

“Demonstrated and Conceptual Compatibility of Deep Stormwater Injection Well Use with
Geotechnical Construction and Land Development Practices in Karst Limestone Terrain”

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ABSTRACT

On-site management of stormwater runoff for up to 2 year storm events and larger in karst limestone terrain can be problematic due to poor infiltration conditions of low permeability and sinkhole risk. Forced infiltration using deep, unlined stormwater ponds can initiate scouring of the soft clayey sediments which plug the epikarst, and the permeability of the aquifer can increase by several orders of magnitude, and sinkholes soon follow. In response to the need for a safe, on-site stormwater management method, a team of geologists, hydrogeologists, and engineers have developed a Class V injection well system for disposal of pre-treated stormwater, with the necessary protections to operate safely in karst terrain. Interconnected karst permeability is located using exploration techniques, and multi-well testing is used to design the number and spacing of injection wells. A disposal rate in-excess of 10,000 gallons per minute for the duration of a 2-year storm event has been achieved at one site with a 19 injection well system occupying roughly 3-acres. A geotechnical engineer inspects rock cores and makes a determination that the karstified bedrock would resist densification during stormwater injection based upon rock skeleton strength. The overburden layer and shallow epikarst are isolated from the stormwater by blank steel casing grouted into place. The stormwater gravity-flows into the deep karstified bedrock through an interconnected piping network which recharges 12 inch diameter wells to depths of up to 135 feet (41 m). The water table throughout the well field is monitored automatically, and the level is manipulated by small adjustments to the recharge rate. About 175 million gallons (4,017 acre-feet) of stormwater have been managed on-site during 42 months of operation. The sustained injection rate lies in the range of 500 to 1,000 gallons per minute rate. The total rainfall during this period of operation was 168 inches (427 cm). No sinkholes have formed in 3 ½ years of continuous operation.

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The stormwater management method has been proposed to help with two different types of road stability problems: (1) the SR422-Palmyra sinkhole area just east of the Borough of Palmyra, where the method would capture and inject stormwater into the deep-lying epikarst to control overburden scouring and sinkhole formation, and (2) the SR33-Stockertown bridge where turbulent-flowing groundwater continues to scour a deep micropile foundation constructed in a karst aquifer.

INTRODUCTION

This paper summarizes the observations about the long term performance of an innovative, Class V injection well system for stormwater which has been operating since 2010 in a karst bedrock terrain without causing ground stability problems. Two additional conceptual applications of gravity injection well technology to geotechnical problems in Pennsylvania are included at the end of the paper. The site of the stormwater management system is a dense, mixed use development of 130 acres in the Philadelphia area where about 80 percent impervious surface cover is planned. The purpose of the system is to manage entirely on-site in excess of a 2-year storm volume by injecting the treated stormwater runoff into karst bedrock, while ensuring ground stability for buildings, roads, and infrastructure which is paramount to the project. The system has the capacity to achieve a disposal rate in-excess of 10,000 gallons per minute for the duration of the storm event, and to recover quickly enough to allow the system to be re-opened for disposal of additional rainfall. The technique has been developed using exploration techniques to locate large interconnected karstic permeability, and field-scale testing of the bedrock, and design and construction of a fully operational 19 injection well system over 3-acres in 2010. An area of the site was identified which contains the required interconnected karstic permeability, and the area was tested for the multi-well injection capacity.

