Design Tools for Upgrading Underground Infrastructure in a Congested Urban Environment

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ABSTRACT

This paper describes how multiple design tools were used to enhance the design of a new relief sewer system and associated hydraulic structures in a congested urban environment. These tools included advanced hydraulic modeling using Computational Fluid Dynamics (CFD) and enhanced field reconnaissance via a detailed Subsurface Utility Engineering (SUE) program. The SUE program was part of a graduated approach to identify and locate underground utilities. Record drawings, CCTV inspections, traditional surveying and 360-degree manhole scans were used to develop a comprehensive database of existing underground infrastructure. Using this information, the basic alignment of the new relief sewer and locations of the near-surface hydraulic structures were established. Based on the data gathered from the SUE program, the designs of the near-surface hydraulic structures were modified to avoid the need to relocate existing utilities. It also identified potential utility conflicts that were not anticipated. Design modifications included changing the size or shape of a structure and/or altering its location. The sizes and configurations of the new, near-surface hydraulic structures were optimized using advanced hydraulic modeling, including the application of CFD analysis methods. The results of this modeling were used to refine structural configurations to improve constructability while preserving the required hydraulic functionality. Two specific near-surface hydraulic structures will be discussed.

KEYWORDS

Subsurface utility engineering (SUE), computational fluid dynamics (CFD), hydraulic modeling, hydraulic structure design, underground infrastructure, relief sewer

INTRODUCTION

The London Road Relief Sewers project consists of new relief sewers and associated hydraulic structures located in the cities of Cleveland and East Cleveland, Ohio. The project is a component of the Northeast Ohio Regional Sewer District’s (referred to as NEORSD or “District”) “Project Clean Lake” program that addresses the current agreement, or Consent Decree, the NEORSD has with the Department of Justice, US EPA, Ohio EPA, and the Ohio Attorney General’s Office. Project Clean Lake is a 25-year program that will reduce pollution in Lake Erie by 4 billion gallons per year by constructing a combination of large tunnels, treatment plant improvements and expansion, and green infrastructure, and reduce the volume of combined sewer overflows (CSOs) discharging to the great lake. The NEORSD service area includes all or portions of 62 northeast Ohio municipalities and more than 1 million residents. NEORSD is responsible for a large network of interceptor sewers and 3 major wastewater treatment plants.

The London Road Relief Sewers project (also referred to as LNDN), as shown in Figure 1, is designed to control CSOs and to provide additional conveyance capacity to help alleviate sewer surcharging in the cities of Cleveland and East Cleveland. The $39.7-million project will reduce the frequency of CSOs to less than 2 events in a typical year at specific permitted overflow locations and decrease the annual CSO volume from 190 million gallons to less than 5 million gallons by diverting flow to new relief sewers, which ultimately discharge to the existing Ivanhoe-Holmes Branch Interceptor.

Figure 1: LNDN Project Location

Figure 2 illustrates the following project components:

- 10,700 linear feet of new 24- to 72-inch-diameter relief sewers installed by tunneling methods
- 870 linear feet of new 12- to 72-inch-diameter sewers installed by open-cut methods
- 6 tunneling shafts/hydraulic drop structures
- 8 large diversion structures for CSO control and flow relief
- Miscellaneous junction structures and manholes
- Modifications to 6 existing regulator structures

The project improvements collectively provide CSO control and relieve flows from the existing infrastructure. The near-surface diversion structures perform two different functions depending on the location of the structure:

1. Achieve targeted CSO control in the typical year of rainfall, while providing relief for larger events through partial overflow to manage the upstream and downstream hydraulic grade lines.

2. Manage the hydraulic grade lines of the existing sewer infrastructure by relieving the existing sewers into new relief sewers to meet the targeted level of service. In some cases, the diversion structure redirects all flows to the new project system.

The near-surface hydraulic structure locations were determined based on hydraulic analysis, anticipated construction methods, geotechnical conditions, existing underground utility impacts, and community impacts. The design balances hydraulic performance with construction risks. The

