DEVELOPMENT OF CAVITY PROBABILITY MAP FOR ABU DHABI MUNICIPALITY USING GIS AND DECISION TREE MODELING

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Abstract

Cavity collapse and settlement due to the presence of shallow solution cavities cause significant geotechnical and other engineering problems in certain areas within the Abu Dhabi City Municipality (ADM). A cavity probability map helps to identify regions that are more susceptible to the formation of cavities by identifying and analyzing influential factors contributing to its formation. Information relating to cavities was cataloged and reviewed based on available data from the Geotechnical Information Management System (GIMS), which is a consolidated geotechnical database developed by the ADM. Geological and geotechnical subsurface conditions are obtained from previous site investigation campaigns performed in the ADM region. All geotechnical, geological, and cavity related datasets are stored in a GIS geodatabase system. Based on detailed literature review, primary factors influencing formations of cavities are identified: presence of soluble bedrock, depth to Gachsaran Formation, cavity density, cavity thickness and distance to nearest neighbor. A decision-tree model based on cavity distribution was developed for cavity hazard assessment. The primary controls on cavity de-

velopment are lithostratigraphic position or bedrock geology and depth to the soluble Gachsaran Formation. Most cavities tend to form in highly concentrated zones. Implementation of the decision-tree model in ArcGIS resulted in a cavity probability map. This cavity probability map is mainly based on existing borehole data. Areas not fully mapped by boreholes must be re-evaluated for cavity risk when new borehole data is available. Low Probability, Low to Moderate Probability, Moderate to High Probability, High Probability, and Very High Probability areas were delineated in the probability map.

Introduction

The Abu Dhabi Municipality (ADM) area has undergone rapid infrastructure development and urbanization in the last two decades (UPC, 2007). Almost the entire urbanized Abu Dhabi City including many of the coastal islands is reclaimed land covered by backfill material. The backfill is found mostly in places in an uncontrolled way over pre-existing, coastal barrier and supratidal sabkha sediments (Price et. al, 2012). During the process of infrastructure development and extension of Abu Dhabi

City, significant issues relating to the presence of subsurface problems including cavities and collapse features have been encountered (Tose and Taleb, 2000). Cavity collapse has presented a significant geohazard across parts of the Municipality (Mouchel, 2012). The Gachsaran Formation, which is composed of interlayered mudstone and gypsum, underlies all of the ADM area and is known to be vulnerable to cavity formation in the area. The mudstone and gypsum beds within the upper part of the Gachsaran Formation are prone to dissolution; numerous sinkholes have been reported, particularly in the zone between Abu Dhabi International Airport and Mafraq (Farrant et al., 2012; Mouchel, 2012).

In recent years, Geographic Information System (GIS) are used for manipulation and management of spatial data. There have been studies that apply GIS as a tool to identify or highlight regions that are more prone to cavity formation (Gao et. al, 2007; Yilmaz, 2007; Dai et. al, 2008; Cooper, 2007; Amin and Bankher, 1996; Hu et. al, 2001). The main objective of this study is to access relative probabilities of cavity occurrences in the ADM using GIS tools.

Geological and Geographic Background

The study area in ADM is approximately 11,000 km². It includes the mainland urban area of Abu Dhabi in addition to the coastal islands. The coastal area is relatively flat. Topographic elevation rises to approximately 35 m

above sea level to the east and southeast across an arcuate ‘escarpment’ trending from Mafraq in the south to Al Shahama in the north (Price et al., 2012).

