order to decrease the sinkhole risks to the bridge. In addition, due to challenging Karstic geology, Micropiles were selected for building a new foundation and considered as an engineering solution during the project [32].

5. Roman bridges in Western Liguria, Italy

Sinking of caves Mala, Ingriv Andrassa, and Caontatto found in Karstic areas adjacent to the Ponci Valley is considered as a hazardous phenomenon for the areas around Motu and Sordo Bridges. Studying these five single Roman Arch Bridges built along the Ponci Valley 2000 years ago shows that they have been built of rock and also been supplemented with dolomite limestone, quartzites and other schists. Mala Cave on the Ponci Stream (a hall of 40 m long, 15 m wide, and 15 m high) and Ingriv Cave on the Landrazza Stream (a meander of about 20 m high) are both caves known as Sinkholes [33].

Although dissolution of limestone develops Karst features, Gypsum is much more susceptible to be dissolved. Therefore, sinkhole formation and its consequences may be triggered by initiating constructions over gypsiferous areas and eventually, causes disastrous damages. As gypsum in the bedrock, either in massive rocks or as veins, dissolution, caverns, and cavities appear underground and make site investigation and even after-construction impractical and in most cases impossible [34].

6. Beards Creek bridge, New York, United States

In March 1994, the bridge crossing the Beards Creek settled 15 ft and moved toward the occurred sinkhole on the creek. Actually, two sinkholes developed on the Beards Creek: One sinkhole was 40 ft deep, ca. 260 ft in diameter, and located 400 ft south of the Beards Creek Bridge and another was 65 ft deep, 600 ft in diameter, and ca. 1300 ft south of the Bridge [35].

Groundwater drainage caused loss of ground in the bridge area. Loss of ground triggers collapses of the overlying soil and the development of sinkholes. These occurred sinkholes filled with runoff water from Beards Creek as they were located on the river path [35].

7. Tramway construction in Orleans, France

Karst features exerts an influence over the public life and construction. Sinkholes may cause unexpectable expenses during projects such as the construction of a tramway line and a bridge over the Loire River, Orleans, France [36]. In these areas, infrastructures such a buildings, roads, bridges, and pipelines all are at the risk of catastrophic damages [37], [38].

Fig. 11 Sinkhole at the top of a Loire River dyke. Adapted from [35]

8. Sackett Harbor's Bridge in Petersham, United States

One abutment of the wooden Sackett Harbor's Bridge over the Swift River was failed because of the sinkhole occurred in this area and also One of its center beams fell down to the river due to instability. The problem occurred because there was no practical system for directing rain water away from the abutments of the bridge [39].

Fig. 12 Sinkhole of Sackett Harbor's Bridge. Adapted from [39]

9. Ripon Bypass in Northern England

In some bridge sites, for example *Bushkill Creek Bridge* example, grouting is practical way to fill the cavities and decrease the damages due to the geology of bedrock. On the other hand, this technique may increase the risk of damages due to the large size of the cavities. Thus, an alternative decision will be used to hinder the large-sized sinkhole expansion and strengthen the road deck, for instance, the New Ripon Bridge has been strengthened by designing a heavy-duty steel girder construction with sacrificial supporting piers which have larger than normal foundation pads, to span a small subsidence event [34].

IV. Conclusion

The construction of structures over Karst areas, especially the bridges, is risky and perilous. The main problem is dissolution of bedrock and decrease in strength of upper soil layers which may causes collapses resulting in damages to bridges. There are a number of methods in order to reinforce the base for constructing these sensitive structures. Some authors have mentioned grouting as an engineering solution. This technique has also been used to fill cavities and stabilize the ground in limestone Karst. Devising a technique in reconstruction projects depends on the damages, types of bridges, and size of sinkholes. Some techniques concerning to building strength and safety measures into the structures have been used such as building foundations which span the likely size of collapse sinkholes, sacrificial supports and extended foundations in bridge construction to protect against sudden subsidence failure, and even controlling the groundwater pumping beforehand.

References

[1] F. Gutiérrez, “Sinkhole Hazards”, *Oxford Research Encyclopedia, Natural Hazard Science*, Retrieved 4 Nov. 2019, from <https://oxfordre.com/naturalhazardscience/view/10.1093/acrefore/9780199389407.001.0001/acrefore-9780199389407-e-40>, 2016, July 07.