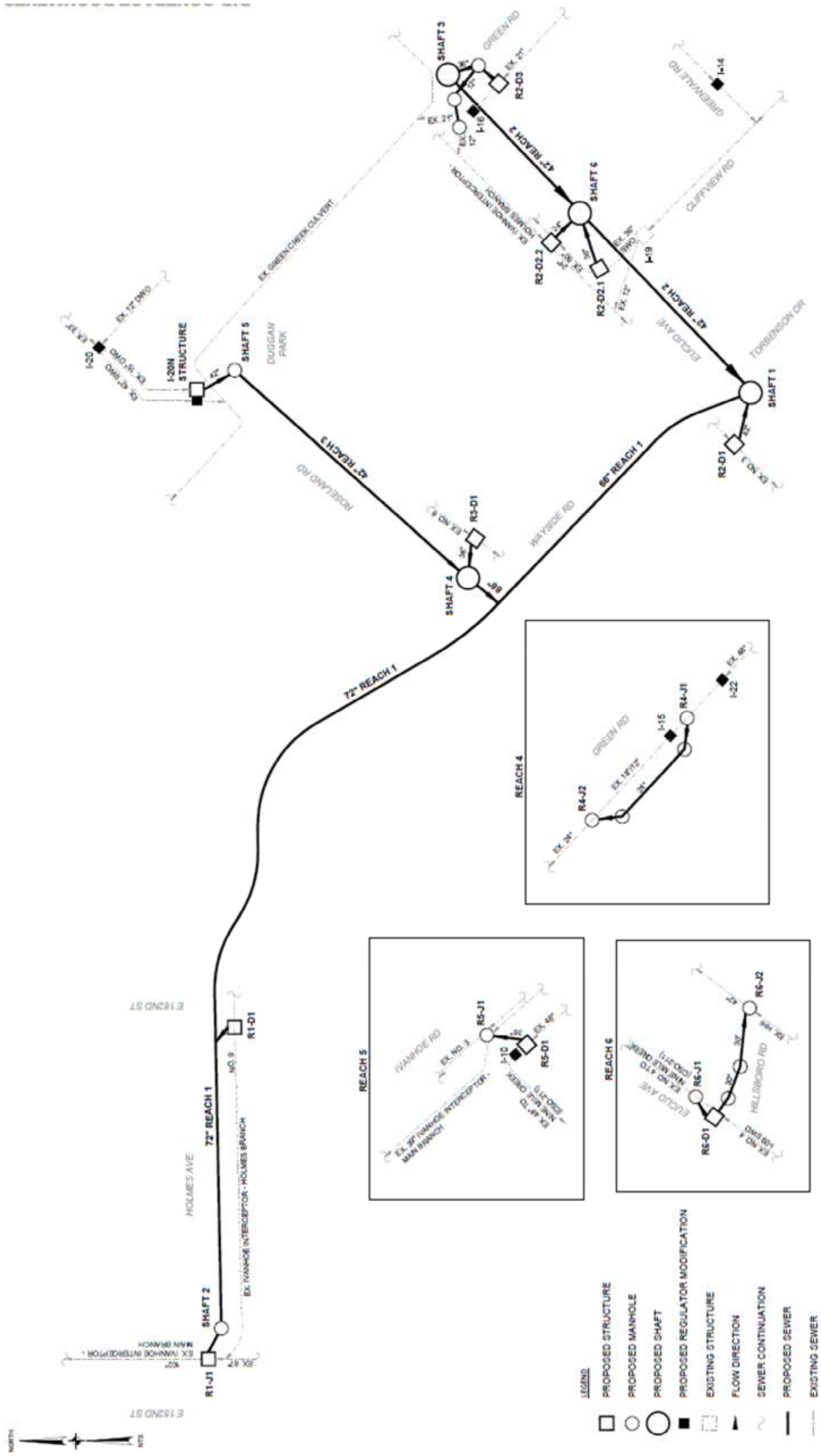


Figure 2: LNDN Project Overview Map with Key Components Labeled

older, urban project area is congested with active and abandoned underground infrastructure, which made for a challenging design at the locations where existing sewers required connection to the new relief sewers. A targeted Subsurface Utility Engineering (SUE) program was used to better define the horizontal and vertical locations of existing infrastructure. Armed with this knowledge, new project components were located and sized to minimize interferences and improve constructability. Extensive collaboration with existing utility owners proved critical for placing the proposed hydraulic structures and relief sewers within the congested rights-of-way.

Two hydraulic structures were particularly challenging to design based on the quantity and location of adjacent existing underground utilities. Diversion structure R1-D1 required an extensive evaluation of alternative locations because the initial proposed location was in a major road with an extreme amount of underground utilities. Once the final location was determined based on achieving a balance of the optimal hydraulic functionality and minimal constructability risks, CFD modeling was used to reduce of the footprint of the structure, resulting in reduced utility impacts and reduced construction cost. SUE test holes were performed to locate adjacent existing underground utilities. The SUE provided valuable information that was used to refine the structure size and configuration.

The second hydraulic structure, diversion structure R6-D1, needed to capture flows from an existing sewer in the vicinity of an extreme amount of underground utilities. Locating these utilities, including a large amount of electric duct banks, was critical to design of this structure. The electric utility owner’s willingness to collaborate and assist the design team with locating their utilities was a key factor to success.

METHODOLOGY

Hydraulic and utility exploration design tools were utilized for the design of the relief sewers project. Hydraulic tools included collection system modeling for relief sewer sizing and locations of near-surface facilities, and computational fluid dynamics (CFD) modeling for the refinement of the critical structures. Utility mapping included desktop studies, sewer televising, and a subsurface utility engineering (SUE) program for critical locations.

Collection System Modeling and Relief Sewer Sizing

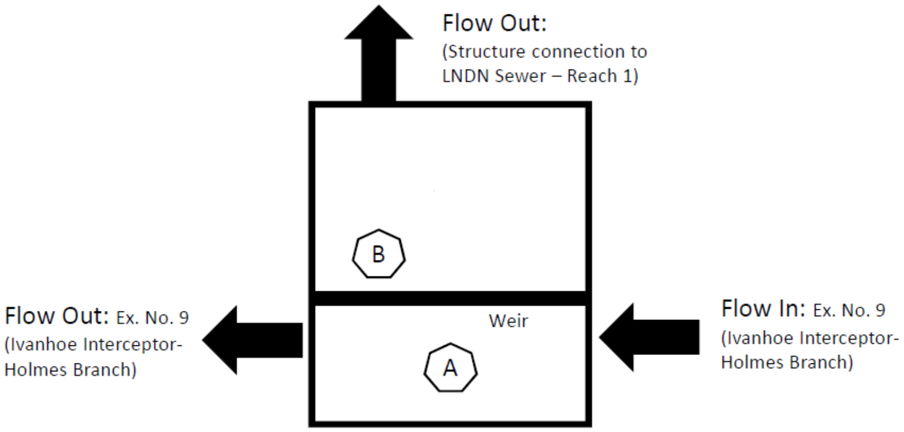
A four-month flow monitoring program was implemented to quantify dry and wet weather response in the LNDN project area. The flow monitors were generally sited to measure system performance at existing CSO regulators, flow dividers, and key locations for monitoring system response. Permanent rain gauges were used to ground-truth the project area’s radar rainfall data to provide a detailed spatial and temporal accounting of the rainfall during the flow monitoring period.

The existing Innovyze ICM collection system model (ICM version 7.5) was recalibrated to the flow monitoring data. Many metered areas showed lower wet weather peak rates and volumes than anticipated from the land use and impervious area. Field investigations were performed to evaluate potential reasons for the lower flows. Many catch basins throughout the area were found to have extensive debris accumulation that, limited wet weather inflow into the combined sewers. The model calibration and project design ultimately considered both the observed flow monitoring and estimated flows based on expectations from the land use and tributary area.