The near surface geology of coastal Abu Dhabi Islands consists of Quaternary marine, aeolian, sabkha, and fluvial deposits overlying variably cemented Pleistocene sands (Macklin et. al, 2012). Most solution cavities occur further inland in regions such as Shakhbout City, Zayed City, and regions surrounding the Abu Dhabi International Airport as shown in Figure 1. Inland geology of the ADM consists of Aeolian sand, active sabkha sequences, dune-bedded sandstone, marine developed carbonate mudstone and sandstone, and evaporite deposits (Tose and Taleb, 2000). The ADM is underlain by the Gachsaran Formation that is part of the Neogene system (Alsharhan and Narin, 1997). The Gachsaran Formation is a thick evaporitic basinal succession that was deposited in a shallow marine/brackish setting with input from a nearby land source indicated by plant matter. It is well known from offshore oil wells, but is only poorly exposed onshore in the Abu Dhabi Area where it is recorded in numerous temporary excavations and boreholes that have penetrated up to 100 m of interbedded mudstone and gypsum (Farrant et al., 2012a). Small exposures occur around Mafraq, Shakhbout City, Shahama, Al Bahya, and along the foot of the Dam Formation escarpment around the Al Dhafra Air Base at Al Maqatrah (Farrant et al., 2012a, b).

Evaluation of the lithological sections indicated that ground excavations had periodically intercepted open voids in the mudstone and gypsum, and the loss of fluid circulation was commonly reported on drilling logs. Borehole data indicated that most of these cavities occur close to the top of rock, often at the interface between the overlying superficial deposits or sandstone and the underlying mudstone and gypsum. The data also showed that the cavities are most prevalent where the Gachsaran is closest to the surface. This formation of cavities is believed to be formed by groundwater movement along the interface of the mudstone and gypsum layers forming cavities that are more vulnerable to collapse in the vicinity of the top of bedrock.

The source for location and information of cavities for the study is mainly from a borehole database maintained by the Municipality of Abu Dhabi. The database consists of 21,257 geotechnical borings (Geotechnica, 2014). This borehole database is called Geotechnical Information Management System (GIMS). The GIMS for Abu Dhabi City supports a consolidated geotechnical database in accordance with internationally accepted standards. A preliminary geodatabase was developed to

Figure 1. Cavity distribution in Abu Dhabi Municipality is concentrated in regions such as Zayed City, Shakhbout City, regions around the Abu Dhabi Airport and Al Falah.

manage spatial data acquired during the data collection process of this study and 1201 cavities were identified and extracted from the GHIMS database.

GIS Geodatabase

In the last decade, GIS and database management systems have been widely developed to manage and analyze spatial data relating to geologic, geotechnical and karstic features (Cooper et al. 2007; Lei et al. 2001, Gao et al. 2005). Spatial data manipulation in GIS environments is a key function of any GIS application (Demers, 1997). There are numerous advantages to manage spatial information and GIS data layers in a geodatabase environment as it allows for coordinated relationships between feature classes, which enable the creation of domains thereby reducing errors during data entry (Ornsby and Burke, 2004). A geodatabase enables storage in a single file or folder and is more efficient for storage of large datasets (FLNRO, 2013). The geodatabase supports a model of topologically integrated feature classes, similar to the coverage model. It also extends the coverage model with support for complex networks, relationships among feature classes, and other object-oriented features (MacDonald et al., 2001)

For this study an ESRI geodatabase called Geohazard Information Management System (GHIMS) was developed to store, manage, and analyze data relating to karstic features, such as cavities, surface subsidence, and presence of soluble bedrock formations, in addition to other information contributing to local geohazards. All

data storage and management were performed in Arc-Catalog and all data manipulations were performed in ArcMap. The GHIMS geodatabase is a tool developed to analyze regional geohazards within the ADM. The geodatabase contains a specific set of feature datasets, feature classes, raster catalogs, and raster classes together with feature attributes, subtypes, and domains; suitable for a variety of geologic, hydrogeologic, and risk assessment maps. In addition to basic geology (lithology, cavity location, etc.), the geodatabase includes damaged buildings and roads survey data, susceptibility of cavity to collapse, and geohazard risk assessment. This paper documents all layers relevant to the karstic geohazards in the region, solution cavities under the surface (Tose and Taleb, 2000). Table 1 shows the major components of the GHIMS geodatabase.