BACKGROUND

Others attempting stormwater disposal into karst bedrock by uncontrolled recharge with poor or no engineering controls, such as sinkholes improved with shallow casings or coarse fill, or dry swales, have usually experienced damaging erosion and subsidence. Local examples of property destruction caused by uncontrolled recharge to improved sinkholes, and shallow

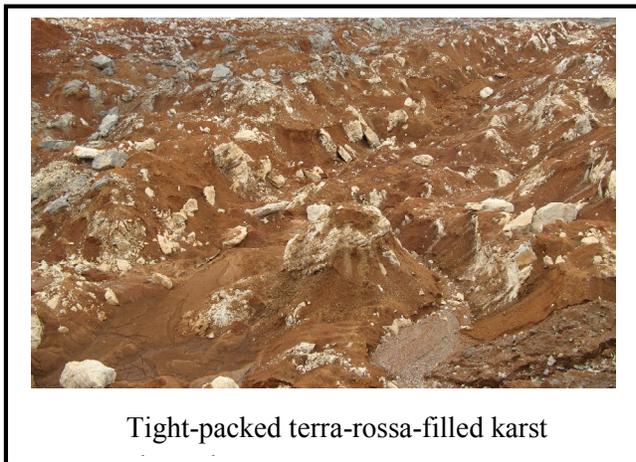
injection well use, can be found in Kochanov (1995) for the Borough of Palmyra, Pennsylvania; in Newton (1987) regarding damages caused by property development; and roadway subsidence and collapse caused by forced recharge to dry swales, in Boyer (1997), pertaining to the Frederick, Maryland area. In fact, a common reaction from others when first discussing the gravity drain concept is that sinkholes will surely form. The technique described in this paper has been developed and constructed by a team of geologists, hydrogeologists, and engineers as a safe alternative to these other, less-controlled methods.

The initial concept for the stormwater injection method was presented by Lolcama and Gauffreau (2008) in ASCE Geotechnical Special Publication 178; and the engineering, construction, and start-up of the system was described by Lolcama, Gauffreau and others in the 2011 Philadelphia Low Impact Development Symposium Proceedings. In 2013, the same authors presented a discussion of the viability of the gravity drain system at the Villanova University Stormwater Management Symposium following 3 years of successful stormwater injection after 175 million gallons managed on-site.

Plans have been submitted for utilizing the injection well technique to stabilize a roadway in Pennsylvania that has failed repeatedly due to sinkhole collapse. Stormwater flows to the site uncontrolled from distant karst-loss areas. Karst-loss (Aron and Kibler, 1981) is the recharge of stormwater to epikarst bedrock through swallets and sinkholes. The water recharges to the epikarst beneath the site causing scouring, soil voids, and ground collapse. The injection method isolates stormwater recharge from the overburden using sealed casing grouted-in-place, and eliminates soil scouring, and delivers the water to the deep karst bedrock beneath the site. Another application of the method which has been submitted is to slow the speed of karstic groundwater flow in the deep subsurface, thereby reducing the groundwater scouring of tight-packed soils from within a micropile foundation which is supporting the abutments of a bridge. The scouring action is destabilizing the foundation, causing densification of the karst and down-drag on the piles. The hydraulic gradient through the zone of scouring will be reduced by a gravity-fed water injection system which would be located at the subsurface downstream end of the foundation.

THE UNIQUE HYDROGEOLOGY OF KARSTIC AQUIFERS

Widespread karst voids and channels in carbonate bedrock can form by mildly acidic, or corrosive, groundwater originating in silicate geology and migrating to carbonate bedrock where the water infiltrates to depth during periods of low water table. Fractures and joints which dissect the bedrock become enlarged by groundwater solutioning. A few of the more permeable openings develop into deeply-penetrating cutters, or grikes, which are separated by pinnacles, or clints. This mechanism of karst development is described in detail by Palmer (2004). The interconnected cutters become plugged with the terra-rossa residuum from the weathering of the bedrock. Solutioned geologic bedding planes interconnect the cutters to drain the corrosive recharge from the bedrock. Over geologic timeframes, they also become plugged with sediment. The result is a network of sediment-filled karst channels (see inset photo).



