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Forensic Engineering Analysis of Residential Underdrain Design Methodologies, Performance, and Failures

By Edward L. Fronapfel, PE (NAFE 675F)

Abstract

In 2014, the basement of a single-family home in a residential subdivision flooded. The homeowner's insurance company engaged an engineer to conduct forensic investigations, which ultimately determined that the resultant flooding was caused by blockage of an underdrain system to which the home was connected. This system included a main line in the street and a lateral that connected the underdrain to the home's foundation drain. Subsequent to this event, other homes in the subdivision reported flooding in the basements and crawlspaces. The author was engaged by the subdivision homeowners association (Common Interest Ownership Community or CIOC). The CIOC's declarations and recorded documents contained no information regarding the existence of the underdrain system. In addition, there was no clear information about the ownership or maintenance responsibility. The author's field investigations determined the underdrain was not constructed to the applicable minimum standards, and the developer did not provide adequate flow capacity for the number of homes served by the underdrain. The CIOC entered into litigation against the developer, and the author evaluated issues associated with the design, construction, transition, and maintenance of the underdrain system.

Keywords

Underdrain, foundations, cleanouts, common interest ownership community, homeowners association, video inspection, sump, sump pump, calcite, pipe blockages, forensic engineering

Background

In 2014, approximately 12 years after construction began on a development that included common areas, public roadways, parks, a clubhouse, school, and more than 1,350 residential homes located in the Front Range of Colorado, flooding occurred in the basement of a home. That home's foundation system consisted of poured-in-place concrete walls on drilled piers.

The basement foundation was constructed with a structural steel/concrete composite floor bearing on interior piers, and a crawlspace was created below the structural floor to mitigate the issues of expansive soils that were identified in the feasibility studies and the site-specific geotechnical evaluations. The foundation system, perimeter drain, common lot underdrain, and site grading were designed to reduce the potential for water migration into the soils and the subsequent damages that can occur with construction of residential lots on expansive soils. Proper control of the subsurface water was necessary to permit the home's basement to be habitable space.

In response to the flooding event, the homeowner's insurance company hired a forensic engineer, who determined that the efflorescence and water staining were representative of long-term flooding present in the structural crawlspace located below the suspended basement floor. The cause of the resultant flooding was ultimately determined to be blockage of an underdrain system. This was discovered by excavating the property from the back of the walkway to expose the lateral that was constructed from the home's perimeter drain and connected to the underdrain. This connection between the home's lateral and the underdrain was found to have been made with duct tape rather than the proper pipe fittings. The forensic evaluation of this home resulted in a further need to

Edward Fronapfel, PE, 5926 McIntyre Street, Golden, CO 80403, (303) 425-7272, efronapfel@callsbsa.com
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understand the ramifications of the construction of the underdrain, its use in the subdivision, its records, and ultimately its legal (contractual) ownership because it was within the public roadway and under the public sewerage system.

Installation of underdrain systems can reduce water migration from the more porous backfill materials in utility trenches that lead to a structure. Underdrains can reduce perched water conditions that occur when water is trapped in lenses of more pervious materials. They also mitigate the negative impact of water from developed landscaping and can positively impact overall drainage conditions within a development. In addition, when combined with dendritic systems, underdrains can aid in lowering the ground water table. In order to evaluate the need for and properly design an underdrain system, the site's geology must be reviewed in combination with the effects of the development on the original materials. An example of one jurisdiction's underdrain criteria is shown below.

City of Colorado Springs, "Colorado Springs Utilities Groundwater Underdrain Voluntary Criteria – 2015," Section 13.01 "General," states the following:

"The purpose of the underdrain system is to provide a method for conveying subterranean groundwater from around a structure/building foundation via gravity to an acceptable discharge point in a drainage channel or storm drain. All new residential developments within the City of Colorado Springs shall install a gravity underdrain system, unless a variance is given by the City of Colorado Springs, Engineering Division. Foundation perimeter drains, whether inside or outside the foundation walls, shall be connected by gravity to the underdrain main line via an underdrain service line."

Feasibility studies provided by geotechnical engineers generally specify the conditions that warrant the use of an underdrain. The incorporation of that underdrain into the subdivision design properly begins with the Official Development Plan and is continued throughout the preparation of land development plans, including utility layouts, home layouts, overlot grading plans, and independent lot drainage plans.

The design of underdrain systems is conceptually similar to the design of sewers and water lines, and underdrain lines must be sized in accordance with the number of homes, floor plan areas, and number of linear feet associated with the foundation types that the systems will serve. The diameter and slope of underdrain lines must be adequate for the expected flow rates that are developed from the ground water conditions that will occur post-development.

The underdrain system collects, directs, and conveys these flows within the pipes. In order to reduce maintenance, the pipe size and slope are designed to provide self-cleansing velocities that will minimize deposition and sediment buildup. The underdrain system can be supplemented at each home with a back-up sump pump. The pump should not activate in normal usage. However, if the system has an overcharge of water beyond its capacity — or if the system is clogged and backs up — the sump provides short-term protection to the foundation while the system can be examined. This is similar in concept to the use of a primary and secondary roof drain system; when the observable secondary drain activates, maintenance personnel can respond to the issues.

Following this first reported instance of flooding, subsequent water intrusion issues, such as flooded basements/crawlspaces and excessive sump pump operation (passive systems should not require the use of pumps), were reported to have occurred at more than 60 residences within the subdivision. The owners of the original home where the flooding was reported ultimately sought legal recourse from the CIOC and the city regarding the underdrain lines. The homeowners were not able to repair the underdrain portion that was in the roadway and the connection to the lateral without involvement of the CIOC or the city. During this process, it was determined that the failed portion of the underdrain responsible for the flooding of the home was located entirely within the right-of-way owned by the jurisdiction. No portion of either the private perimeter drains around the foundation or the 4-in. lateral line to the street was found to have contributed to the flooding.

In order to evaluate the system, the CIOC engaged a geotechnical engineering firm to provide a preliminary report of the system and engaged legal firms to review their governing documents. Based on those initial reviews, it was determined that the original construction of the underdrain and the laterals was improper. In addition, the rights of the common interest community were not clearly assigned. Upon discovery that the underdrain was to be controlled by the community — and that the city would not partake in the repairs to the system — the CIOC entered into a legal dispute with the subdivision's developer to determine the ownership, transference, responsibilities, and jurisdictional issues.