[2] M. A. Detman, “Sinkhole Dropouts Due to Underground Utility Installation on Construction Sites”, *International Conference on Case Histories in Geotechnical Engineering*, vol. 5, 1998, pp. 963–966.

[3] J. Chen, and S. Xiang, “Sinkhole Collapse Resulting from Pumping of Karst Groundwater: A Problem and its Solutions”, *Land Subsidence (Proceedings of the Fourth International Symposium on Land Subsidence, May 1991)*, IAHS Publ. No. 200, 1991.

[4] R. Shamet, "Site Specifc Sinkhole risk assessment in Central Florida using Cone Penetrometer Testing", *Electronic Teses and Dissertations*, 5360, 2017.

[5] A. Demas, “EarthWord–Karst”, *Department of the Interior, U.S. Geological Survey (USGA)*, Reston, *VA 20192*, *United States*, viewed 7 Nov. 2019, < https://www.usgs.gov/news/earthword-karst>, 2016.

[6] W. C. Sinclair, “Sinkhole Development Resulting from Ground-water Withdrawal in the Tampa Area, Florida”, *U.S. Geological Survey (USGA)*, Water-Resources Investigations, (Prepared in cooperation with the SOUTHWEST FLORIDA WATER MANAGEMENT DISTRICT), 1982.

[7] G. R. Khanlari, M. Heidari, A. A. Momeni, M. Ahmadi, A. R. Taleb Beydokhti, “The effect of groundwater overexploitation on land subsidence and sinkhole occurrences, West of Iran”, *Quarterly Journal of Engineering Geology and Hydrogeology*, November 2012.

[8] T. Gross, “Cone of Depression: Pumping a Well can cause Water Level Lowering”, *U.S. Geological Survey (USGA)*, viewed 7 Nov. 2019, <https://www.usgs.gov/media/images/cone-depression-pumping-a-well-can-cause-water-level-lowering>, 2018, July 24.

[9] R. M. Pokhrel, T. Kiyota, R. Kuwano, G. Chiaro, and T. Katagiri, “Site Investigation of Sinkhole Damage in the Armala Area, Pokhara, Nepal”, *International Conference on Geotechnical Engineering – Colombo 2015*, August 2015, pp. 109–112.

[10] Geological Survey 2018, *Sinkholes*, viewed 8 Nov. 2019, <https://www.usgs.gov/special-topic/water-science-school/science/sinkholes>.

[11] M. H. Nateqi, H. Niroumand, “Characteristics of Sinkholes in the United States of America”, *International Conference of Young Scientists GeoTerrace-2018*, Lviv Polytechnic Publishing House, 2018, pp. 104–109.

[12] H. karimi, K. Taheri, “Hazards and mechanism of sinkholes on Kabudar Ahang and Famenin plains of Hamadan, Iran”, *Natural Hazards*, 2010, 55: pp. 481–499.

[13] Texas State Parks n.d. *Devil’s Sinkhole State Natural Area*, viewed 2 November 2018, <https://tpwd.texas.gov/publications>.

[14] A. S. Engel and S. A. Engel [ed.] 2009, “Select Field Guides to Cave and Karst Lands of the United States”, Karst Waters Institute, Inc., Leesburg, Virginia 2017.

[15] National Park Service 2018, *Deep Lake*, viewed 23 November 2018, <https://www.nps.gov/bicy/learn/historyculture/deep-lake.htm>.

[16] Atlas Obscura 2018, *Santa Rosa Blue Hole*, viewed 27 October 2018, <https://www.atlasobscura.com/places/santa-rosa-blue-hole>.

[17] Curt Bowen Multimedia 2016, *Santa Rosa Blue Hole*, viewed 4 November 2018, <http://santarosabluehole.com>.

[18] The University of Kansas, *Big Basin and Little Basin*, viewed 8 Nov. 2019, <http://geokansas.ku.edu/big-basin-and-little-basin>.

[19] M. H. Nateqi, H. Niroumand, “Investigation and Evaluation of Sinkholes Occurrence in Iran (submitted for publication)”, *International Journal of Geology Engineering*, Kharazmi University, 2019 (submitted for publication).