The collection system model was utilized to determine the relief sewers and near-surface facilities needed to achieve the CSO control and surcharge relief of the existing infrastructure. Alternatives were evaluated relative to the locations, quantity, and objectives of the near-surface facilities to minimize disruption and utility conflicts. The size and extent of the infrastructure were evaluated for a range of design storm events including the typical design events, events with larger return periods, and events with higher rainfall intensities, and for hydrologic assumptions that flow entering the system is larger than measured during the model calibration due to operational improvements such as clean catch basins. The sizes and slopes of relief sewers and locations of diversion structures were evaluated for the various conditions. From the evaluation, relief sewers were sized to provide the targeted CSO control and relief while, in some cases, allowing for additional capacity for future flows or potential additional CSO control. Sizes were determined based on both hydraulic aspects as well as constructability and access considerations.

Diversion Structure R1-D1 Overview and Objectives

Diversion structure R1-D1, as shown in Figure 3, is needed to reduce surcharging in an existing No. 9 (5.54 feet high by 4.38 feet wide) brick combined sewer of the Ivanhoe Interceptor – Holmes Branch towards the downstream end of the project area. The R1-D1 structure will convey dry weather flows (DWF) and controlled wet weather flows (WWF) through the existing sewer. Excess wet weather flows will be intercepted and diverted to Reach 1 of the LNDN Relief Sewer. One objective of the R1-D1 diversion structure is to maximize the conveyance capacity of the existing No. 9 combined sewer along Holmes Avenue prior to diverting flows to the LNDN relief sewer to utilize existing capacity.



A – DWF and controlled WWF to manage downstream HGL.
B – WWF relief to new sewer.

Figure 3: Schematic of Diversion Structure R1-D1

Diversion Structure R1-D1 Location

Three alternative locations were evaluated to determine the preferred location for the R1-D1 structure to balance hydraulic, construction, and community considerations. The first location, on St. Clair Avenue, achieved the optimal hydraulic impact, but had the most construction and community impacts because it was on a main city roadway with many large underground utilities, heavy traffic, and multiple businesses. The two other locations were on nearby residential streets, Holmes Avenue and Wayside Avenue. The Holmes Avenue alternative provided better hydraulic results than the Wayside Avenue location, and both locations had similar construction and community impacts. Therefore, the Holmes Avenue location was identified as the preferred location of the structure.

Diversion Structure R1-D1 Refinement Through Computational Fluid Dynamics (CFD) Modeling

The R1-D1 structure will incorporate a lateral weir and provide energy dissipation prior to the relief sewer due to the elevation difference between the existing sewer and the relief sewer. The elevation difference is approximately 12.5 feet between the sewer inverts and 16.3 feet between the weir crest elevation and the relief sewer invert elevation. The existing sewer is also at a relatively steep slope, resulting in velocities exceeding 10 feet per second during wet weather events.

Computational Fluid Dynamics (CFD) modeling was utilized during decision-making to better understand the hydraulic performance of the R1-D1 diversion structure and to refine the configuration. Flows over the weir, head losses and velocities along the existing sewer and relief sewer, and energy dissipation performance for various configurations were evaluated.

The CFD modeling was performed using Flow Science FLOW-3D simulation software (version 11.2.3.3). FLOW-3D is commercially available CFD modeling software particularly well suited to open channel flow simulations. The model solves for three-dimensional, transient, turbulent flow conditions using a numerical algorithm called Volume of Fluid (VOF). The model solves the Reynolds-Averaged Navier-Stokes equation in three-dimensional space and time using a structured non-uniform finite difference grid and Fractional Area/Volume Obstacle Representation (FAVOR) algorithm for geometric definition. The FAVOR method defines the solid surface as a plane through the computation cells. FLOW-3D can simulate Reynolds stresses (internal shear stresses due to turbulence) using one of several built-in turbulence closure models. Technical information including capabilities and applications for FLOW-3D can be found at www.flow3d.com.

Diversion Structure R6-D1 Overview and Objectives

Diversion structure R6-D1, as shown in Figure 4, is needed for CSO control for two existing regulators in the vicinity of Euclid Avenue at Hillsboro Road and for downstream surcharge relief. The diversion structure is located adjacent to an existing over/under sewer system consisting of a No. 4 brick sewer carrying CSOs over a 15-inch-diameter intercepting sewer. The new diversion structure will capture flows from the existing No. 4 sewer to meet the targeted CSO control.

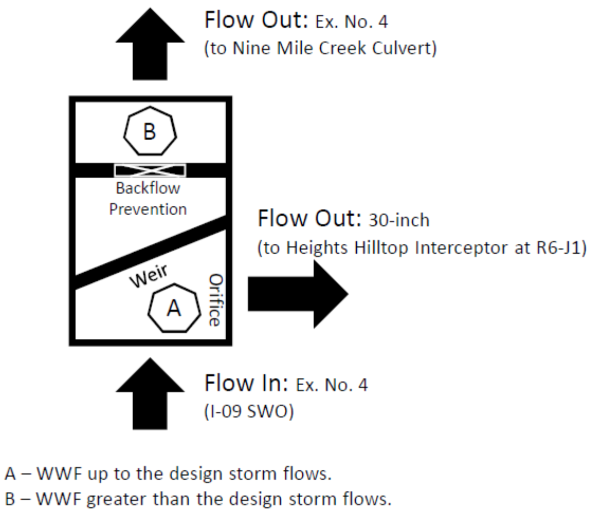


Figure 4: Schematic of Diversion Structure R6-D1

Reduction to Infrastructure Improvements for Diversion Structure R6-D1

Collection system modeling was used to refine the improvements needed due to the additional captured flow rates. The initial configuration, shown in Figure 5, sent the captured flows through a new sewer parallel to the existing sewer. This alignment was congested with utilities and involved a complex crossing of a large culverted stream.

As an alternative, a nearby existing interceptor system was found to have adequate capacity for the captured flows. The alignment to connect to the alternative interceptor allowed for an open-cut sewer through a street with much fewer utilities. Therefore, this became the preferred configuration for the design.