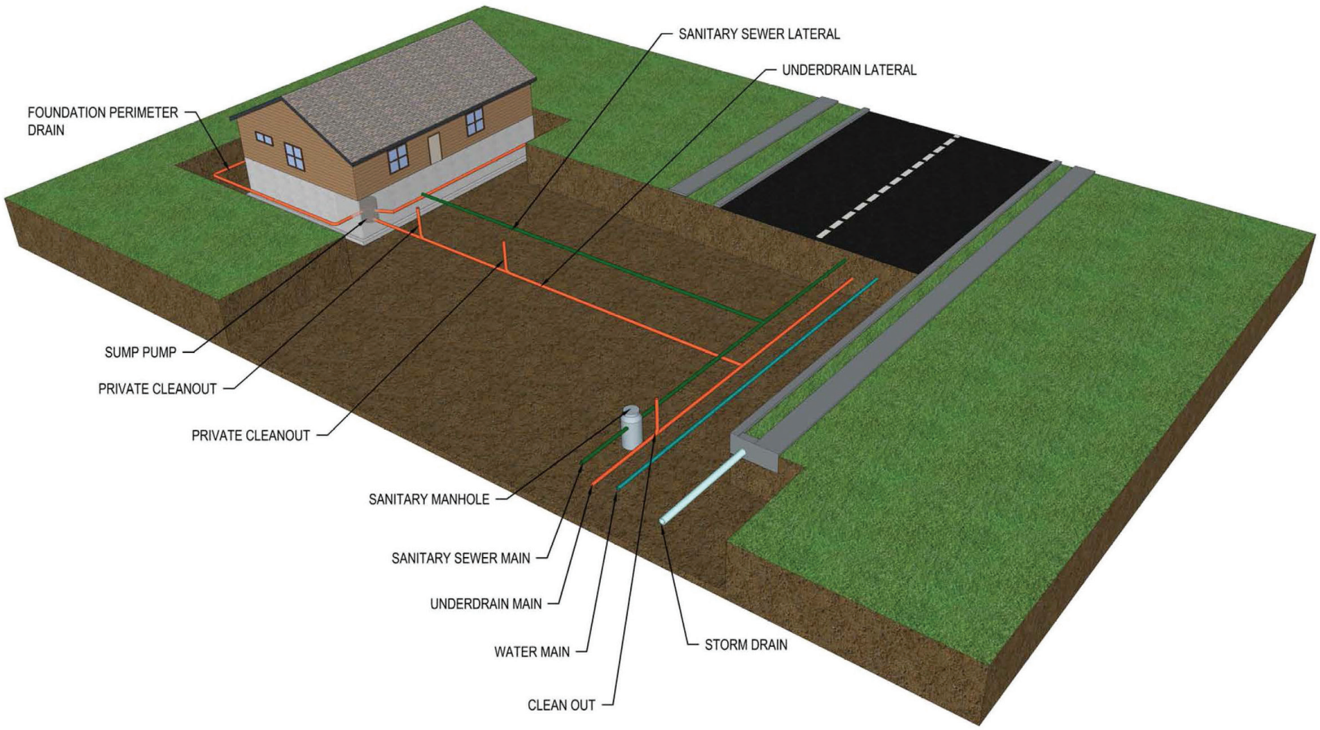

Figure 1
Schematic layout showing typical building perimeter drain, lateral and underdrain located within the right-of-way under the street.

The finding of the forensic engineering work necessary in the litigated matter determined that of the 1,350 homes in the subdivision, 1,180 (87%) were connected to the common underdrain. The complete as-constructed collection system generally consisted of 4-in. perforated drains installed around the perimeter of each home, main underdrain lines in the streets and laterals connecting the two systems. The 4-in. perforated foundation drains terminated at a sump pit in the basement of each home or at tee connections along the perimeter of the foundations, and 4-in. non-perforated laterals connected these to the main underdrain lines in the streets. The underdrains were installed alongside and slightly below the city-owned sanitary sewer lines, and generally followed the sanitary sewer laterals from the homes for discharge into the subdivision-wide underdrain located under the underdrain in the street (**Figure 1**).

The subdivision was divided into four separate areas (**Figure 2**), each served by a separate, dedicated underdrain system. These four separate systems served 12, 201, 678, and 289 residential structures.

Since the individual homes were constructed by multiple builders, varying construction techniques were used for the residential buildings in each area. The municipality required that a site-specific geotechnical report be provided for each individual lot; however, the builder of each home may or may not have relied on the findings and recommendations contained in those specific geotechnical reports.

The underdrain systems were generally co-located (installed below and adjacent to) with the sanitary sewer mains. To provide access to the underdrain, cleanouts were generally constructed near the sanitary sewer manholes. The underdrain systems were intended to discharge to the surface at specific locations within drainage easements via non-pressurized gravity flow. At least one builder provided sump pumps in the passive pits as a redundant backup in the event of a failure or overwhelming of the underdrain or perimeter drain systems.

A number of builders and homeowners also installed sump pumps in response to high water levels in the pits or actual flooding of the basements. The methods of warranty request documents, CIOC reports, disclosure of previously unreported incidents, and other potentially forensically important documents were reviewed. These reviews resulted in an imperfect record resource that was used in determining the underdrain's performance.

