BUILDING CODES TO MINIMIZE COVER COLLAPSES IN SINKHOLE-PRONE AREAS

George Veni
National Cave and Karst Research Institute, 400-1 Cascades Avenue, Carlsbad, New Mexico 88220-9215, USA, gveni@nckri.org

Connie Campbell Brashear
Bracken Engineering, Inc., 2701 West Busch Boulevard, Suite 200, Tampa, Florida 33618, USA, conniecb@brackenengineering.com

Drew Glasbrenner
Bracken Engineering, Inc., 2701 West Busch Boulevard, Suite 200, Tampa, Florida 33618, USA, dglasbrenner@brackenengineering.com

Abstract
Cover-collapse sinkholes are forming with increasing frequency under buildings. Analyses of sinkhole distribution in Beacon Woods, Florida, preliminarily indicate their occurrence is an order of magnitude greater in urban versus undeveloped areas, suggesting the structures themselves are enhancing the collapse process. The most likely causes are induced recharge via at least one of two sources. First, runoff and drainage from roads, structures, and impoundments that is not adequately dispersed will promote sinkhole development. Second, leaking water, sewer, and septic systems beneath or adjacent to a structure will also promote collapse. The process of cover-collapse from induced recharge is well understood. However, building codes generally do not require drainage and structural engineering practices that would reduce induced recharge and thus reduce the risk of collapse. This paper proposes engineering practices that measurably restrict the accidental discharge of municipal water through leaking subgrade drainage systems or the deliberate discharge of stormwater runoff, induced shallow groundwater recharge from retention ponds and septic drainfields, or heavily-irrigated land use. We recommend these practices be incorporated into building codes and ordinances to reduce induced sinkhole development in areas prone to cover-collapse.

Introduction
Tragedy struck. Mr. Jeff Bush was sleeping in his home the night of 27 February 2014 in Seffner, Florida, when a sinkhole opened under his bedroom and swallowed him. His body was never recovered.

Sinkhole collapses are often viewed with fascination and a certain excitement about their potential danger. The tragedy in Seffner stands as proof that their hazard should not be underestimated. But what was the cause of that collapse? Media interviews mostly pointed to groundwater pumping, which could have lowered the water table, piping soil and sediment downward, resulting in the collapse. This is certainly plausible, as are natural processes unrelated to human activities. However, the opening of the sinkhole directly beneath the Bush home may indicate another origin.

Cover collapse sinkholes from induced recharge are perhaps the most widespread type of collapse. Collapse from groundwater withdrawal is more widely publicized due to the dramatic collapses in Florida, but induced recharge collapses occur frequently in Florida and far beyond. The location of the Seffner collapse, under the Bush home, suggests a recharge-induced origin potentially from leaking water or sewer pipes, roof runoff, and/or an adjacent shallow retention pond. Unfortunately, evidence of the mode of this and other collapses is often lost in the collapse, non-forensic excavation, and/or from filling or other form of remediation.

Many books and papers describe geotechnical measures to remediate sinkholes and prevent them once subsidence is detected (e.g. Sitar, 1988; Sowers, 1996; and the 13 volumes of Sinkhole Conference proceedings, 1984-2013). This paper promotes a proactive approach that we believe will prevent some collapses from ever occurring. We begin by describing the general causes of recharge-induced collapses. Next we use a case study to demonstrate how and why they occur with greater frequency under and around buildings, making them potentially deadlier than other types of sinkholes. While the case study area is in Florida, this paper is not
focused on Florida so details of some geologic processes are kept general to be relevant to most regions where cover collapses occur. We end by proposing building codes to minimize such collapses.

**Origin of Recharge-Induced Cover Collapses**

Cover collapse sinkholes form where thick mantles of soil, regolith, and/or sediment overlay cavernous bedrock. With time, these unconsolidated sediments move down into conduits in the bedrock. If the sediments move slowly and have little structural strength, the land surface above gradually subsides. Where the sediments are more structurally competent and may also move more rapidly, a cavity develops within until it becomes unstable and abruptly collapses.

The sediment movement results from gravity and the flow of water and occurs in two ways, mechanisms that have been well described and understood for many years (e.g. Newton, 1987; Galloway et al. 1999). First, if the water table of a karst aquifer extends into overlying sediments, declines in groundwater levels below the bedrock will wash some sediment into bedrock conduits. Other sediment will slump and fall into the cavities due to its increased water-saturated weight. Repeated rises and falls in the water table will carry more sediment into bedrock conduits where they are flushed away and through the aquifer. Eventually, subsidence or collapse may be seen at the surface.

This paper focuses on the second mechanism of sediment movement: induced recharge. In this case, the karst water table generally remains within the bedrock, below the unconsolidated sediments. The sediments move into the bedrock conduits when water sinks consistently into the ground at a particular location, saturating the sediment and carrying it downward. As long as water flows in that location, whether constantly or intermittently, underlying sediment will be lost into the aquifer and a subsidence or collapse sinkhole will eventually form (Figure 1).