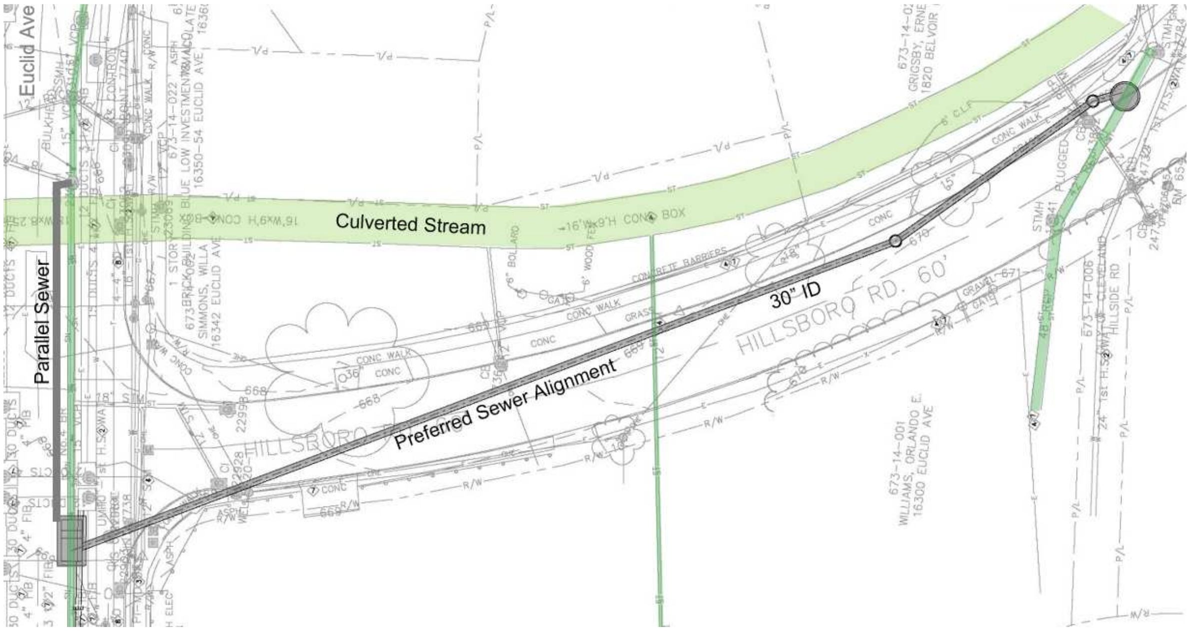


Figure 5: Improvements Needed for CSO Capture from R6-D1

Utility Mapping

Existing information was gathered and evaluated to develop the design. Information gathered included, but was not limited to, existing sewer and other utility record drawings and documents of existing infrastructure from public and private utility owners. This information was transposed to a survey in CAD where the relief sewer alignment was established. Existing sewers within the project area were televised using CCTV inspection to confirm their existence, location, and condition.

Subsurface Utility Engineering (SUE) Program Overview

A Subsurface Utility Engineering (SUE) investigation was performed to verify the horizontal and vertical locations of specific utilities at conflict locations predetermined by the design team and to confirm the accuracy of the utility locations compared to the record drawings.
The SUE was performed was in general accordance with ASCE Standard 38-02 *"Standard Guideline for the Collection and Depiction of Existing Subsurface Utility Data"*.

A records research (Quality Level D) was conducted during the 60% design phase, and utility records were received from multiple Ohio Utility Protection Service (OUPS) design requests. Additional utility information was received via utility research with the Cleveland Electric Illuminating Company (CEI) a First Energy company.

The Quality Level A and B SUE investigations were initiated in order of site importance. Specific utilities were designated (Quality Level B) at each of the proposed test hole locations. The SUE Quality Level A test hole investigations were performed between the 60% and 90% design submittals, which provided confidence in the structure locations while allowing for design revisions prior to the 90% design submittal. The Quality Level A explorations consisted of vacuum excavation to expose and record the horizontal and vertical position of the underground utility, as shown in Figure 6.

Prior to performing Quality Level A test hole excavations, the required City of East Cleveland ROW permits and the City of Cleveland Street Opening permits were obtained. Per Ohio State law, OUPS was contacted at least 48 hours before any test hole excavation was performed. Field staff coordinated the SUE efforts with the project designers, surveyors, MOT providers, law enforcement officers, and utility representatives. The SUE information was surveyed. A set of figures was developed for the design team for each of the LNDN sites, showing the results of the SUE investigation, and details regarding the work performed.

Figure 6: Example SUE Quality Level A Investigation

RESULTS

The configuration of diversion structure R1-D1 was refined through the implementation of CFD modeling for three main alternatives. The SUE for diversion structures R1-D1 and R6-D1 was utilized to establish additional confidence in the location of existing utilities and to refine the structures within the constraints.

Diversion Structure R1-D1 Hydraulic Refinement

The following three alternatives were evaluated with computational fluid dynamics modeling as potential configurations for the R1-D1 structure:

- Alternative 1: Preliminary Design Alternative. This configuration was 20 feet long and included a 3.8 foot H x 12 foot L lateral weir, an intermediate transition, and connection to the relief sewer.
- Alternative 2: Box Alternative with Diagonal Weir. This box configuration was 12 feet long and included a 3.8 foot H x 8.5 foot L diagonal weir. A bench was also included to step the flow prior to connection to the relief sewer.
- Alternative 3: Box Alternative with Stepped Channel. This box configuration was 12 feet long and included a 4.2 foot H x 9 foot L lateral weir. A stepped channel with dividing walls was incorporated to dissipate energy as flows drop down the chamber.

Each alternative was evaluated with a CFD model under the 5-year, 6-hour (1-hour rainfall hyetograph) design storm flows. Alternative 3 was also evaluated using the 5-year, 6-hour (15-minute rainfall hyetograph) design storm, which has a peak rainfall intensity that is nearly twice as large compared to the 1-hour hyetograph. CFD results are discussed in the following sections.