The forensic evaluations also included review of many

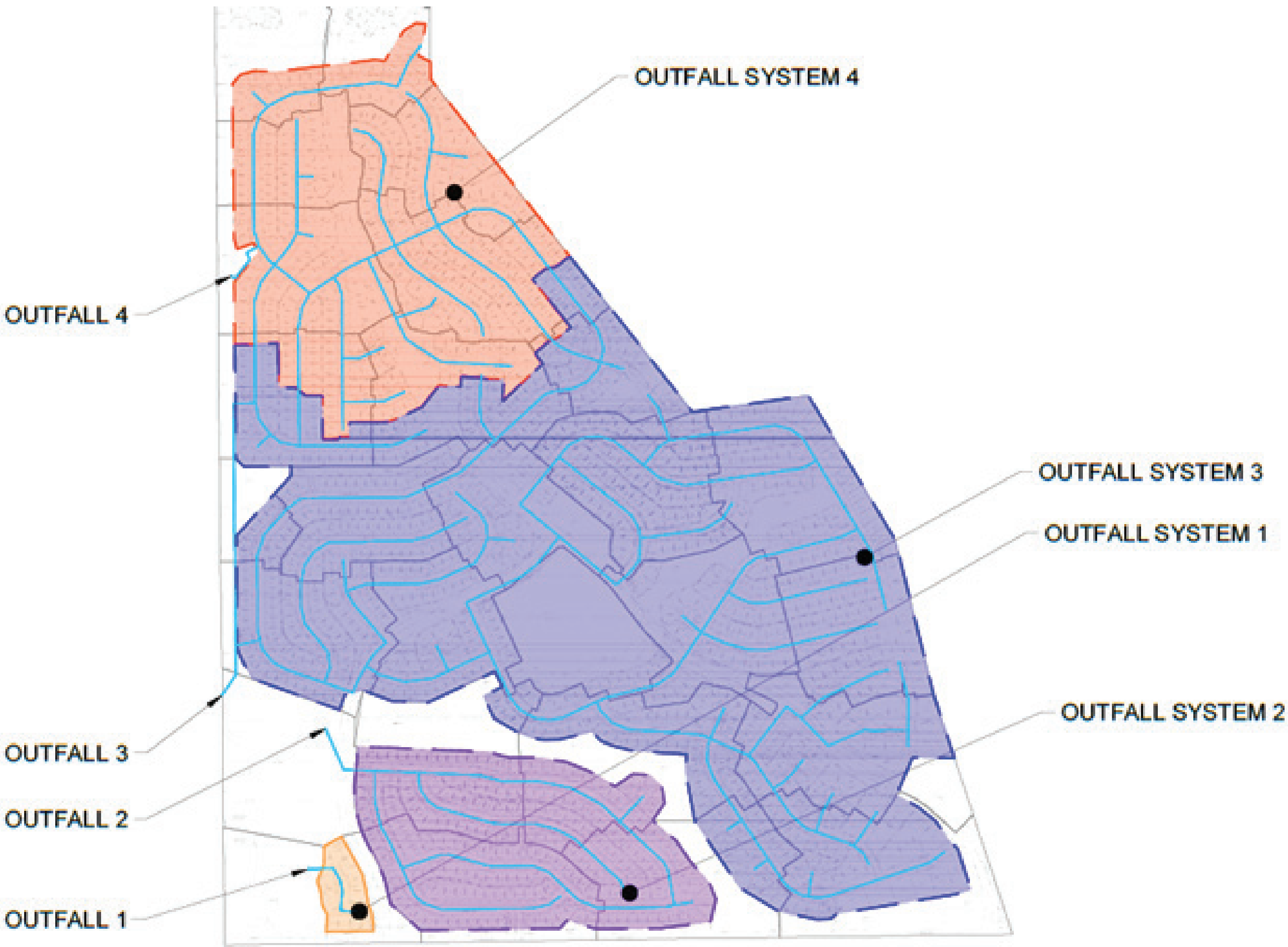

Figure 2
Identification of separate underdrain systems. Each system is labeled by an outfall number, and outfall systems 1, 2, 3, and 4 served 12, 201, 678, and 289 lots, respectively.

potential sources of information from multiple builders, developers' records, and reported flooding events. In some cases, where structural basement floor systems were constructed, flooding of the crawlspaces below the visible floor areas was not previously reported because the owners were unable to see below the floors without directly accessing them.

Determining the ownership of the systems was also critical to the forensic analysis of the subdivision and the underdrain systems. Detailed review of the CIOC's declarations, plat maps, and other recorded documents revealed no information indicating the presence of the underdrain systems or the CIOC's responsibility to own and maintain these systems. However, the underdrains were shown on the Civil Sanitary Sewer Construction Plans, and review of aerial mapping during construction indicated that they were being placed in the street system.

Approach

To provide a comprehensive review of the system, the forensic evaluation began with an analysis of publicly available documents. Once the project entered the judicial system, further information could be obtained (in part). Several aspects of the project (involving its design, construction, and documentation) were identified for forensic investigation, including:

1. Review of applicable design codes, standards, criteria, and other reports.
2. Review of the design of the underdrain system.
3. Review of documentation from the developer to the CIOC at turnover.
4. Inspection of locations where problems were reported.

5. Inspection of the as-constructed underdrain system.

6. Documentation of the findings.

7. Repairs.

8. Design flows.

9. Applicable codes.

10. Hydraulic analysis.

Applicable Codes

Review of the Jurisdiction with Authority's "Standards and Specifications, Water, Sanitary Sewer and Storm Drainage Infrastructure," applicable at the time of design and construction, determined that underdrains were never (and will never be) maintained by the jurisdiction — and that these systems remain private in perpetuity. The developer's obligation was therefore to provide the CIOC with a properly designed, constructed, and maintainable underdrain system.

The developer's obligation was also to clearly inform the CIOC that the private underdrain system would become its property, and that it would be responsible for the system's maintenance and all costs associated with damages due to potential failures of the system. The underdrains should have been transferred patently to the CIOC in the Declaration of Covenants, Conditions and Restrictions, wherein the designation of lots, common elements, and limited common elements are transferred to the CIOC.

Proper transfer of ownership allows the receiving entity, the CIOC, to set budget guidelines and develop a complete understanding of the system's needs. These include legal access to the lines as well as performing maintenance duties and budgeting for regular observations, repairs, and replacement of the lines on the municipally owned lots and within those areas where the underdrain laterals transition from the right-of-way to the individual properties. Proper transfer of ownership also allows for the legal discharge of the underdrain flows into the storm drainage infrastructure owned by other districts or municipalities. The forensic investigations established that the CIOC was never informed of the existence of the underdrains or the fact that it was the owner of the system and required to maintain it.

Design of the Underdrains

Several geotechnical investigations and reports were provided prior to design and construction of the subdivision. The earliest, dated August 1999, found that the soil and groundwater conditions on the site required the construction of foundation drains around the buildings' foundations and an underdrain system in the streets. The report went on to state that the underdrains should be smooth, perforated, or slotted polyvinyl chloride (PVC) pipe and should be installed below the sanitary sewers at a minimum slope of 0.5%. The report also noted that a single 4-in. PVC line would be adequate for the flows expected from up to 100 homes and that the system should be provided with cleanouts. This geotechnical report also noted that the underdrains were to be maintained by the CIOC or another entity. This report was not provided to the forensic investigator in a timely manner but served to confirm research.

The forensic evaluation included contact with the original geotechnical engineer, which resulted in the discovery that the engineer was providing expert consulting to the developing entity as a non-disclosed expert. The legal ramification of the original designer working on the case would likely have prejudiced those opinions, making it difficult to obtain any information that was lacking in the public or produced files. The engineer provided a statement noting that the standards used around the state could not be relied on in this case. Without telling the forensic evaluator of their present involvement in this matter, that information would ultimately be used in the discovery and depositions.

The Jurisdiction with Authority's "Standards and Specifications, Water, Sanitary Sewer and Storm Drainage Infrastructure" stated that the underdrains were required to be designed by a registered professional engineer. In addition, the standard drawings contained in that document required a minimum underdrain size of 6-in. PVC.

The forensic investigations determined that the civil engineer's Sanitary Sewer Construction Plans correctly referenced the municipality's standard underdrain cleanout detail, which clearly showed that the underdrains and cleanouts were required to be constructed of 6-in. PVC pipe. However, within the same note, the civil engineer specified that the underdrains were required to be constructed of solid 4-in. PVC pipe. This discrepancy shows a lack of understanding on the part of the designer regarding underdrain systems. In addition, no engineering calculations were provided for review by the municipality or in the files provided to the developer regarding determination of the flows into the underdrain system from the perimeter drains in each lot or the combined flows into each branch of the underdrain system and ultimately into the outfall of each underdrain system.

During discovery, it was found that the underdrains were, in fact, never designed for any standard rates of flow. In lieu of performing detailed geohydraulic and hydraulic calculations, a prescriptive approach similar to water system or sanitary sewer design could have been used to size the underdrain pipes. Typically, a geotechnical engineer would recommend a 4-in. diameter underdrain line for the first 100 lots in a region when ground water is not a consideration. Reference is made to reports prepared by geotechnical engineering firms in Colorado for various communities in the Front Range area of Colorado. However, because of the litigation of this project, the names of those firms cannot be disclosed. These geotechnical reports contain preliminary underdrain sizing tables that provide minimum required pipe sizes based on the number of residences connected at varying longitudinal slopes.

The jurisdiction did not have prescriptive requirements for the sizing and layout of the underdrains and instead relied on engineering to develop this system. Therefore, the geotechnical report had to provide sufficient information and forecasting of the developed effects on the lots and subdivision to determine the flow that would occur from each home's foundation drain system.