Drainage of the water from the carbonate aquifer, by pumping or other means, induces scouring of the sediment-fill material, and the rate of flow through the carbonate aquifer increases over time. The turbulent scouring action is observed when Reynolds Numbers exceed 100, and with prolonged scouring action comes an open and flowing karst aquifer. The permeability

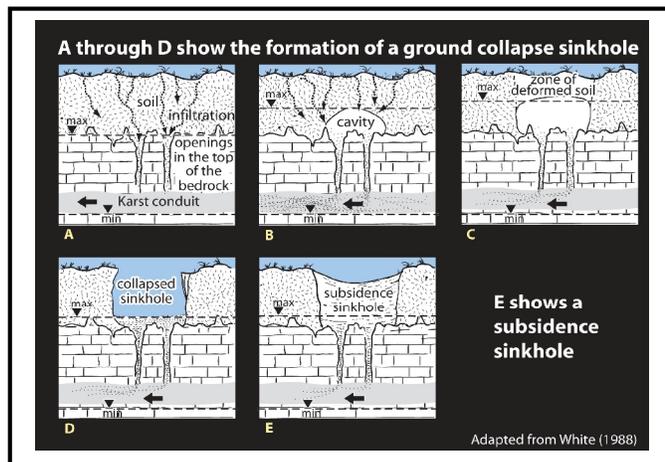
of the aquifer can increase by several orders of magnitude in this way, and the transformation to karstic permeability can occur rapidly. The karstic, or turbulent groundwater flow equation from Darcy – Weisbach is discussed in White (1988) and is expressed in terms of hydraulic head loss h_f :

$$h_f = \frac{fL\bar{v}^2}{4gr}$$

where f is a dimensionless friction factor derived from wall roughness; L is distance; \bar{v} is velocity; g is gravitational acceleration; and r is flow-pipe radius. In the Mid-Atlantic area, the epikarst aquifer layer within which turbulent flowing groundwater occurs, can penetrate to 150 feet (46 m), and deeper in some areas.

Sinkholes form over epikarst when superficial soil layer or soil bridge collapses into a pre-existing soil void, or in the case of a subsidence sink, when soil material is gradually piped into the underlying karst aquifer causing the soil layer to slowly subside forming a ground depression. Newton (1987) provides an excellent discussion of sinkhole formation mechanisms. Solutioned openings act as drains for stormwater and other sources of surface water to enter the bedrock. White (1988) provided a review of the mechanics of sinkhole formation, and the inset figure has been adapted from his work.

The groundwater storage capacity of karst bedrock is large as compared to porous or fractured media. Uncontrolled surface water recharge to the bedrock can raise the water table by tens of feet and more, over several days, as the result of the recharge filling the karst voids. The water table can rise upwards into the overburden. The karst conduits can drain equally as fast



following cessation of the recharge. Drainage causes the water table to return into the bedrock, and the rapid drainage causes soil scouring. The process is repeated during uncontrolled stormwater recharge causing soil cavities to form and expand. The expanding cavity weakens the support of the shallow soil bridge, which collapses suddenly into the underlying cavity (see Figure 1). Newton (1978) describes the continuous wetting and drying of the soil layer causing drying and spalling of the soil cavity walls. Wetting of the soil layer adds weight, and stress, to an already unstable condition, which accelerates the rate of soil collapse.

DESIGN, INSTALLATION, AND OPERATION OF A GRAVITY DRAIN INJECTION WELL SYSTEM

Typically, the site civil engineering firm will mark possible locations to be drilled and tested for water injection capacity, and those locations will be considerate of easements, infrastructure, planned use, among other parameters. A reconnaissance-type, rapid drilling and injection testing method is used to install pilot boreholes, and to identify locations with sufficient injection capacity to be developed into permanent gravity drains. A geotechnical engineer



Figure 1. Sinkholes from uncontrolled stormwater losses to epikarst bedrock.

inspects rock cores and makes a determination that the karstified bedrock would resist densification during stormwater injection based upon rock skeleton strength. If multiple wells are to be used to meet a required injection rate, the zone of influence around each injection well is determined and the maximum possible injection rate is measured at which the water table level remains inside of the bedrock. A minimum separation

distance between wells is established, and the wells are spaced accordingly to lessen the interference effects of one well on the surrounding wells during stormwater injection, thus enabling the greatest combined rate of recharge. A multi-well test is performed on the entire well field, and the capacity of the field to accept stormwater at an acceptable recharge rate, and to dissipate the stormwater rapidly is confirmed, with the water table remaining well below the top of the epikarst bedrock.