CFD Model Results for Diversion Structure R1-D1 Alternative 1

Figure 7 shows the CFD model results for the preliminary design configuration for the peak flow rate associated with the 5-year, 6-hour design storm. Flow depths and depth-averaged velocities for a cross section through the proposed structure and a three-dimensional perspective are shown.

The existing No. 9 sewer in Holmes Avenue has high velocities up to 11 feet per second, which results in non-uniform flows over the weir. Most of the flow overtops the weir at the downstream end of the structure.

The trajectory of the flow over the lateral weir caused pooling in the middle chamber with velocities less than 2 feet per second, indicating a potential for sedimentation.

Flows also entered the 6-foot diameter relief sewer with a high velocity at the downstream end of the structure and dropped near the crown of the sewer. This resulted in high velocities up to 12 feet per second in the sewer in addition to a 1-foot HGL difference between the relief sewer inlet and outlet pipes due to turbulent mixing.

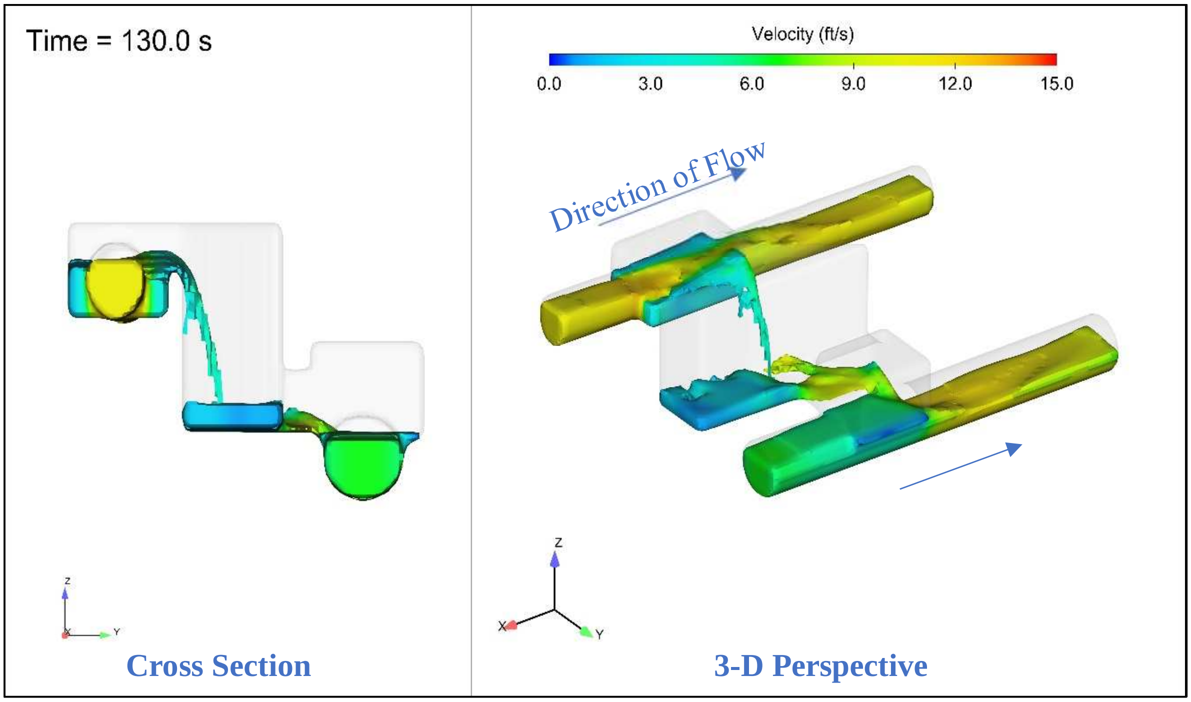


Figure 7: Alternative 1 CFD Model Results for 5-Year, 6-Hour (1-Hour Hyetograph) Design Event

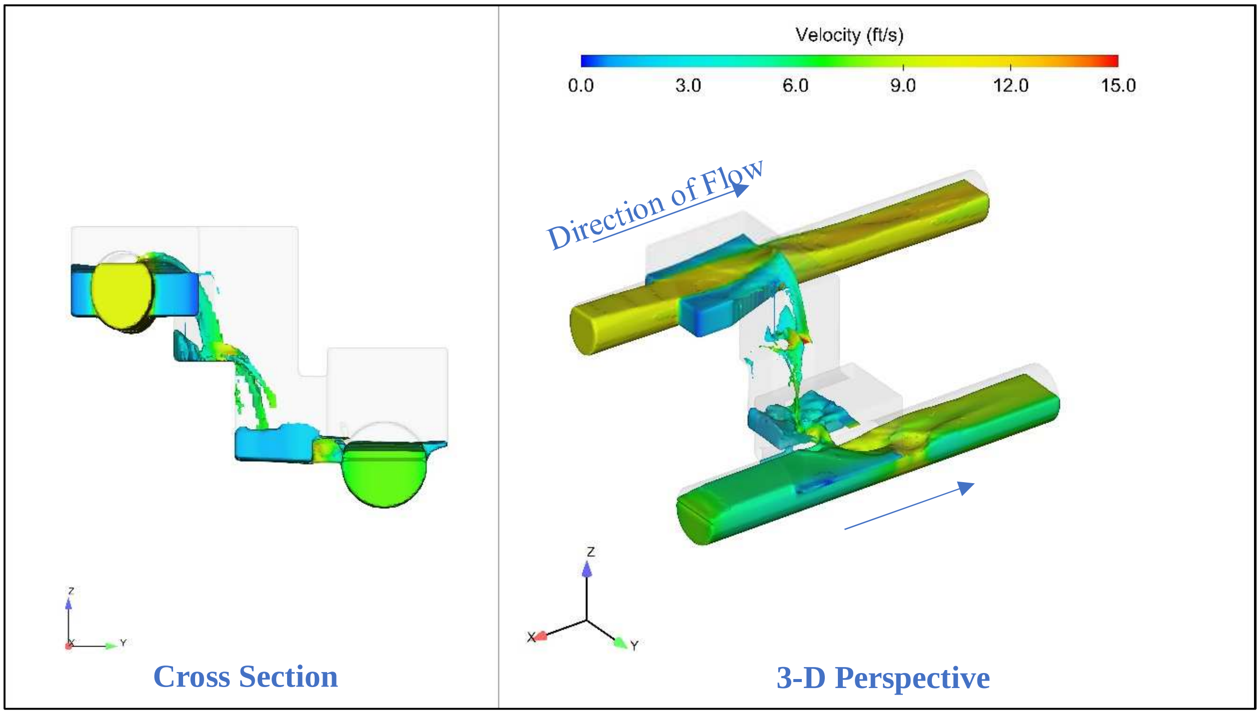
Due to the non-uniform flows over the weir, dead zones, and high velocities in the relief sewer, the CFD modeling indicated that improvements could be made and that the overall structure footprint could be decreased.