Many induced sinkholes form along highways, where road runoff sinks into adjacent drainage channels (i.e. swales). Most sinkholes in non-karst areas are induced, often by leaking water and sewer pipes that can supply water to saturate sediments and carry sediment away to create cavities, the most famous and fatal of which were up to 30 m in diameter by 60 m deep, formed in Guatemala City in 2007 and 2010 and killed six people (Hermosilla, 2012).

Less recognized are sinkholes resulting from recharge induced by homes and other buildings. Recharge from roof runoff, if not directed away from a building, infiltrates soil along the building’s foundation, putting the building at risk from subsidence or collapse. Unseen induced recharge also occurs beneath buildings from leaking water and sewer pipes. While leaking water pipes might be indicated by water usage on monthly water bills, sewage outflow is not measured and leaks are not detected without direct testing (Figure 1B). With the Seffner and other collapses occurring directly beneath buildings, the possibility that these buildings and their infrastructure caused some of the collapses must be considered, especially as global increases in population in sinkhole-prone areas may be putting more people at risk.

**Case Study: Beacon Woods, Bayonet Point, Pasco County, Florida**

To test the hypothesis that roads and other urban infrastructure may result in a greater frequency of cover
collapses than undeveloped land, we selected Beacon Woods as our study area. Located approximately 50 km northwest of Tampa, Florida, the district of Beacon Woods is at the north end of the community of Bayonet Point, about 6 km east of the Gulf of Mexico. Beacon Woods study area covers roughly 8 km² of residential and light commercial developments planned in the 1970s and mostly built out by 1980. With the exception of a golf course, the land use is relatively homogenous across the study area, which is defined by US Highway 19 to the west, Hudson Avenue to the north, Fivay Road and Little Road to the east, and State Road 52 to the south. This study area was selected because of the age of the residential developments, the detailed property/permit records readily available online, the karst topography, and the mapped cave and sinkhole system running its length. The blue lines overlain on Figures 2 through 5 are simplified footprints of the documented sections of this cave system.

Historical aerial photography of the vicinity was downloaded and reviewed, the oldest dating from 1941 when very few buildings had been constructed in the area (Figure 2) (Aerial Photography: Florida Collection [Internet]; Florida Department of Transportation’s Aerial Photo Look-Up System [Internet]). According to the pre-development topography, the ground surface ranged in elevation from about 6 m (20 feet) along Fivay Road down to 3 m (10 feet) to the west; below a depth of 1.5 m (5 feet) the closed drainage features were water-filled (all elevations relative to the National Geodetic Vertical Datum).

In the western half of the study area, the shallow geologic unit is the Suwannee Limestone (Arthur, 1993). While a few limestone outcrops occur in this part of the study area, most observed limestone is in the form of saprolitic boulders, many excavated and placed as decorations during development. The cover soils are fine sands, with minor amounts of sandy clay collected in occasional isolated pockets. Moving east, an overlay of sand dunes (Arthur, 1993) provides topographic relief, guiding surface drainage. The multitude of closed depressions, some water-filled and some dry, provide an indication of the high degree of karstification of the underlying limestone.

While groundwater levels have fluctuated and refinements in surveying and mapping have improved in accuracy, there is an undeniable gradual increase in the areal extent of surface waters evident across the three major map revisions published by the US Geological Survey since 1954 (Figure 3). Most of the wetlands and water-filled features in Figure 3 are now developed.
as drainage canals and stormwater retention ponds or greenspace in the most current topographic map (Figure 4).

The large Beacon Woods Cave System is present beneath the center of the study area, trending, and its groundwater flowing, south to north. Multiple sinkholes provide entrance into the system for both exploration and a considerable volume of surface water from Bear Creek. The mapped portions of the cave system have an average water depth of 46 m, although some sections are considerably shallower. The lower sections of the cave contain brackish water, with diffuse haloclines at depths consistent with the Ghyben-Herzberg principle. A resurgence of the cave system is approximately 4.3 km north-northwest of Smokehouse Pond (Figure 3), at the former Hudson Springs, while dye tracing in the 1960s linked a further upstream yet impassable sinkhole with a spring in the Gulf of Mexico (Wetterhall, 1965).

Compaction grouting of residences affected by collapse or subsidence in the vicinity of the underlying cave system has a high potential, by design, of intersecting some zone of increased permeability such as a fracture, joint, or eroded bedding plane, as well as a somewhat lesser possibility of directly impacting a cave passage. While the impact to endangered cave biota cannot be understated, the more pressing economic concern may be the potential to trigger a collapse of a large section of cave and drastically reducing the capacity for drainage of the basin.

To correlate the occurrence of cover-collapse sinkholes, the predominant type in the region, with urban infrastructure, we compiled “potential ground settlement investigation” and “ground settlement repair” permits filed for the properties within the study area filed in the last 25 years in the Pasco County Florida Public Access to Permit Applications database (Pasco County Florida Public Access to Permit Applications [Internet]). Our analysis found about 750 investigations and 650 repairs documented with the Pasco County Building Department, which accounted for over 6% of all building permits recorded for this 25-year time period. The building coordinates were filed with each of the repair permits and their locations are plotted as red squares on the aerial photograph in Figure 5.