Each pilot hole is replaced with a 12 inch diameter injection well, with casing that extends through the overburden and stainless steel screen that is installed deep into the epikarst bedrock layer. No filter pack is installed around the screen, as is would restrict the rate of flow outwards into the karst bedrock. The annular space through the overburden is grout-sealed to control water seepage and the migration of fines downward around the drain, which mitigates the risk of sinkhole formation at that location. A groundwater piezometer is installed near to the

gravity drain, and the water table is continuously monitored using automated telemetry equipment at the piezometer.

The water is pre-treated prior to entering the injection well. Pre-treatment would consist of mechanical oil-water separation, and sediment and floatables removal. The water enters a settling pond where additional sediment removal takes place, and passes through a manhole containing a slide gate valve, where the flow rate to the injection well system is measured. This is where the flow can be adjusted or temporarily stopped if necessary, such as when maintenance is required in the well field. Each well is fitted with an intake riser which has been designed to control the recharge rate to its pre-determined capacity. To prevent flooding of the well system, an overflow pipeline would carry water to a lower, large storage basin. Flow rates through these pipelines are monitored and automatically reported to the off-site datacenter.

MANDATORY WATER TABLE MANAGEMENT DURING INJECTION

A pre-existing condition of water injection is a water table, whether perched or ambient, that resides deep inside of the epikarst aquifer within the area of influence of the injection well field. The condition must be established by monitoring for the seasonal high water table. The incremental rise caused by injection must not elevate the water table into the overburden, or risk sinkhole formation. At the injection well site, state-of-the-art telemetry technology has been employed to monitor the water table level and groundwater temperature of the injection well field. An off-site datacenter receives a continuous feed of monitoring data through GSM transmission, and the datacenter is programmed to compare the site data to pre-set thresholds. When water table conditions have reached the pre-set elevation thresholds, warning messages and then alarm messages are automatically sent to the project hydrogeologist via email and text. The stormwater flow rate to the drains may be manipulated manually using the inlet flow-control valve; an automated flow control capability is in the planning stages. The reduced recharge rate provides the aquifer with time to dissipate the stormwater. These conditions have occurred during very large storms (tropical storms; hurricanes), or during very closely timed larger storm events.

Figure 2 shows the water table elevation hydrograph during soil infiltration and injection well operation, for a representative location within the 19 well field. The elevation of the epikarst bedrock is indicated, and the water table level in the karst aquifer is managed by automated monitoring and

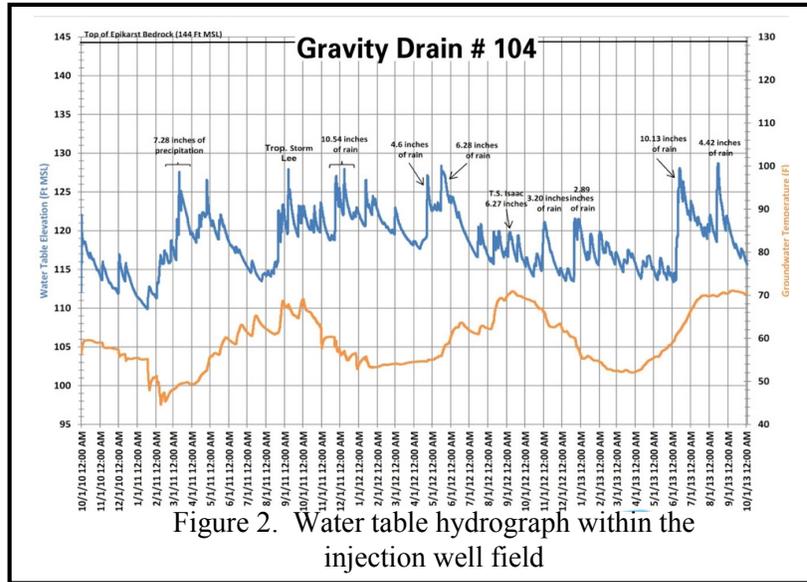


Figure 2. Water table hydrograph within the injection well field

manual adjustments to the recharge rate as described above. No sinkholes have formed in 3 ½ years of continuous operation.