CFD Model Results for Diversion Structure R1-D1 Alternative 2

Alternative 2 was developed as a shorter structure with 12 feet of interior length to eliminate dead zones compared to the Alternative 1 configuration that was 20 feet long. A diagonal weir was incorporated into this alternative to allow for a wider upper chamber to examine the potential to decrease velocities of incoming flows prior to the weir. A bench was added on the downstream side of the weir to help dissipate energy prior to flows entering the relief sewer and to direct flows towards the middle of the bottom chamber. A v-notch weir was also added at the chamber outlet, and the chamber invert was lowered to meet the relief sewer springline to help decrease velocities entering the relief sewer.

As illustrated in Figure 8, the distribution of flows along the weir remained non-uniform with most of the flow at the downstream end of the weir. Significant splashing also occurred from the bench. The splashing and the v-notch weir together help to decrease velocities in the relief sewer. However, the flow patterns were highly variable and unstable, which resulted in varying flow trajectories. There were moments during the simulation where flows had more of a jet trajectory over the v-notch weir and into the relief sewer. There also did not seem to be noticeable benefits from the angled weir. The simulation showed flows were generally unstable and not being controlled well throughout the structure.

Although this alternative resulted in lower velocities in the relief sewer, this alternative was not preferred because of the unpredictable flow patterns and splashing within the structure.



Cross Section

3-D Perspective

Figure 8: Alternative 2 CFD Model Results for 5-Year, 6-Hour (1-Hour Hyetograph) Design Event

CFD Model Results for Diversion Structure R1-D1 Alternative 3

Alternative 3 maintained a structure interior length of 12 feet with a similar footprint to Alternative 2 but utilized a stepped channel and dividing walls to help dissipate energy from the flows going over the weir. The lateral weir was positioned parallel to the existing sewer, and walls were incorporated to better control flows through the structure. Two scenarios were evaluated for this alternative: with and without a v-notch weir at the relief sewer. With the v-notch weir, velocities up to 11 feet per second were observed in the relief sewer due to a smaller opening for flows. Removing the weir resulted in velocities up to 10 feet per second and a lower head loss. Therefore, the configuration without the v-notch weir was preferred.

Flow patterns and velocities for the preferred alternative are shown in Figure 9. The hydraulics through the structure are significantly improved compared to the other configurations. The dead zones of the preliminary configuration are eliminated, the unsteady splashing of Alternative 2 is eliminated, and the outlet hydraulics to the relief sewer are improved compared to the other alternatives. The final design of the structure is shown in Figure 11.

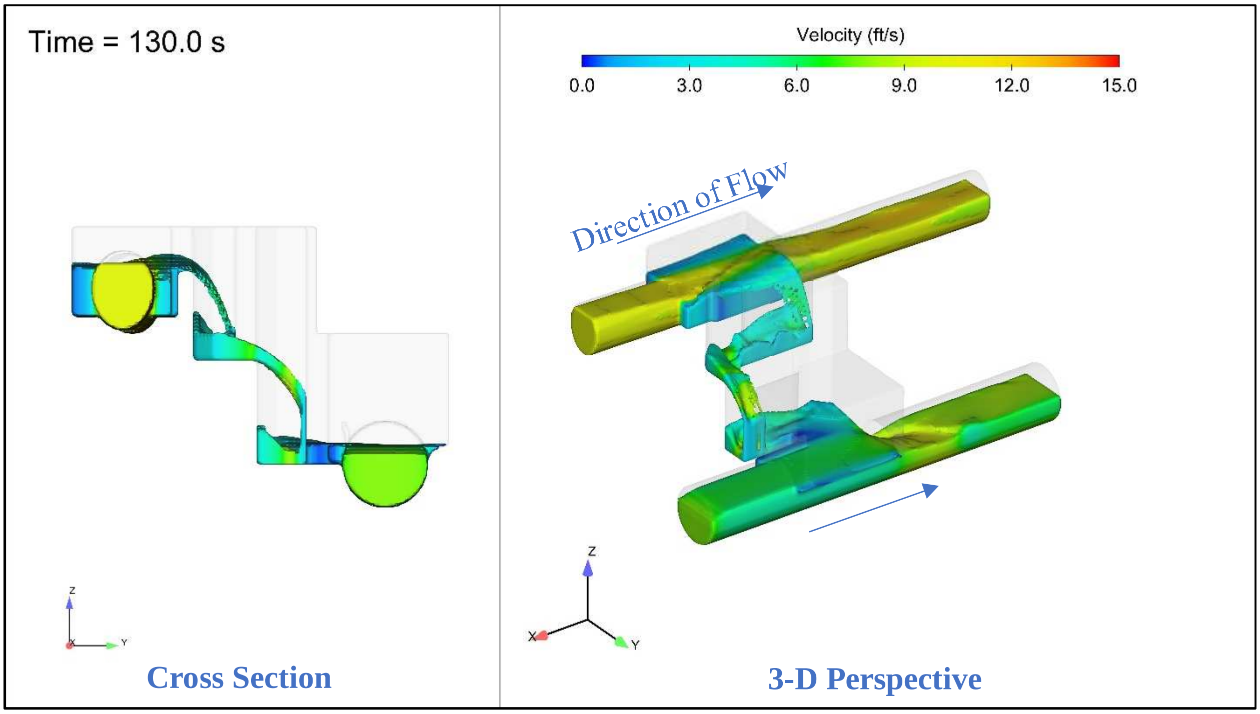


Figure 9: Alternative 3 CFD Model Results for 5-Year, 6-Hour (1-Hour Hyetograph) Design Event