Since 2008, the Pasco County Building Department has recorded the specific details from the repair reports. After extensive data mining we determined that a staggering $33,801,000 dollars (US) have been spent from March 2008 to March 2015 in compaction or slurry grouting, chemical grouting, and/or underpinning the structures within the 8 km² study area. Also, the subsidence incident database compiled by the Florida Geological Society as of October 2014 was sorted for the study area and the limited descriptions were evaluated for applicability to our analysis (Subsidence incidents...
Proposed Building Code to Minimize Recharge-Induced Collapses

Considering the above results, we believe that building codes for sinkhole-prone areas should address the likely dramatic increase of induced collapses around roads and urban infrastructure with measures that will reduce or prevent their occurrence. For the study area, we reviewed the historic aerial photography and found the shallow native soils were reworked or sandy fill soils imported to raise grades below foundations and roadways in order to install a system of curb and drainage pipe to channel surface runoff to isolated retention ponds within nested residential streets or to long swales bordering major roadways. We determined that the typical sources of water infiltration that could be mitigated include:

- roof runoff
- street drainage from curb to culvert
- automatic lawn irrigation systems (operational without a rain gauge or if broken and leaking)
- effluent from septic drainfields
- leaking plumbing below or beside buildings
- obsolete or unrepaired shallow irrigation wells
- unlined stormwater ponds
- leaking swimming pools, and
- wastewater spray fields.

The following code modification suggestion is generated from a review of the current 2010 Florida Building Code - Building, specifically Chapter 18 – Soils and Foundations (International Code Council, Inc., 2010). Though shown here as specific to this statute, it is written for general adaptation to any building or roadway construction code in any karst area prone to cover-collapse sinkholes. Under “1803.5, Investigated conditions,” many deleterious soil and groundwater conditions (even seismic) are detailed or reserved, but cover-collapse isn’t among them. There may be future avenues available with an addition of a hypothetical Section 1803.5.13 Cover-Collapse Risk Zones:

Where historical photographic evidence of cover-collapse sinkholes exist or where geophysical surveys and subsurface explorations at the project site indicate substantial risk of sinkhole incidence, the building official shall be permitted to deem the site a no-build zone or require a registered design professional to demonstrate that the intended construction will measurably restrict the accidental discharge of municipal water through leaking subgrade drainage systems, the deliberate discharge of stormwater runoff from buildings, roads, parking lots, or other constructed impervious cover, induced shallow groundwater recharge from retention ponds and septic drainfields, heavily-irrigated land use such as plant nurseries, golf courses and water reclamation sprayfields, and/or swimming or decorative pools.

Some terms in the above proposed code would need to be defined, often in accordance with local or state statutes. The proposed code inherently encourages design professionals working in these high risk zones to develop stormwater runoff management options that emphasize detention and evaporation instead of the typically highly-desired rapid infiltration in concentrated areas. This could be accomplished with lined shallow ponds, which would create the added benefit of wildlife habitat between neighborhoods. Also, specifying leak-proof double-walled piping and reinforced fittings as well as the removal or restriction of septic drainfields by requiring municipal sewer lines and transfer stations outside of the high risk zone would likely reduce induced recharge-related subsidence as well as improve water quality. For the homeowner currently living in a high risk zone, the addition of a rain barrel or other catchment system at the discharge point of each gutter would delay the infiltration of roof runoff and reduce the risk of soil settlement or erosion on their property.

Conclusions

Sinkhole collapse and subsidence are often treated as sensational fascinating events of mysterious origin by the media. That perception has often masked the fact that the sinkhole process is well understood and action can be taken to minimize its occurrence.

Our findings in the Beacon Woods study area show that close to $6 million/year have been spent in that 8 km² study area in sinkhole and subsidence remediation and associated repairs. The February 2014 collapse under
the Bush home in Seffner, Florida, proved the cost can be much greater.

Further, our research indicates a potentially greater than order of magnitude increased frequency of sinkhole and subsidence development in association with urban infrastructure over undeveloped land, strongly indicating a causal relationship likely due to induced recharge. While additional research will better quantify this relationship, we believe our results thus far should prompt government agencies charged with public protection through roadway and building codes to adopt codes that would minimize induced cover collapse and subsidence, such as through the example code we have provided.

References


Florida Department of Transportation Aerial Photo Look-Up System [Internet], [Florida Department of Transportation, Office of Surveying and Mapping] [cited March 8, 2015] Available from: https://fdotwp1.dot.state.fl.us/AerialPhotoLookUpSystem/


Pasco County Florida Public Access to Permit Applications [Internet]. [Pasco County Building Department]; [cited March 8, 2015]. Available from: https://secure.pascocountyfl.net/bccpapa/Default.aspx