3-YEAR-PLUS PERFORMANCE REVIEW

Under challenging conditions of record rainfalls during the first year of operation, and above average rainfall during the second and third years of operation, the performance of the permanent drain field and the automated remote monitoring system has been excellent. Gravity drain injection wells have disposed of about 175 million gallons (4,017 acre-feet) of stormwater during 38 months of operation and monitoring, with a combined maximum injection rate achieved of 10,140 gallons per minute. The sustained injection rate lies in the range of 500 to 1,000 gallons per minute. The area of injection is roughly 3 acres. The total rainfall during this period was 168 inches (427 cm); of note were several tropical storms delivering 7 to 10 inches (18 cm to 25 cm), one storm at 12 inches (31 cm), and one storm at 16 inches (41 cm). During these storms, all of the rainfall captured by the gravity drain stormwater management system was managed on-site.

The automated hydrologic and hydrogeologic monitoring equipment and datacenters have performed extremely well; the field equipment and auto-notification technology has proven to be very reliable and robust, even under challenging hydrogeologic conditions. The auto-

notification feature has exceeded design expectations for enabling the project hydrogeologist to manage the stormwater recharge rate to the karst aquifer, to maintain stable operating conditions in the gravity drain field.

No sinkholes have formed at the Site as the result of the operation of the gravity drain field which demonstrates that the gravity drain field can continue to be operated using the existing design.

A ROADBED STABILIZATION APPLICATION FOR KARST TERRAIN

A karst feature in the form of a bedrock flow channel network underlies the SR422-Palmyra sinkhole area. The karst conduit network directs the flow of stormwater recharge from off-site infiltration areas to the sinkhole site. Stormwater recharge reaches a depth of up to 110 feet, and possibly deeper at the site. Recharge from specific features in the Palmyra drainage basin, estimated by others to be about 270 acres, recharges the shallow epikarst and mixes with groundwater. Stormwater flows overtop of, and through the epikarst, scouring natural sediments and fill material, and transporting the material into the deeper regions of the channel network, and beyond to the closed point of groundwater discharge. The scouring promotes the formation of soil-cavities and sinkhole formation. A cycle of wetting and drying of the soil cover over the soil void results in upward growth of the void towards the ground surface and deformation and collapse of the soil cover after wetting. Both small scale subsidence, and catastrophic collapses are being caused by these processes at the Site.

The gravity drain injection well method has been proposed for this Site. The method can capture and convey stormwater to the Site, and isolate the fugitive stormwater from the overburden and fill materials to control scouring, and inject the water into a deep-lying zone of karst permeability. The targeted depth for water injection is around 100 feet below grade. Figures 3 and 4 show the conceptual layout of the manhole and flow control system, and the injection well head, respectively.