Using Manning's equation, the steady state hydraulic capacity of a 4-in. PVC line at 2% slope is 0.32 cfs (144 gpm). Per **Figure 3**, a 4-in. line would have the capacity to serve 100 lots; therefore, each lot would generate approximately 0.0032 cfs or 1.4 gpm over 24 hours. Performing these reverse calculations for non-pressurized flow would have allowed for design of the underdrain system as the number of homes served increased. The largest system constructed on the site, which serves 678 lots, would have

PRELIMINARY UNDERDRAIN SIZING

SLOPE = 0.05 (0.5 PERCENT)				
Pipe Size (in)	4	6	8	10
Maximum Number of Residences	50	100	200	400
SLOPE = 0.01 (1.0 PERCENT)				
Pipe Size (in)	4	6	8	10
Maximum Number of Residences	75	150	300	600
SLOPE=0.02 (2 PERCENT)				
Pipe Size (in)	4	6	8	10
Maximum Number of Residences	100	300	600	1200

If this underdrain system is planned to connect to up-gradient systems, larger

Figure 3
Preliminary underdrain sizing guidelines from a geotechnical report for a middle school in Colorado Springs, Colorado. These preliminary sizing guidelines show that a 4-in. underdrain at 2% slope is required for 100 residences.

been constructed with lines starting with 4-in. pipe for the first hundred homes and increasing the size of the lines for each subsequent 100 homes.

This 678-lot system would have therefore required a collection system that would convey the full flows and would have required pipes increasing in size from 4-, 6-, 8-, 10-, and 12-in. lines. Similar to the way the sanitary sewer system was designed for the subdivision with the pipe sizes expectedly ranging in size from 4 to 18 in., the underdrain sizing methodology requires determination of the number of units served, the per capita flows from each lot and an estimation of the quantity of water infiltration from the ground surrounding each home. An example of a codified underdrain sizing requirement can be found in the City of Longmont Municipal Code, Section 15.05.070 "Underdrains," which states:

"C. Area underdrains and underdrain collection systems.

1. Design and plan approval.

a. The area underdrain or underdrain collection system must comply with all applicable city, state, and federal regulations in place at the time of construction.

b. A professional engineer registered in the State of Colorado must design, and stamp the area underdrain plans, underdrain collection system plans, and underdrain report. The system shall be designed in consideration of seasonal high groundwater levels anticipated at the project site.

c. All area underdrains and underdrain collection systems shall have a positive gravity outlet piped to an approved underdrain collection system, to a storm sewer, or to a drainage channel. The use of any conveyance system other than a gravity system, such as a lift station, must be approved in writing prior to installation by the public works and natural resources director or designee.

d. Area underdrains and underdrain collection systems, six inches in diameter or smaller, placed adjacent to and in the same trench as sanitary sewer mains shall be rigid walled nonperforated pipe and shall have a minimum clearance of one foot from the side of the underdrain pipe to the side of the sanitary sewer main pipe. Access points on underdrain systems are not allowed to connect to or surface into sanitary sewer manholes."

Determining the quantity of water infiltrating into the soils around the buildings must take into account the contribution of water from the loose backfills around the homes in addition to the native materials. The flow of water on the excavated cuts for each foundation can impact downstream lots, and even the bedrock geology can change the flow rates to each individual lot. The flow rate and volume from each lot entering the underdrain are thus dependent on a number of factors that include soil permeability, building size, the duration of the rainfall events causing the infiltration, the moisture content of the soils, bedrock profiles, ground water, and even the lot's grading characteristics.

There are a number of published sources that can provide the expected flow rates to a perimeter drain. Using these published sources as a guideline, the infiltration can be estimated to range from 0 gallons per lot per day to more than 20,000 gallons per lot per day for a representative 1,000-sq-ft building footprint. In addition to the individual lot, the design of the underdrain collection system must anticipate each lot's cumulative contribution to the flow in the overall system. The cumulative flow rate would, at peak design, have to estimate the potential number of lots contributing to the system at the same time and determine what that potential number of contributing lots would be at any single event.

Duane Friend and Doug Peterson, University of Illinois Extension, College of Agricultural, Consumer and Environmental Sciences, "Land & Water," August 2005, Number 8, "Sizing Up a Sump Pump," states:

"If you're building on sandy soil, plan for a system capacity of 14 gallons per minute for every 1,000 square feet of home. If you're building on clay soil, plan for a system capacity of 8 gallons per minute for every 1,000 square feet of home."

City of Ann Arbor - Developer Offset-Mitigation Program, Guidelines for Completion of Footing Drain Disconnections, Updated November 30, 2005, states:

"A typical single-family residence in Ann Arbor contains 1,200 square feet of footprint area, most often with a standard basement depth of 5' to 8'. These structures have been found to generate an average of 4 gallons per minute (gpm) from monitoring data within the City during peak wet weather conditions."

Those same features should have been considered in the analysis by the civil engineer providing the underdrain design at the subject site. Based on this author's experience, the incorporation of infiltration from water sources pre- and post-development must be considered, and a factor of safety to ensure the longevity of the system used must also be accounted for in the design. An underdrain system would not be designed to operate at full flow conditions, and the peak capacity of the system should also be considered in the design to allow for the acceptance of risk of the system's capacity during its useful life. The system can also be diminished in capacity by long-term scale buildup. Thus, similar to the sewer system, the developed system must include a means to allow maintenance.

Upon forensic evaluation of the property, substantial sediment and hardness buildup were identified in the pipes. Laboratory testing confirmed the calcite materials within the drain line. Ultimately, the defense concluded the most likely source was the decalcification of the soils in the subdivision. The findings in this forensic analysis indicated that no original engineering work for the development was ever provided in the actual sizing of the system. In addition to the lack of engineering analysis, the construction failed to comply with both the provided engineering details or the city's requirements. There are, as mentioned, a number of prescriptive requirements, such as one Colorado geotechnical engineering firm's "Geotechnical Subsurface Exploration Program," which states:

"Geotechnical Parameters for Underdrain Design. The underdrain system(s) for the project should be designed in accordance with the parameters below. The actual underdrain layout, outlets, and locations should be developed by a civil engineer...

8) The underdrain system should be designed to discharge at least 25 gallons per minute of collected water.

9) The high point(s) for the collection pipe flow lines should be below the grade beam or shallow foundation bearing elevation as shown on the detail. Multiple high points can be beneficial to reducing the depths to which the system would be installed. The collection and discharge pipe for the underdrain system should be laid on a slope sufficient for effective drainage, but a minimum of 1 percent. (Flatter gradients may be used but will convey water less efficiently and entail an increased risk of local post-construction movements.) Pipe gradients also should be designed to accommodate at least 1 inch of differential movement after installation along a 50-ft run.

10) Underdrain 'clean-outs' should be provided at intervals of no more than 100 feet to facilitate maintenance of the underdrains. Clean-outs also should be provided at collection and discharge pipe elbows of 60 degrees or more.

11) The underdrain discharge pipes should be connected to one or more sumps from which water can be removed by pumping, or to outlet(s) for gravity discharge.

We suggest that collected waters be discharged directly into the storm sewer system, if possible.