Discussing all datasets stored within the GHIMS geodatabase is not within the scope of this paper. Only layers that store information relevant to the solution cavities, which serve as input data is discussed. The KARST_CAVITY (KC) feature dataset consists of six feature classes as shown in Figure 2. There are four point feature classes and two polygon feature classes. Cavity_collapseability (KC_CVT_CLLPB) is a point feature class that shows the distribution of stable or unstable cavities. The stability of cavities depends on a series of stability charts produced from running simulations on a finite difference model using a software called FLAC 3D. This analysis is outside the scope of this paper. Halite_Bhs (KC_HALITE_BH) is a point feature class that provides

Name	Abbreviation	Type	No. of Datasets
BOREHOLES	BH	Feature Dataset	2
CUT_FILL	CF	Feature Dataset	2
DAMAGE_SURVEY	DS	Feature Dataset	8
GEOLOGY_MODEL	GM	Feature Dataset	8
HYDROGEOLOGY	HG	Feature Dataset	6
*KARST_CAVITY	KC	Feature Dataset	6
SABKHA_DISTRIBUTION	SD	Feature Dataset	2
*CAVITY_PROBABILITY	CP	Raster catalog	3
CUT_FILL_DISTRIBUTION	CD	Raster catalog	2
GEOLOGY_ADM	GA	Raster catalog	54
HYDROGEOLOGY_R	HR	Raster catalog	6
INTEGRATED_RISK	IR	Raster catalog	2

Table 1. Major components of the GHIMS geodatabase are listed here. The GHIMS geodatabase is suitable for storing and managing a variety of geologic, hydrogeologic, and risk assessment related information. "*" indicates data layers that are relevant to this paper.

Figure 2. KARST_CAVITY (KC) feature dataset stores all information relating to location of sub surface cavities, locations of collapsible cavities, and information on the presence of evaporate layers susceptible to dissolution

the locations of boreholes that have halite or rock-salt listed in the geology description of the boring logs. The halite or salt layer is an evaporite crust that is susceptible to dissolution. Old_Risk_Map (KC_OLD_RSK_MP) is a polygon feature class that represents the existing cavity risk map developed based on previous studies (Tose and Taleb, 2000). This feature class has been used only as a reference and is not used in the development of the cavity probability map. Salt_Layer (KC_SLT_LR) is a polygon feature class that provides the possible spatial extent of sub-surface halite zones. It is derived from the existing cavity risk map and from querying geologic descriptions provided in the GIMS borehole database. Void_Depths (KC_VD_DPTH) is a point feature class, which stores information relating to the presence of cavities or voids, and the depth to these cavities or voids based on data from borehole log descriptions from the GIMS database. Water_Loss (KC_WTR_LOSS) is a point feature class, which stores information relating to the event of water or drilling fluid loss at the time of drilling as noted from borehole log descriptions from the GIMS database. This layer could indicate probable locations of subsurface voids or cavities. Since it is not a confirmatory source for presence of cavities, this layer is also used for reference only.

Parameters Contributing to Cavity Formation

Karstic cavities are geologic features that result from water erosion in soluble rocks over time due to seasonal groundwater variation and/or groundwater flow and the associated seepage forces. The developed void system results in randomly shaped cavities that vary widely in size, geometry, and location within the soluble rock. In Abu Dhabi area, cavities were detected as sizable caves encountered during construction of infrastructure and during drilling from the loss of fluid circulation or string drop as documented in boring logs. The formation

and collapse of the karstic cavities may be triggered by changes in the groundwater regime, changes in surface drainage, and construction work or urban development. In the Abu Dhabi area, irrigation inland and construction related dewatering within the urban area is likely to be one of the key triggers for sinkhole development via enhanced dissolution and flushing out of existing sediment filled cavities (Farrant et al., 2012).