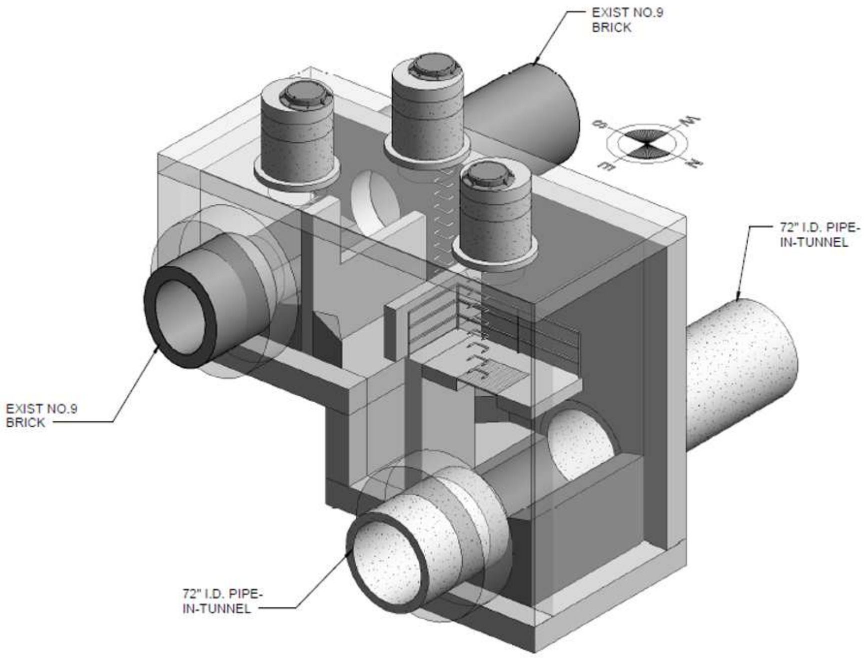


Figure 10: Final Design of Diversion Structure R1-D1

Refinement of Utility Identification Through SUE

In addition to configuring hydraulic structures for hydraulic performance, interference with existing underground utilities needed to be minimized.

The Quality Level A utility investigation confirmed the specific utility locations requested as well as depths and/or edges of utilities for the following:

- CEI Electric facilities
- Dominion East Ohio natural gas facilities
- AT&T telephone facilities
- City of Cleveland water facilities
- City of Cleveland sewer facilities

For purposes of this manuscript, the SUE Quality Level A utility investigation in the proximity of diversion structure R1-D1 and R6-D1 are discussed in detail.

SUE for Diversion Structure R1-D1 (Holmes Avenue at E. 162nd Street)

Five test holes, shown in Figure 11, were requested for this site: one on an AT&T telephone facility, one on Dominion gas facilities, one on a City of Cleveland 6-inch water main and two on a No. 9 brick sewer. Through Quality Level B investigation on the Dominion gas facilities, only one of the two gas mains in the project limits could be identified. Dominion gas records and direct coordination with Dominion gas representatives indicated abandoned and new gas mains. The actual location of the 6-inch water main was shallower than anticipated, which allowed for temporary relocation during construction and avoided conflict with the proposed ceiling of the R1-D1 structure. The SUE results for the one AT&T telephone facility showed that the existing duct bank was much closer to the proposed structure and was located above the structure instead of adjacent to the structure. The SUE results allowed the design team to provide a solution to deal with this utility.