[20] R. Shamet, “Site Specific Sinkhole risk assessment in Central Florida using Cone Penetrometer Testing”, *Electronic Teses and Dissertations*, 5360, 2017.

[21] B. Beck, “Soil Piping and Sinkhole Failures”, *P.E. LaMoreaux & Associates, Inc. Encyclopedia of Caves*, 2012.

[22] G. Veni et al. “Living with Karst”, *A Fragile Foundation, American Geological Institute*, *AGI Environmental Awareness Series*, pp. 10-35.

[23] P. R. Kemmerly, “Corrective Procedures for Sinkhole Collapse on the Western Highland Rim, Tennessee”, *Transportation Research Record*.

[24] M. Parise, J. D. Waele, F. Gutierrez “Engineering and Environmental Problems in Karst – an introduction” *Engineering Geology*, pp. 91-94.

[25] A. A. Rajabi, “Sinkhole Detection and Quantification Using LiDAR Data”, *Electronic Teses and Dissertations*, 5776, 2018.

[26] J. P. Galve, F. Gutiérrez, J. Guerrero, J. Alonso, I. Diego, “Optimizing the application of geosynthetics to roads in sinkhole-prone areas on the basis of hazard models and cost-benefit analyses” *Geotextiles and Geomembranes*, 2012, 34: pp. 80–92.

[27] J. P. Galve, F. Gutiérrez, J. Guerrero, J. Alonso, I. Diego, “Application of risk, cost–benefit and acceptability analyses to identify the most appropriate geosynthetic solution to mitigate sinkhole damage on roads” *Engineering Geology*, 2012, 145-146: pp. 65–77.

[28] G. Y. Wang et al. “Earth fissures triggered by groundwater withdrawal and coupled by geological structures in Jiangsu Province, China”, *Environ Geol*, 2009, 57: pp. 1047–1054.

[29] Y. Meng, M. T. Lei, Y. S. Lin, J. L. Dai, Z. D. Guan, “Models and mechanisms of drilling-induced sinkhole in China”, *Environ Earth Sci*, 2012, 67: pp. 1961–1969.

[30] Z. Gu et al. “Analysis and prevention of sinkhole collapses during the reconstruction and extension of Guang-Qing freeway, China”, *Environ Earth Sci*, 2016, 75: 788.

[31] K. M. Gray, “Central Florida Sinkhole Evaluation (Unpublished work style),” unpublished.

[32] A. Cadden, K. Petrasic, “When is Enough Enough? SR 33 Micropiles for Bridge Stabilization (Unpublished work style),” unpublished.

[33] P. Brandolini, F. Faccini, A. Maifredi, A. Benedettini, “Geomorphological hazard and cultural heritage: a casestudy of the Roman bridges in the Finalese karstic area (Western Liguria - Italy)”, *Disaster Advances*, 2012, 5.

[34] A. H. Cooper, J. M. Saunders, “Road and bridge construction across gypsum karst in England”, *Engineering Geology*, 2002, pp. 217–223.

[35] S. E. Walker, J. W. Matzat, “Planning the replacement of the Beards Creek bridge”, *Engineering Geology*: 52, 1999, pp. 35–43.

[36] K. Samyn, F. Mathieu, A. Bitri, A. Nachbaur, L. Closset, “Integrated geophysical approach in assessing karst presence and sinkhole susceptibility along flood-protection dykes of the Loire River, Orléans, France”, *Engineering Geology*, 2014.

[37] H. Xiao, H. Li, Y. Tang, “Assessing the effects of rainfall, groundwater downward leakage, and groundwater head differences on the development of cover-collapse and cover-suffusion sinkholes in central Florida (USA)”, *Science of the Total Environment*: 644, 2018, pp. 274–286.

[38] D. Whltman, T. Gubbels, U. Powell, “Spatial Interrelationships between Lake Elevations, Water Tables, and Sinkhole Occurrence in Central Florida: A GIs Approach”, *photogrammetric engineering & remote sensing*, 1999, pp. 1169-1178.

[39] A. D. Duczynski, C. J. O'Hara, N. N. Velazquez, “Design of Sacket Harbor's Bridge”, *Worcester Polytechnic Institute*, 2008.