A total of 1201 cavities are identified by querying the GIMS borehole database using SQL. The Shakhboub City areas contained 67% (i.e., 806 out of the 1,201 inventoried cavities). Other areas where significant number of cavities occurred include the southeastern Zayed City, the Abu Dhabi International Airport and the Al Falah areas. A small number of cavities were sparsely distributed in other areas. However, some boreholes indicate the presence or multiple cavities at different depths. In such cases the cavity closest to the surface is used for the cavity risk assessment. Eliminating multiple cavities in the same boreholes, the total dropped to 729 cavities nearest to the surface. Bedrock solubility, depth to Gachsaran Formation, cavity density, cavity size, and point pattern analysis were used as contributing factors in the formation of cavities.

Depth to Gachsaran Formation

The Gachsaran Formation, which is composed of inter-layered mudstone and gypsum, underlies all of the ADM and is known to be vulnerable to cavity formation in the area. The mudstone and gypsum beds within the upper part of the Gachsaran Formation are prone to dissolution; numerous sinkholes have been reported, particularly in the zone between Abu Dhabi International Airport and Mafraq (Farrant et al., 2012; Mouchel, 2012). Evaluation of the lithologic sections indicates that ground excavations have periodically intercepted open voids in the mudstone and gypsum, and the loss of fluid circulation

is commonly reported on drilling logs. Borehole data indicate that most of these cavities occur close to the top of bedrock, often at the interface between the overlying superficial deposits or sandstone and the underlying mudstone and gypsum. The data also shows that the cavities are most prevalent where the Gachsaran is closest to the surface. This formation of cavities is believed to be formed by groundwater movement along the interface of the mudstone and gypsum layers forming cavities that are more vulnerable to collapse in the vicinity of the top of bedrock. In other areas such as Abu Dhabi Island and Al Falah, cavities have been encountered within the stratigraphically higher sand and sandstone layers, as well as at the interface with the Gachsaran.

Figure 3 shows a histogram of the distribution of cavities in relation to the depth to Gachsaran formation at the cavity location. It is evident that the closer to the surface of the Gachsaran Formation the more likely the formation of cavities. Figure 4 shows the extent and depth to the Gachsaran Formation.

Cavity Density

Cavity density provides the number of cavities present per square kilometer. The cavity density is calculated using the Point Density tool under the Spatial Analyst toolbar in ArcMap application. The Point Density tool calculates the density of point features around each output raster cell. Conceptually, a neighborhood is defined around each raster cell center, and the number of points that fall within the neighborhood are added together and divided by the area of the neighborhood (Silverman, 1986). Figure 5 shows the cavity density output calculated in ArcMap.

Cavity Size

In the field, cavities tend to propagate in vertical and lateral directions, but since the source of cavity data is

Figure 3. Histogram showing the distribution of cavities in relation to the depth to Gachsaran formation.

discreet points, cavities are assumed as two dimensional features. Cavity size is estimated using the thickness of voids based on boring log data. Cavity size varies from 0.1 m in thickness to 3 m in thickness. Cavities with thickness greater than 3 m were also observed although these were few in number compared to the total dataset. The largest cavity encountered is around 17.5 m thick. Majority of the cavities are 0.1 to 1 m thick. Cavities

Figure 4. The areal extent and vertical depth of the Gachsaran Formation below ground surface level.

Figure 5. Cavity density raster output created using location of cavities as input source in ArcMap environment using the point density tool.

smaller than 1 m were found to be generally stable, as supported by the numerical analyses results. Figure 6 shows the histogram for cavity distribution with respect to cavity size and Figure 7 shows the areal distribution of cavities based on cavity size.

Point Pattern Analysis

Pattern analysis is the study of the spatial arrangement of point features in two-dimensional space. A pattern analysis usually demonstrates if a distribution pattern is random, dispersed, or clustered (Gao et al., 2005). In addition, a distribution pattern containing clusters of high or low values can also be identified by pattern analysis. Distances to the first through the 9th nearest neighbors were conducted for cavities in different lithological ma-

Figure 6. Cavity size variation represented in histogram format. Majority of the cavities fall between 0.1 m to 1 m in thickness.

Figure 7. The spatial distribution of cavities based on cavity size.

terials and geographical clusters. Figure 8 demonstrates a histogram of the distance to the nearest cavity for all cavities. The median distance to the first through the 9th nearest cavity is linearly increasing within the Gachsaran Formation as shown in Figure 9.