12) Underdrain systems should be periodically inspected and flushed/cleaned as necessary. Maintenance/repairs should be performed to ensure proper performance."

Documentation Review

The forensic evaluation included a review of the CIOC's Declaration of Covenants, Conditions and Restrictions and other developer-provided documentation. These documents are required for proper identification, transition, and turnover of common elements and limited common elements from the control of the developer to the CIOC. The Municipality's Standards and Specifications, the overall and site-specific geotechnical report, and the Sanitary Sewer Construction Plans all stated that the underdrains are private and are required to be owned and maintained by the CIOC.

A review of the file found that the developer/builder provided a letter to the management company indicating that the underdrain was transferred to the CIOC. It included an engineering evaluation using a dye test to determine that the underdrain was functional. This letter and engineering evaluation were prepared near the front end of the construction of the project. Specifically, the tested portion of the underdrain was within an upstream location on the site and the letter, as written, did not inform that other underdrains had been constructed in the subdivision or that the CIOC was the owner of that system.

In the documents reviewed, two reserve studies were also discovered, both of which were prepared by the developer/builder and the management company. One reserve study pre-dated the other, and that included a fixed fee cost in a 20-year reserve projection for an underdrain. The second reserve study did not include that line item. In fact, it was provided through the management company as the official reserve study.

Based on the author's experience with common interest communities, in most controlled associations, the best interest of the community is served by the creation of a clear and comprehensive framework, which should include financial stability and budget setting guidelines. The inspection, maintenance, repair, and replacement of the underdrain system should have been fully considered similar to if the work involved a municipality providing capital expenditure planning for sanitary sewer or water lines.

Site Inspections

Field observations and mapping of the as-constructed underdrain systems were necessary components of this forensic evaluation. Due to the lack of available information in the public record, such as as-built drawings or daily construction logs, the system had to be video-scoped and specific portions excavated for analysis. The underdrains constructed in the street right-of-way could only be accessed by removal of the asphalt pavement and roadway subbase to expose the cleanouts or, in some cases, the underdrain itself. Secondly, inspections were also required at specific homes, and, where necessary, these could only be accomplished through separate access.

Determining which homes would be reviewed would be reached after review of lengthy owner questionnaires and/or maintenance records were discovered from the multiple builders, insurance reports, or management reports. These reports would have to be evaluated based on flow rate issues, flooding, failures, or as other systematic issues related to perimeter and underdrain problems became known. The locations of the reported flooding or sump pump incidents were then overlaid on each underdrain system's map to allow the forensic team to develop potential correlations between incident locations and types, and the knowledge of the underdrain construction based on the plan reviews and/or physical findings.

In a best-case scenario, the entire underdrain would have been physically inspected. However, because of many constraints, the first phase of the forensic work involved locating approximately 40 cleanouts on one segment of one of the underdrain systems. The first phase of work found that no cleanouts meeting the municipality's standards were provided, and the non-compliance included location, type, depth, and accessibility.

The municipality's standard detail for underdrain cleanouts (capped vertical risers) required that an underdrain cleanout be provided at each sanitary sewer manhole. The vertical riser sections of the cleanouts were required to be constructed along the outside of the vertical portion of the manhole barrel, and each was required to be connected to the manhole wall with stainless steel straps for stability. The riser sections were also required to be capped and terminated directly below the street pavement. Per the standard detail, access to the underdrain cleanouts would require removal of a small section of asphalt immediately adjacent to the manhole covers to expose the caps at the tops of the riser sections. After removal of the asphalt on the appropriate side of the manholes, it was found that the cleanouts were not located at the manholes, as required. The asphalt removal was then extended all the way around the manhole, yet no caps or risers were found.

The next step was the vertical excavation of the roadway around each manhole, which required street closures and safety measures at the areas being examined. Those excavations revealed varying non-commonality of construction of the cleanouts at each manhole. This included improper placement of the vertical risers, lack of structural attachment to the manhole barrels, damage of the risers, de-attachment of the pipes, and, in some cases, cleanouts that were never extended or installed.

This non-compliant construction made the entire system inaccessible and unmaintainable, and considerable effort was required to provide excavations at each manhole in order to expose and raise each cleanout to allow access to the subsurface lines. It should also be noted that per the municipal standard, cleanouts were required to be 6-in. lines; however, all cleanouts were discovered to be 4-in. lines. The transfer of the underdrain system to the common interest community without the ability to access, maintain, and thus inspect, clean, or repair the system was evaluated as part of the forensic work on this project.

The capital plan that would have provided reserve funding should have included the operational and capital expenses necessary to provide for access, inspections, maintenance, and repair of the system. This capital plan should also have provided for the replacement of the system at the end of its expected useful life (EUL), which with equivalency to the city sewer located above it would be 50 to 100 years. In comparison, a home's foundation would require an EUL of up to 200 years based on FHA criteria, and there would be little expectation that an owner would excavate a basement to replace the drain system.

Following the exposure of the cleanouts, camera inspections were attempted on the underdrains. Due to the presence of calcites, construction debris, sediment, and damaged lines, this proved to be difficult. The camera inspections found that the majority of the randomly selected underdrain segments contained blockages and were either partially or completely filled with water. At many locations, blockages were also found within the riser sections of the cleanouts, and underdrains were completely inaccessible. During the litigation process, segments of the underdrains were excavated and physically examined, including the repairs that were necessitated by the flooding of another residence, where the excavation of the lateral, the street lines, and significant length of the underdrain had to be undertaken to reduce the damages occurring to the properties upstream from the determined location of blockage.

The discovered conditions of the excavated line segments were correlated with the reported flooding and excessive sump pump operation locations, revealing that the lines were completely blocked with construction debris, gravel and/or calcite buildup — and that the systems were neither operational nor maintainable. Where complete blockages occurred, all underdrain flows backed up into the closest upstream basements, and the sump pumps installed at these homes had been operating continuously for several months. In some cases, the affected homeowners directed the sump pump flows to the curbs and gutters in the streets, which was in violation of the municipality's ordinances that prohibit the flow of the water across the walkways and into the roads.

Documentation

Since the CIOC was found to be responsible for ownership and maintenance of the underdrain system, a comprehensive map of the system was prepared for ongoing use. This map showed the known locations of cleanouts and blockages in the lines, and also identified non-flowing line segments discovered up to the time of the creation of this work. However, it was based on limited access to the underdrain, and it is likely that not all problems had been discovered. Based on this information, to the extent possible, a comprehensive repair plan was also developed for the existing underdrains. The intent of the repairs was to provide access to repair, restore or upgrade the entire underdrain based on the potential flow rates to create a functional system, and to allow for the necessary access, inspection, maintenance, and repair of the system over its EUL.

Repairs

Following successful litigation, repair plans were developed for the CIOC based on the following:

1. Determination of expected flows in the underdrain systems.

2. Review of applicable design codes, standards and criteria in the design and construction of the system.

3. Hydraulic analysis of the system to determine the

critical velocities, potential surcharge areas, and impacts of the flows on the private residences.

4. Coordination with the districts and municipalities for permitting, design, inspection and transfer of maintenance or acceptance of easement agreements.