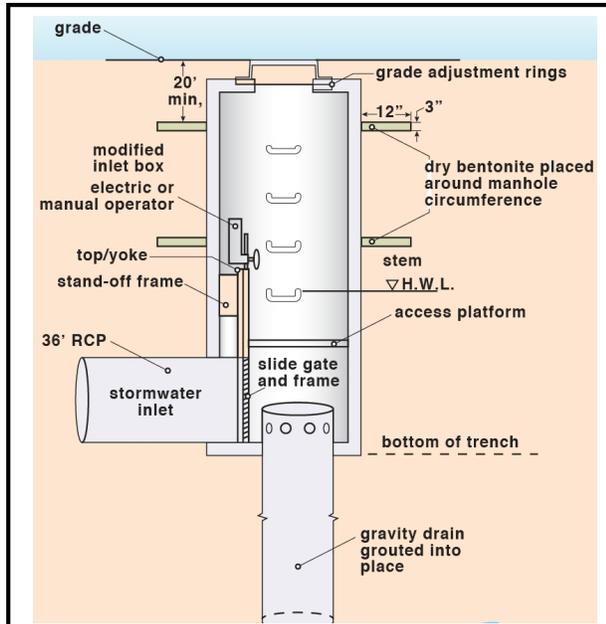


Figure 3. Injection well manhole design

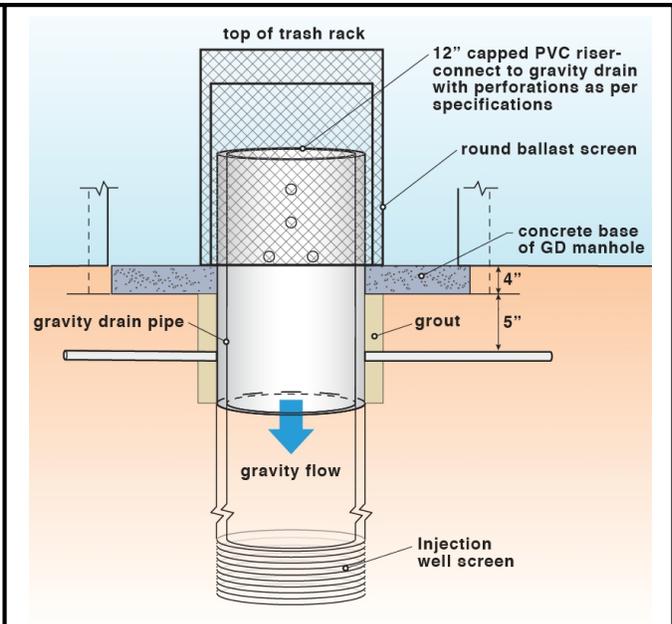


Figure 4. Gravity drain flow restrictor

A MICROPILE FOUNDATION PROTECTION APPLICATION

Figure 5 presents the hydrogeologic background information for a novel, conceptual application of gravity drain injection wells which has been designed to solve a groundwater scouring problem that is degrading a deep micropile bridge foundation in a karst aquifer. The new bridge, which is a replacement of the original bridge which failed, is located along Highway

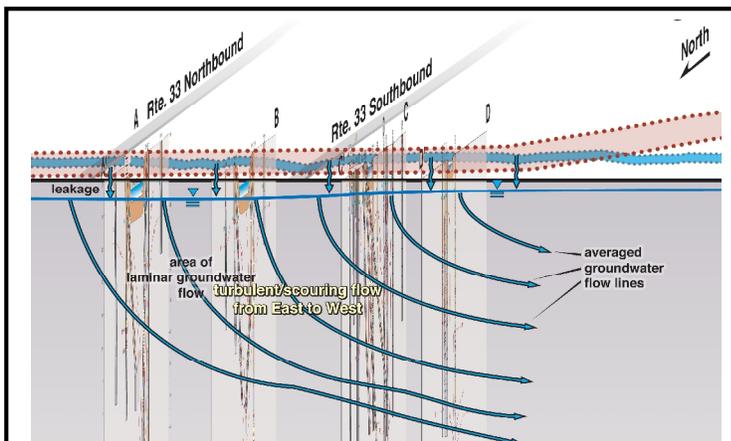


Figure 5. Scouring of a Deep Bridge Foundation by Turbulent Flowing Groundwater

SR33 in Pennsylvania, and spans the Bushkill Creek near Stockertown. A karst tracer study demonstrated that turbulent-flowing groundwater moves through the extensive micropile foundation to about 450 feet below grade. The water table is 70 feet below grade and fluctuates seasonally depending on recharge from the creek. Seepage losses to

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