The overall Distance to Nearest Neighbor (DNN) distribution of all cavities does not follow Poisson, Normal,

Figure 8. Histogram and cavity distribution with respect to distance to nearest cavity. The distribution of cavities with distance to nearest cavity greater than 160 m follows a normal distribution.

Figure 9. The median distance to the first through the 9th nearest cavity in the Gachsaran formation.

or Log-Normal distributions. However, the distribution of the DNN for all cavities more or less follows normal distribution once DNN is greater than 160m.

Decision Tree Model and Implementation

One of the important advantages of geoinformatics techniques is that it can be used to extrapolate the occurrence of local events over a wider territory using statistical methods and predict the possibility of occurrence of these local events over an expanded territory. Geoinformatics technology or GIS applications can be used to develop multi-parametric models that can make predictions based on a set of training examples. Several studies have developed multi-parameter models based on multi-scenario considerations to make predictions on the occurrence of sinkholes, cavities and other geohazards (Koutepov et al. 2008; Gao et al. 2007; Yilmaz, 2007; Cooper, 2007; Tolmachev, 2003; Ragozin and Yolkin, 2004, Kaufmann, 2008)

The purpose of multi-parametric model in assessing cavity collapse hazards is to divide the study area into subareas of different hazard or probability levels. To this end, spatial data mining aids in discovering spatial patterns among various contributing parameters (Shekhar and Chawla, 2002). A study in Great Britain uses a detailed karst database and assigns severity of dissolution hazards by assessing local bedrock and superficial geology and sub dividing regions into high, moderate, and low risk zones based on a ranking or scoring system (Cooper, 2007). A similar scoring system was developed in Missouri by assigning scores to sub classes of multiple parameters such as depth to water table, bedrock characteristics, proximity of nearest sinkhole, and distance to nearest structure from existing sinkholes (Kaufmann, 2008).

A more rigorous multi-parameter model is the frequency ratio model. Parameter maps that are used in the collapse susceptibility analyses are divided into four groups such as: geological and hydrological, topographical, land use, and vegetation cover. Each of these parameters is further subdivided into sub classes and cavity collapse hazard is calculated as a function of the frequency of cavities occurring each of the subclasses (Yilmaz, 2007).

Another common multi-parametric modelling approach is the probabilistic method (Tolmachev, 2003; Ragozin and Yolkin, 2004). In the probabilistic approach, sinkhole or cavity collapse risk is expressed in terms of the probability P_s of formation of sinkholes in a specified period (for example, during the service life of a building) on the studied territory, which may cause impermissible deformation of structures, or in terms of the probability

P that there will be no such sinkholes (reliability), i.e., $P = 1 - P_s$.

Decision tree models are one of the most widely used techniques for inductive inference (Mitchell, 1997; Winston, 1992). A decision tree model uses a top-down approach and consists of multiple nodes (Gao et al., 2007; Hu et al., 2001). Each node indicates a test condition followed by the next node all the way to the last node (Tan et al., 2005). In this study the decision tree model is implemented to develop a cavity probability map given the study area and extent. The decision tree method is more suitable for integrated and regional scale assessments of complicated phenomena such as occurrence of cavities (Hu et al., 2001). Based on the contributing parameters listed in this study a decision tree model was developed as shown in Figure 10. The primary controls on cavity development were lithostratigraphic position or bedrock geology and depth to the soluble Gachsaran Formation. The majority of the cavity population tends to form in highly concentrated zones. Neighborhood effect plays a very important role in cavity distribution and formation.

Figure 11 represents the various spatial data manipulations performed in ArcMap to create the input layers for the final cavity probability calculations. The existing bedrock geology layer was reclassified into soluble and insoluble bedrock units based on their susceptibility to dissolution. The depth to Gachsaran Formation raster layer was queried from the GHIMS geodatabase and reclassified in to two units: pixels representing values of depth to Gachsaran Formation less than 30 m and pixels representing values of depth to Gachsaran Formation greater than or equal to 30 m.