Design Flows

The current state-of-the-art of underdrain design and construction was researched by the forensic engineer, and the findings were used in part to determine the expected design flows in the underdrains. Some examples of the industry knowledge are shown below:

Duane Friend and Doug Peterson, University of Illinois Extension, College of Agricultural, Consumer and Environmental Sciences, "Land & Water," August 2005, Number 8, "Sizing Up a Sump Pump," states:

"If you're building on sandy soil, plan for a system capacity of 14 gallons per minute for every 1,000 square feet of home. If you're building on clay soil, plan for a system capacity of 8 gallons per minute for every 1,000 square feet of home."

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ASCELIBRARY.org, Narender Kumar, PE, M.ASCE, FACEC, Kumar & Associates, Inc., Denver, Colorado, "Effective Use of Underdrain System in Construction on Expansive Subsoils," states:

"Measurements in the underdrain systems indicate continuous flow of groundwater throughout the year and that the amount of flow far exceeds the surface drainage and water use in the area. The author has measured continuous ground water flow between 0.23×10^{-2} m^3/h (0.01 gpm) and 0.45 m^3/h (2 gpm). This flow is sufficient to cause additional expansion of subgrade and distress."

The variables analyzed included the site surface and bedrock topography, soil permeabilities, groundwater expectations post-development, land use and climatic data. In addition to reviewing available design guidelines, the existing flows in the system were measured and correlated with the analysis to arrive at design flows that were consistent with the actual conditions observed on the properties.

Additional geotechnical investigations were also performed to evaluate the soil conditions, aid in determining the potential permeability of the backfill soils next to the buildings' foundations, and, in some cases, to evaluate the general geohydrology of the developed site. The evaluation was based on average soil conditions and resulted in the evaluation of non-saturated versus saturated conditions of the native and re-mixed or re-used soil. These evaluations determined that hydraulic conductivity of the onsite soils ranged from 10^{1} to 10^{-5} centimeters per second for backfill material or native clays, respectively.

It was determined that proper selection of hydraulic conductivity values is critical to proper design of underdrains, and it was possible that this parameter was incorrectly determined in the provided conditions of design. This underestimation of the permeability would have resulted in difficulty in determination of the flows to be used in the design of the system. As stated, there are a number of peer-reviewed publications that could serve the designer in sizing the system. One such publication is the American Society of Civil Engineers Manuals and Reports on Engineering Practice, No. 95, Urban Subsurface Drainage, which indicates that the following parameters should be considered: topography, geography, climate, water table, geology, water sources, soils information, environmental factors, physical constraints, and legal or political constraints.

American Society of Civil Engineers, "Standard Guidelines for the Design of Urban Subsurface Drainage ANSI/ASCE 12-92 ANSI Approved March 15,1993 Standard Guidelines for Installation of Urban Subsurface Drainage ASCE 13-93 Standard Guidelines for Operation and Maintenance of Urban Subsurface Drainage ASCE 14-93," 1994, states:

"5.0 Site Inspection

5.2 Surface Features

The surface features of the site should be located through a topographic survey and shown on the plans. The plans should be compared with existing field conditions to determine whether there are any differences between the topographic survey and present conditions. Discrepancies are to be brought to the attention of the engineer or project *manager.*

5.3 Subsurface Features

Subsurface features principally consist of utilities and geological conditions. All subsurface conditions are subject to field verification by the contractor prior to construction.

5.3.2 Geologic Conditions. All appropriate and available geological conditions should be shown on the plans. An assessment should be made with respect to rock and groundwater conditions.

7.2 Water Sources

7.2.1 Subsurface Water Sources.

In this document, subsurface water is considered to be all water beneath the ground or pavement surface and will be sometimes referred to as groundwater. Soil water is generally of three types: drainable water, plant-available water, and unavailable water. Plant-available water is often referred to as "capillary water," since it is retained by the soil in small soil pores where capillary forces prevent gravity influenced drainage and is available for plant root absorption.

Drainable water may be considered to be water that readily drains from soil under the influence of gravity. Drainable water moves through soils in direct proportion to the soil's permeability and hydraulic gradient, thus low permeabilities result in slow natural drainage of saturated soils.

Unavailable water is held tightly in thin films surrounding individual soil particles. The strong film bond makes this water nondrainable and unavailable to the vegetation. The amount of this hygroscopic water varies with the surface area of the soil particles and, therefore, is highest in clay and organic soils.

Most subsurface water results from surface infiltration, although water can enter the subsoil from adjacent areas. Another potential contributor to excess soil wetness is a perched water table that generally forms above an impermeable soil layer.

Water infiltration in soils is governed by soil type, season of the year, degree of soil moisture content at time of rainfall or irrigation, type and extent of vegetative cover, surface "crusting" tendency from rainfall impact, and characteristics of the particular rainfall event.

7.2.2 Surface Water Sources.

Water from a rainfall or irrigation event that does not infiltrate the soil appears as surface water. An exception to this generalization is a condition of interflow, wherein infiltrated water moves along an impermeable strata and exits the soil mass at a hillside or cut. Surface water becomes a consideration in subsurface drainage analysis when it becomes runoff or interflow to the drainage area under study and contributes to the anticipated water removal requirements of the subsurface drainage system. Surface water runoff is a major concern in urbanized areas, where development results in a high percentage of impervious surfaces such as roofs, driveways, and streets. In evaluating the subsurface water removal requirements of a specific area, adjacent areas that represent potential watersheds must be considered. Urban watersheds usually have greatly reduced water absorption and interception capacity, resulting in significant surface water discharge quantities. Surface water may be free to flow to adjacent areas (runoff) and contribute to soil saturation in another zone and/or streamflow. Some surface water is retained on the ground surface in depressions which, if soil permeability is extremely low, will evaporate or pond.

7.3 Establishing the Need

7.3.2 Removal Criteria for Different Environments and Climates.

Climatic conditions must be considered. Soils in humid regions often require more extensive drainage systems than soils in arid regions. Temperature and humidity conditions interact with soil characteristics to influence moisture control requirements."

Another publication that provides such guidance is the "Standard Guidelines for Operation and Maintenance of Urban Subsurface Drainage ASCE 14-93," 1994, which states the following:

"5.0 Water Quality

5.2 Environmental Indicators

A review of the area should be performed to determine any changes since the construction of the subsurface system. These changes will then have to be evaluated as to possible effects on the subsurface flow. Water sampling of aquifers and watershed sources representing existing and potential sources of subsurface water supply may be required. Certain parameters and their background levels can be expected to occur naturally in the water due to the existing environment. By visual inspection or through personal observation, a determination can be made for the necessity and extent of a field sampling program. If test results show unusual concentrations or unexpected constituents in the water, further investigations could be necessary. A treatment program may need to be implemented, or modifications may need to be proposed that would mitigate or eliminate adverse impacts caused by the problem constituents".

The forensic evaluation included the review and analysis of each of these parameters in the ultimate design of the system. Only the common interest portion of the underdrain, located within the street right-of-way, was evaluated. The traverse systems (laterals) that provided connections to the homes were neglected in the evaluation of construction, unless repairs to that residence were necessitated by the failure of the main underdrain.