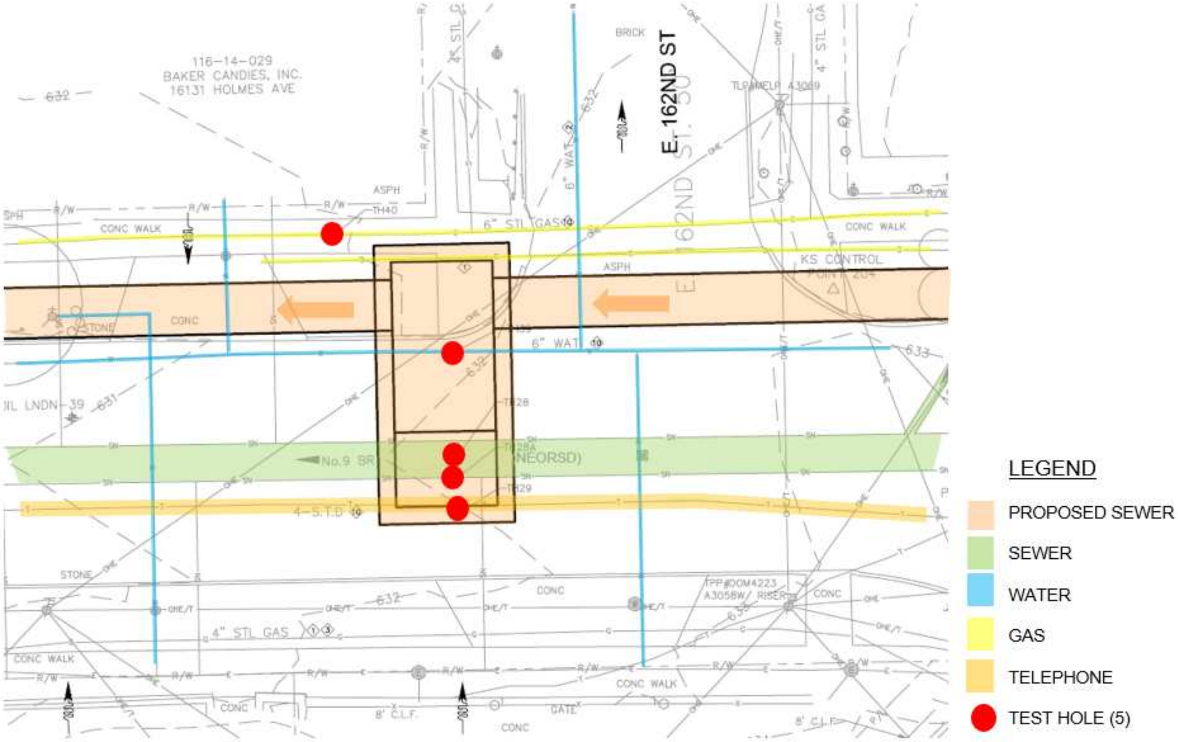


Figure 11: SUE Test Holes at R1-D1

SUE for Diversion Structure R6-D1 (Euclid Avenue at Hillsboro Road)

This site originally consisted of performing four test holes on CEI electric facilities and one test hole on a No. 4 brick sewer facility. Upon further site inspection, two of the original test hole locations on CEI facilities were eliminated because the facilities in question were “out of service” and deemed not critical. Due to the results of a test hole on a critical CEI electric facility, a total of 12 test hole locations, as shown in figure 12, were requested and performed. Due to the depth of a critical CEI electric utility facility and a known layer of existing shale, the vertical thickness of the electric facility could not be determined.

The design team had horizontal and vertical conflicts with the existing CEI utility duct banks and no viable alternative locations for the R6-D1 structure.

The design team contacted and coordinated extensively with representatives of CEI. These representatives provided record drawings of the existing CEI duct banks and manholes, observed the performance of the SUE test holes, opened the five existing adjacent electric manhole chambers and provided measurements down to the duct banks, met on several occasions in the offices of the design team, and provided input and design ideas around their facilities, and hand sketched their interpretation of the configurations of their facilities. The CEI staff was dedicated to assisting the design team with identifying their utilities and providing real solutions and valuable construction guidance to design around their facilities. This information was vital to providing a confident structural design within the horizontal and vertical constraints set by the CEI utilities.

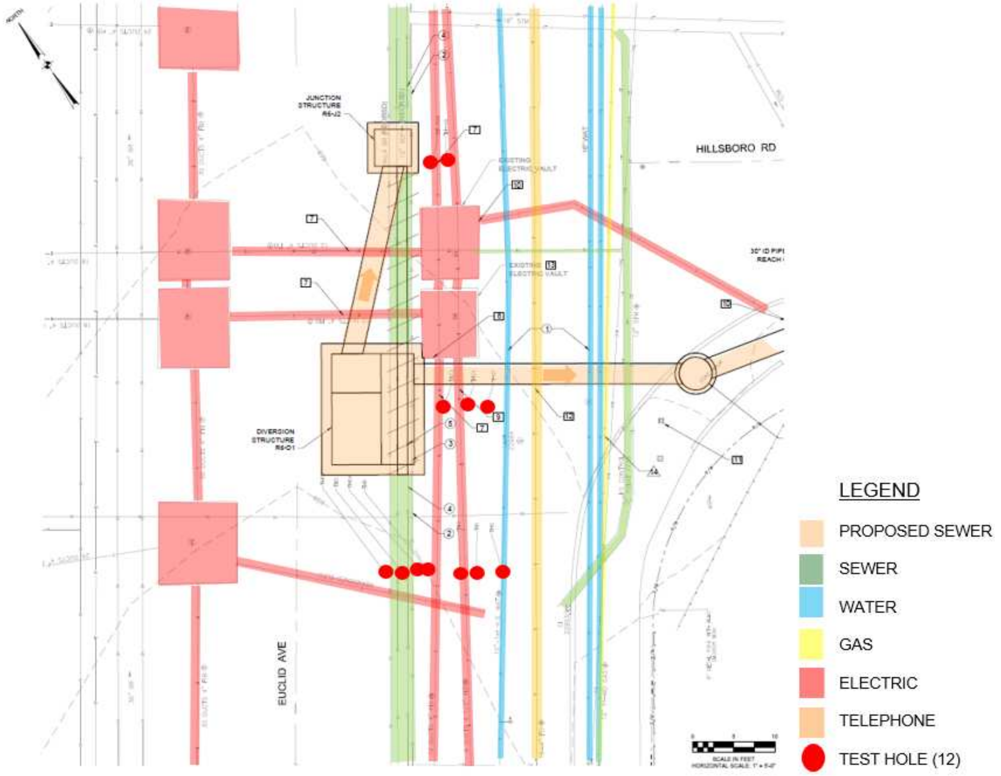


Figure 12: SUE Test Holes at R6-D1

DISCUSSION AND CONCLUSIONS

Design is an inherently iterative process. As the design converges on a preferred configuration, it is important to deploy additional tools at the appropriate time. For the London Road Relief Sewers project, the hydraulic modeling coupled with flow monitoring established the flow values and necessary layout of sewers and hydraulic structures. Sensitivity analysis and CFD allowed refinement of facility sizes and configurations. The CFD was used to improve hydraulics through the structure and to significantly decrease the footprint from the preliminary configuration. SUE was utilized to effectively fit structures within existing utility corridors. The SUE program for the LNDN project was completed between the 60% and 90% design submittals, thus requiring some redesign of structures. While the results were able to be incorporated into the final design, to maximize the value of this information, the SUE program should be implemented as early in the design process as possible, but late enough to select cost-effective quantities and locations of test holes. Implementation of a variety of design tools resulted in a more cost-effective final design.

REFERENCES

ASCE Standard 38-02 *“Standard Guideline for the Collection and Depiction of Existing Subsurface Utility Data”*.