Similarly cavity density raster layer and cavity thickness layers were reclassified in two value rasters as shown in Figure 11. To create the input layer for distance to nearest cavity the mean and standard deviation of DNN were used to define boundaries (Gao and Alexander, 2003). Using the Buffer tool in ArcMap environment raster layers indicating boundaries within 210 m, 400 m and 600 m were created and were combined using the Union tool in ArcMap. Using Model Builder tool in ArcMap, the decision tree model was implemented using the input layers shown in Figure 11. A pictorial representation of the model built to calculate the cavity probability map is shown in Figure 12.

Results

Implementation of the decision tree in ArcGIS resulted in a cavity probability map. Figure 13 shows the cavity probability map developed for the ADM area. The cavity

Figure 10. Decision tree model created to assign cavity risk probability for the ADM region. The decision tree includes characteristics of bedrock geology, depth to the Gachsaran Formation, cavity density, cavity size, and distances to the nearest cavities in the ADM area.

Figure 11. Cartographic flow chart representing the implementation of the decision tree model in ArcMap environment. This flowchart represents the process to create the input layers for the final cavity probability calculation.

probability map divides the study area into regions of low probability, low to moderate probability, moderate to high probability, high probability, and very high probability. The descriptions of these probability areas are as follows.

LOW PROBABILITY

Areas underlain by the soluble Gachsaran Formation and the depth to the Gachsaran Formation is equal to or greater than 30m are shown on the map as having low probability for cavity development.

LOW TO MODERATE PROBABILITY

Areas underlain by the soluble Gachsaran Formation and the depth to the Gachsaran Formation is less than 30m are shown on the map as having low to moderate probability for cavity development. The cavity density is less than one cavity per square kilometer. The expected future cavity development is generally low in these areas, but is moderate where small cavity clusters have developed.

MODERATE TO HIGH PROBABILITY

Areas in which cavities are a routine part of the subsurface and the minimum cavity density is 1 cavity per square kilometer. Higher probability cavity clusters are

Figure 12. Pictorial representation of the ArcMap Model Builder file used to calculate the final cavity probability map.

Figure 13. The cavity probability map developed in ArcMap environment based on decision tree modeling technique.

usually contained with the moderate to high probability. The minimum distance to the nearest cavity is 400 m for smaller cavities (less than 3m in thickness) and 600m for larger cavities (greater than and equal to 3m).

HIGH PROBABILITY

Areas in which cavities are a common part of the sub-surface and the minimum cavity density is 1 cavity per square kilometer. The minimum distance to the nearest cavity is 210 m for smaller cavities (less than 3m in thickness) and 400m for larger cavities (greater than and equal to 3m). New cavities are expected to form in these areas.

VERY HIGH PROBABILITY

Areas in which cavities are dominant features of the sub-surface and the minimum cavity density is 1 cavity per square kilometer. The minimum distance to the nearest cavity is 210 m and at least a large cavity (greater than and equal to 3m) occurs within these areas. Four of these clusters containing extremely large cavities (greater than and equal to 10m) would be very susceptible for future cavity development.

Discussion and Conclusions

The cavity probability map, when compared with earlier, elementary versions of zone level cavity risk assessment studies, produces a more structured and objective approach towards analyzing patterns in the spatial distribution of cavities (Tose and Taleb, 2000). However, other influential parameters controlling formation of cavities such as groundwater chemistry and fluctuation, land use and topography, as well as anthropogenic changes to landscape and groundwater were not considered in the study due to the lack of data availability. This cavity probability map is mainly based on existing borehole data. Areas not fully mapped by boreholes need to be re-evaluated for cavity risk once new borehole data are available. Also, in this study cavities are assumed as discontinuous 2D features, while in reality cavities tend to develop and propagate in vertical and lateral directions.