The ownership and legal responsibility of the lateral was assumed for the purpose of this author's work to begin and end at the right-of-way. The portion on the private lot would not be maintained as common elements and, therefore, would be required to be maintained by the individual lot owners. Based on the failures occurring in the system, the portions of the underdrain systems constructed on the individual lots will likely also have similar damages that are not discoverable until excavation of the systems is performed, primarily in regard to scale buildup from the leaching of the materials in the native and backfill soils into the poorly sloped sections of the underdrain's system.

The determination or averaging of hydraulic conductivity values used in the design of an underdrain system encompassing more than 490 acres was critical to the sizing determination to be used. Averaging of soil types is one method that could be used. This method is based on the properties and extents of the near surface soils from the United States Department of Agriculture, Natural Resources Conservation Service mapping for non-saturated or saturated permeability conditions. For example, if the site was overlain with 50% Nunn loam and 50% Renohill-Buick loam with a saturated hydraulic conductivity (Ksat) of 6-micrometers per second (0.85 in. per hour) and 4-micrometers per second (0.6 in. per hour), it would produce an average of 5 micrometers per second on average.

According to the USDA Web Soil Survey, Arapahoe County, Colorado (CO005):

"Renohill-Buick loam
Properties and qualities
Slope: 3 to 9 percent
Depth to restrictive feature: 20 to 40 inches to paralithic bedrock
Natural drainage class: Well drained
Runoff class: Medium
Capacity of the most limiting layer to transmit water (Ksat): Moderately low to moderately high (0.06 to 0.20 in/hr)"

Weld County, Colorado, Southern Part:

"39 — Nunn loam
Properties and qualities
Slope: 0 to 1 percent
Depth to restrictive feature: More than 80 inches
Natural drainage class: Well drained
Runoff class: Medium
Capacity of the most limiting layer to transmit water (Ksat): Moderately low to moderately high (0.06 to 0.20 in/hr)"

However, if one soil type, such as the terrace escarpments, was more conductive by a factor of 40 times, (14-micrometers per second or 2.0 in. per hour), that condition could result in a surcharging effect not accounted for in averaging.

Arapahoe County, Colorado (CO005):

"Tc — Terrace escarpments
Properties and qualities
Slope: 10 to 60 percent
Depth to restrictive feature: 10 to 30 inches to paralithic bedrock
Natural drainage class: Well drained
Runoff class: High
Capacity of the most limiting layer to transmit water (Ksat): Moderately low to high (0.06 to 2.00 in/hr)"

The hydraulic conductivity (Ksat) of the on-site soils, therefore, significantly affects the quantity of water entering the underdrain system. **Figure 4** is excerpted from the 2007 edition of the publication "Hydraulics of Groundwater" by Jacob Bear. This figure shows the variance in hydraulic conductivity and permeability for various soil

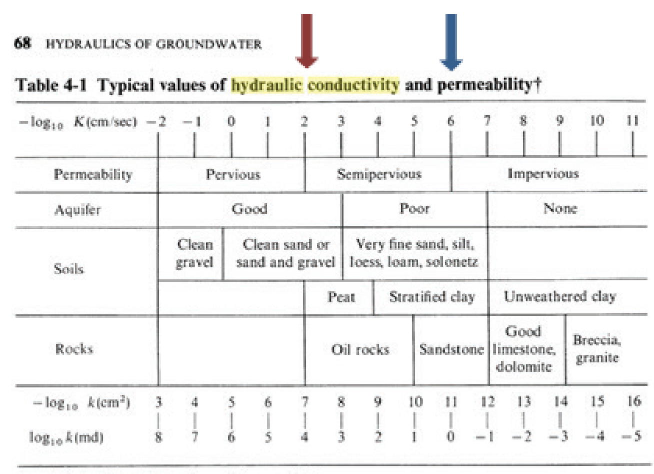
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Table 4-1 Typical values of hydraulic conductivity and permeability†

$-\log_{10} K$ (cm/sec)	−2	−1	0	1	2	3	4	5	6	7	8	9	10	11
Permeability	Pervious				Semipervious				Impervious					
Aquifer	Good					Poor				None				
Soils	Clean gravel	Clean sand or sand and gravel				Very fine sand, silt, loess, loam, solonetz								
					Peat		Stratified clay			Unweathered clay				
Rocks					Oil rocks			Sandstone		Good limestone, dolomite		Breccia, granite		

$-\log_{10} k$ (cm²)	3	4	5	6	7	8	9	10	11	12	13	14	15	16
$\log_{10} k$ (md)	8	7	6	5	4	3	2	1	0	−1	−2	−3	−4	−5

† From Bear, Zaslavsky, and Irmay, 1968.

Figure 4
Typical values of hydraulic conductivity and permeability.
"Hydraulics of Groundwater," 1979, by Jacob Bear, p. 68, 2007 Edition.

types. The hydraulic conductivity of typical backfill soils around a building's foundation can range from clean sand, Ksat = 102 (red arrow), to stratified clay, Ksat = 105 (blue arrow).

The soil permeability between the trench gravels and the fine silts varies by a factor of more than 1,000. Based on multiple sensitivity analyses performed by this author, the variation in hydraulic conductivity of the backfill soils can significantly impact the sizing of underdrain systems. The design of these systems must take into account the presence of water in the backfill and other site conditions, including ground or perched water and water conveyed in the gravel bedding used in utility and other trenches within the site.

In addition to the sensitivity analyses regarding the impact of placing low permeability backfill around the buildings, this author's work also determined that sequential grading (upslope lots discharge onto downslope lots) of multiple residential lots can also significantly affect the quantity of water introduced into the soils directly adjacent to the buildings' foundations where this water is directly intercepted by the perimeter drains and conveyed to the underdrain system.

By contrast, a generic site analysis would assume that construction of the residences and roads could result in impervious features covering up to 70% of the original site, concentrating the rooftop flows from precipitation into gutters and downspouts or delivering that flow directly into the backfill or rework zones. It is difficult to fully evaluate the effects of water migration into the foundation backfill soils for the conditions described above in determining the required sizes of the underdrains. The impact of multiple storms, time between storms, and rainfall intensities also contribute to variations in the rates of infiltration since the hydraulic conductivity of the backfill soils is directly dependent on whether the soils are saturated or unsaturated when water is collected in the backfill areas.

The material characteristics of the backfill soils as well as the presence and condition of utility trenches, basement excavations and the in situ native soils all play a role in the amount of water that ultimately reaches the underdrain system, both at the house locations as well via the trenches themselves. An attempt could be made to determine the infiltration characteristics of the site by averaging the hydraulic conductivities of the various soil types; however, even such an analysis could not, on its own, account for the multitude of poor construction practices that cause additional quantities of water to pond next to foundations and within sites and infiltrate into the soils after construction. Other engineering considerations such as the seasonal variations in precipitation, irrigation, evapotranspiration, and localized drainage conditions at the backfill boundaries create conditions where the use of engineering judgment must be relied upon in determining the contributory flows from each residence and the cumulative flows to the common underdrain.