References

- Abu Dhabi Urban Planning Vision 2030. 2004. Abu Dhabi: Urban Planning Council [UPC]; [cited 2007]. p. 22. Available from: <http://www.upc.gov.ae/template/upc/pdf/abu-dhabi-vision-2030-revised-en.pdf>
- Alsharhan AS, Nairn AEM. 1997. Sedimentary basins and petroleum geology of the Middle East. 1st ed. Amsterdam (AE): Elsevier Science B. V. p. 441.
- Amin AA, Bankher KA. 1996. Karst Hazard Assessment of Eastern Saudi Arabia. *Natural Hazards* 15. 1997. c 1997 Kluwer Academic Publishers. p. 21-30.
- Cooper AH. 2007. The GIS approach to evaporate-karst geohazards in Great Britain. *Engineering Geology* 53: 981-992. DOI 10.1007/s00254-007-0724-8
- Demers MN. 1997. Fundamentals of geographic information systems. Wiley, New York, p. 486
- Dai, J; Lei, M; Liu, W; Tang, S; Lai, S. 2008. An assessment of karst collapse hazards in Guilin, Guangxi Province, China. In: Yuhr LB, Alexander CE Jr., Beck FB, eds. In: Yuhr LB, Alexander CE Jr., Beck FB, editors. Sinkholes and the Engineering and Environmental Impacts of Karst; 2008 Sept. 22-265; Tallahassee, Florida(FL): Geotechnical Special Publication No. 183, p. 156-164.
- Farrant, AR, Ellison, RA, Merritt, JW, Merritt, JE, Newell, AJ, Lee, JR, Price, SJ, Thomas, RJ, And Leslie, A. 2012. Geology of the Abu Dhabi 1:100 000 map sheet, United Arab Emirates. (Keyworth, Nottingham: British Geological Survey). ISBN 978 085272 725 6
- Farrant, AR, Ellison, RA, Merritt, JW, Merritt, JE, Newell, AJ, Lee, JR, Price, SJ, Thomas, RJ, And Leslie, A. 2012. Geology of Al Wathba 1:100 000 map sheet, United Arab Emirates. (Keyworth, Nottingham: British Geological Survey). ISBN 978 085272722 5
- File geodatabase standards for data creation, publication, and distribution. 2013. British Columbia: Ministry of Forests, Lands and Natural Resource Operations [FLNRO]; p. 5. Available from: http://www.data.gov.bc.ca/local/dbc/docs/geo/services/standards-procedures/file_geodatabase_standards.pdf
- Gao Y, Alexander EC Jr. 2008. Sinkhole hazard assessment in Minnesota using a decision tree model. *Environmental Geology*, 54(5): 945-956.
- Gao Y, Alexander EC Jr. 2007. Sinkhole hazard assessment in Minnesota using a decision tree model. *Environ Geol* 54:945-956
- Gao Y, Alexander EC Jr. 2003. A mathematical model for a sinkhole probability map in Fillmore County, Minnesota. In: Beck BF (eds) Sinkholes and the engineering and environmental impacts of karsts. Proceedings of the ninth multidisciplinary conference. Huntsville, Alabama, September 6-10, ASCE Geotechnical Special Publication, no. 122, p. 439-449.
- General Geotechnical Investigation Report (Draft), Spektra Jeotek. 2012. Presidential Affairs Building, Khalifa City-B., February 16 2012.