Therefore, in this author's opinion, in light of the engineering difficulties in accurately ascertaining what the actual quantity of infiltrated water would be as a factor of a site's post-developed soil conditions, a reasonable factor of safety should be considered in the ultimate design of these systems. Similar to geotechnical studies, the range of assumptions made should be provided with a reasonable factor of safety. Put in this author's words: "The less you know, the safer your design should be. The more you know, the more economical and precise you can be."

Reverse hydraulic calculations based on the previous preliminary pipe sizing guidelines used in the design industry that allowed 50 to 150 homes per 4-in. diameter lines (depending on pipe slope) provide some method of determining the contributions of individual lots to the underdrains. Secondly, the impact of other sources of water must also be considered in this evaluation. This author's analysis involved solving Manning's equation for open channel flow for each of the conditions, and the forensic engineering calculations performed determined that at full pipe flow conditions, the design flows in the pipes ranged from 1.16-gallons per minute per house to 2.27-gallons per minute per house.

It should also be noted that the design should not allow pipes to operate at more than 80% full flow capacity under gravity flow conditions so that pressurized flow conditions do not develop. In addition to evaluating the hydraulic capacities of the underdrain lines, consideration should also be given to the designed pipe slopes, since the selected slope of the pipe is critical to the achievement of self-cleansing velocities at the given flow rates, typically 1.5 ft per second or greater.

A number of other resources from across the United States were reviewed, and flow rates varying from 0.5 gallons to 8 gallons per minute were found to be typical expected flow rates for residential properties.

Duane Friend and Doug Peterson, University of

Illinois Extension, College of Agricultural, Consumer and Environmental Sciences, "Land & Water," August 2005, Number 8, "Sizing Up a Sump Pump," states:

"If you're building on sandy soil, plan for a system capacity of 14 gallons per minute for every 1,000 square feet of home. If you're building on clay soil, plan for a system capacity of 8 gallons per minute for every 1,000 square feet of home."

The City of Ann Arbor - Developer Offset-Mitigation Program, Guidelines for Completion of Footing Drain Disconnections, Updated November 30, 2005, states:

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The loss of a pipe's smoothness over its lifespan should be considered as well as the impact of loss of slope due to the expansive nature of the local soils. All of these parameters underscore the need for higher factors of safety being used in the original designs. Some municipalities now require that underdrain lines be sized for no more than 50 percent of full flow, allowing some factor of safety and reduced potential for surcharging the laterals from the residence to the underdrain.

During the litigation, the original geotechnical site report was provided, and that report indicated that a 4-in. pipe should be used to serve 100 residential homes. Reverse calculating the pipe hydraulics at minimum slope and 80% full flow conditions for PVC pipe would equate to a flow rate of 0.85 gallons per minute per residential lot. To put that into context, a standard residential sump pump, typically rated at 25 gallons per minute flow rate operating with 10 ft of head pressure and operating for 10 minutes every four hours, would have a similar rate of flow.

Based on the review of the as-functioning systems and multiple hydraulic scenarios, updated soils data and field measurements, the design flows in the underdrains were ultimately determined to be based on each lot contributing 0.85 gallons per minute as a reasonable design rate of flow, which falls within standard design rates for the industry. The system could then be analyzed and properly sized for each of the four sections of underdrains.

Applicable Codes and Design Criteria

In this author's opinion, based on the research performed, in many jurisdictions, the design criteria and guiding documents related to underdrain design are unclear and not definitive. The Jurisdiction with Authority for this project has recently proposed updates to the relevant sections of their Standards and Specifications Manual for underdrain design and construction. Although not yet adopted, these updates were incorporated into the design of repairs to the existing underdrain systems.

Hydraulic Analysis

Since the original underdrain system was never hydraulically designed — and given the constraints of the as-constructed conditions — accurate hydraulic modeling of the system was necessary to determine the repairs required to make the system functional and to provide the required level of protection to the individual homes. Using the information contained in the Sanitary Sewer Construction Plans and the results of this author's field observations, a hydraulic model of each underdrain system was developed. The software application "Autodesk Storm and Sanitary Analysis, 2015" produced by Autodesk, Inc. of San Rafael, California, was utilized for the hydraulic modeling of the underdrains because of its easy integration with the previously prepared drawings and other data.

The hydraulic design was optimized through multiple iterations to develop repairs that minimized the percentage of the system that needed to be replaced to provide a hydraulically functional and maintainable underdrain system.

Conclusions and Professional Opinions

Significant research was performed to complete the extensive forensic investigations related to this project. Because of the particular geographic and climatic conditions, the research was predominantly restricted to Colorado and included the following findings:

1. The responsibility for ownership and maintenance of underdrain systems varies across municipalities and jurisdictions. In a few cases, the authority having jurisdiction (city, county, metro district, etc.) will own and maintain the underdrains. More often, these systems are private and are the property of the Common Interest Ownership Community in perpetuity. As such, the private owner is required to provide all maintenance and repairs as needed, thus requiring proper legal

conveyance, easement agreements, access, and funding.

2. There is no standard or consistent industry guidance and design information available to enable civil engineers to determine flows in underdrains to properly size these systems. Forensic engineering research (as per the references below) has found literature stating that underdrains should be designed for flows varying from 1 gallon per minute per lot to more than 20 gallons per minute per lot depending upon the building footprint sizes and local conditions.

Duane Friend and Doug Peterson, University of Illinois Extension, College of Agricultural, Consumer and Environmental Sciences, "Land & Water," August 2005, Number 8, "Sizing Up a Sump Pump," states:

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3. In many cases, geotechnical engineers state that a certain number of homes can be serviced by underdrains of a particular size. These guidelines vary widely, however, and in many cases are not incorporated by the design professionals. As noted above, geotechnical reports provide preliminary sizing tables that state that no more than 50 lots can be served by a 4-in. PVC line while others allow up to 200 lots can be on a 4-in. PVC line. However, in this author's opinion and based on the observed field condition and analyses performed under this project, these preliminary sizing guidelines appear not to be substantiated by sound engineering principles.

4. Specific underdrain design procedures need to be developed, and the design of underdrains should be required by municipalities or other approving jurisdictions. Designers should understand the relationship between the permeability of the backfill soil used next to the foundations of the buildings on a site. Failure of portions of underdrains can have significant negative impact to homes or other buildings served by those systems.

5. The CIOC must understand that it owns the underdrains and is required to maintain these systems in perpetuity, even though the underdrains may not be located in common tracts. In many cases, the existence of the underdrains is not communicated to the owners — only when problems develop are these discovered.

6. Similar to other utilities, the responsibility for ownership and maintenance of underdrain systems needs to be clearly established. The foundation perimeter drains and the laterals from the buildings to the underdrains in the streets are the responsibility of the homeowners, and the underdrains within the streets or common elements or tracts are the responsibility of the CIOC or other authority. However, a clear line of demarcation needs to be established for the laterals. This may be at the property lines, the backs of curbs or sidewalks, or other easily identifiable elements.

7. Underdrain systems need to be maintained on a regular basis and developers need to communicate this to the CIOC at the transition of ownership. This should also be contained in operation and maintenance manuals and programmed into reserve or capital studies.

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