- Geotechnical Risk Map, Presidential Affairs 44 Plots Khalifa City-B, Spektra Jeotek. 2011. Abu Dhabi, UAE.
- Hu RL, Yeung MR, Lee CF, Wang SJ, Xiang JX. 2001. Regional risk assessment of karst collapse in Tangshang, China. *Environmental Geology* 40: 1377-1389.
- Jiang X, Lei M, Li Y, Dai J. 2005. National-scale risk assessment of sinkhole hazard in China. In: Beck BF (ed) *Sinkholes and the engineering and environmental impacts of karst*. Proceedings of the tenth multidisciplinary conference San Antonio, Texas, September 24–28, ASCE geotechnical special publication, no. 144, p. 649–658.
- Kaufmann JE. 2008. A statistical approach to karst collapse hazard analysis in Missouri. In: Yuhr LB, Alexander CE Jr., Beck FB, editors. *Sinkholes and the Engineering and Environmental Impacts of Karst*; 2008 Sept. 22-26; Tallahassee, Florida(FL): American Society of Civil Engineers. p. 257-268.
- Koutpov VM, Mironov OK, Tolmachev VV. 2007. Assessment of suffosion-related hazards in karst areas using GIS technology. *Environmental Geology* 54: 957-962
- Lei M, Jiang X, Li Y. 2001. New advances of karst collapse research in China. In: Beck BF, Herring JG (eds) *Geotechnical and environmental applications of karst geology and hydrology*. Proceedings of the eighth multidisciplinary conference on sinkholes and the engineering and environmental impacts of karsts. Louisville, KY, 1–4, April, A. A. Balkema, Lisse, p. 145–151.
- Macklin S, Ellison R, Jason M, Farrant A, Leon L. 2011. Engineering geological characterization of the Barzamam Formation, with reference to coastal Dubai, UAE. *Bulletin of Engineering Geology and the Environment* 7: 1-19.
- MacDonald A, Brown T, Andrade J, Hoel E, Bailey J. 2001. *Building a Geodatabase: GIS by ESRI*. ESRI User Manual 2001.
- Mitchell TM. 1997. *Machine learning*. McGraw-Hill, New York, p. 414.
- Mouchel Report. 2012. Abu Dhabi Capital District – Infrastructure Project Consultancy Services for the Emirati Neighborhood – Package 2A and 3. Abu Dhabi.
- Ormsby T, Napoleon, E, Burke, R, Groesl C, Bowden, L. 2008. *Getting to know ArcGIS Desktop: Basics of ArcView, ArcEditor and ArcInfo*, 2nd Edition, p. 592.
- Price SJ, Farrant AR, Leslie A, Terrington RL, Merrit J, Entwisle D, Thorpe S, Horabin C, Gow H, Self S, and McCormick T. 2012. A 3D superficial and bedrock geological model of the Abu Dhabi urban area, United Arab Emirates. British Geological Survey Commercial Report, CR/11/138.
- Ragozin A, Yolkin V. 2004. Technique of quantitative assessment of karst risk on the local and regional levels. In: Hack R, Azzam R, and Charlier R (eds) *Engineering Geology for Infrastructure Planning in Europe: A European Perspective (Lecture Notes in Earth Sciences)*, June 14, Lecture Notes in Earth Sciences, no. 104, p. 760–766.
- Shekhar S, Chawla S. 2002. *Spatial databases: a tour*. Prentice Hall, p. 300.
- Silverman, B.W. 1986. *Density Estimation for Statistics and Data Analysis*. New York: Chapman and Hall.
- Tan P-N, Steinbach M, Kumar V. 2005. *Introduction to data mining*. Addison Wesley, Reading, USA, p. 769.
- The Geotechnica. 2004. Equipe Group, p. 27. Available from: http://www.equipegroup.com/pdfs/theGeotechnica_August_2014.pdf
- Tennant EW. 2007. A sample geodatabase structure for managing archaeological data and resources with ArcGIS. *Technical Briefs in Historical Archaeology* 2: 12-23
- Tolmachev VV. 2003. An analysis of studies in the field of probabilistic methods for predicting sinkhole danger. *Power Technology and Engineering* 37: 350-353
- Tose JA, Taleb A, 2000. Khalifa city ‘b’ ground conditions program. In: Mohamed & Al Hosani, editors. *Georngineering in Arid Lands*. Balkerna, Rotterdam. p. 75-81
- Winston PH. 1992. Learning by building identification trees. In: Winston P (ed) *Artificial intelligence*. Addison-Wesley, Reading, USA, p. 423–442
- Yilmaz I. 2007. GIS based susceptibility mapping of karst depression in gypsum: A case study from Sivas basin (Turkey). *Engineering Geology* 90: 89-103.