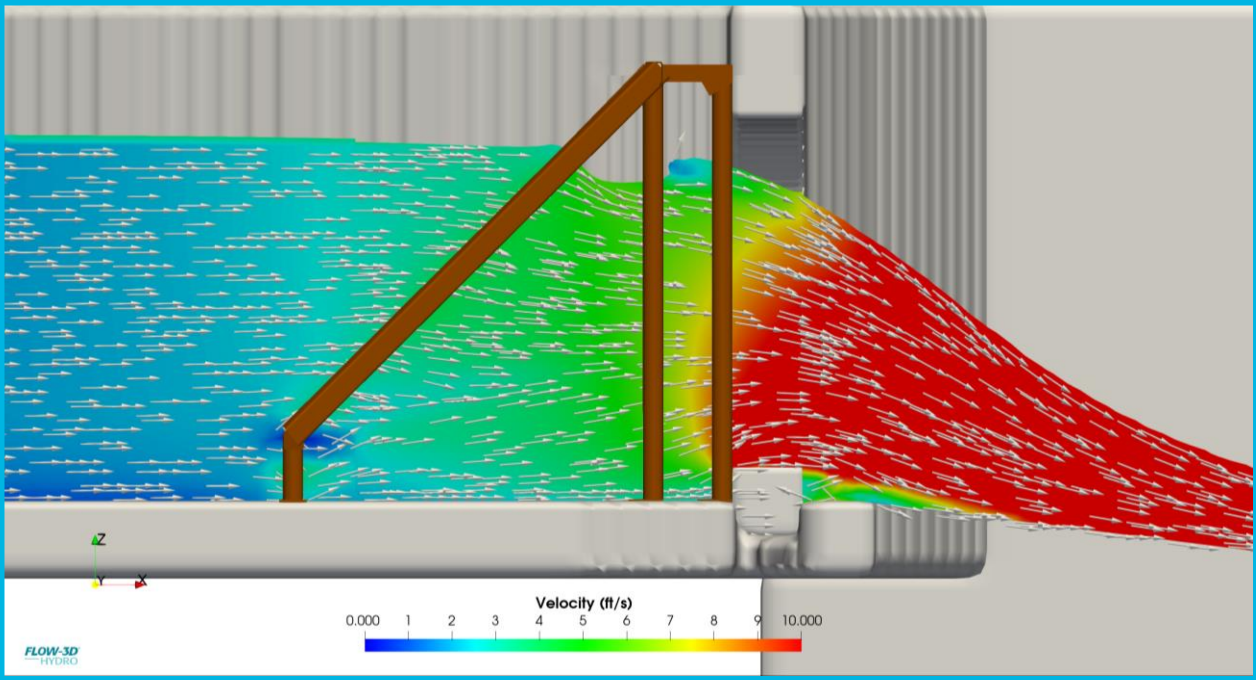
Final Draft



Storm Drain Safety Grates
Computational Fluid Dynamics Modeling Report

MHFD MILE HIGH FLOOD DISTRICT

AECOM Project Number 60658260

April 26, 2024

Quality information

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Revision History

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0	07/18/2023			Frank Lan, PhD, P.E.	Project Manager
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List of Abbreviations

2D	Two-dimensional
3D	Three-dimensional
CFD	Computational Fluid Dynamics
cfs	cubic feet per second
CSU	Colorado State University
El	Elevation
Ft	Foot/Feet
Ft(s)	Feet per second
H:V	Horizontal to Vertical
IDF	Inflow Design Flood
In	Inch(es)
lb(s)	Pound(s)
MHFD	Mile High Flood District
RNG	Renormalized Group
VOF	Volume of Fluid
WSEL	Water Surface Elevation

1. Introduction

At the request of Mile High Flood District (MHFD) and Colorado State University (CSU), computational fluid dynamics (CFD) was conducted to simulate the hydrodynamics upstream of storm drain inlets sized 30-in and 48-in to provide key hydraulic characteristics upstream of the inlet for determining the placement of MHFD safety grates in front of the inlets.

The scope of work was subsequently modified to expand the modeling to estimate dynamic forces acting on an object falling on the grate, in the form of a body dummy, that lays on top of the selected MHFD safety grate and two additional types of grates (a vertical grate and a flared end section grate) for various inlet opening dimension from 12-in to 60-in and flow conditions ranging from 25 cfs to 150 cfs. The dynamic forces obtained from these model runs were used to determine when a combination of flow rates and dynamic forces became a safety concern in field application during a flood.

This report provides a summary of the model development and modeling results.

The CFD modeling of the storm drain inlets was completed by utilizing the three-dimensional CFD computer program FLOW-3D (solver version 12.0 Update 2, Flow Science, Inc. 2020) developed by Flow Sciences, Inc. (2020). FLOW-3D is a commonly used CFD industry standard modeling platform and has been tested and utilized in many water environment applications such as hydraulics at an inlet. One of the significant advantages of FLOW-3D for hydraulic analysis is its ability to simulate scenarios involving free surface flow with great precision. In FLOW-3D, free surfaces are modeled using the Volume of Fluid (VOF) technique. The VOF method consists of three components: a scheme to locate the surface, an algorithm to track the surface as a sharp interface moving through a computational grid, and a means of applying boundary conditions at the surface. It handles transitions between sub-critical and super-critical flow within a single model set up.

2. CFD Model Development

2.1 Physical Conditions for Model Development

The configurations of the storm drain inlet along with the upstream approach channel and exit channel modeled in CFD were provided by CSU in CAD designs that were converted to 3-dimensional solids used in the development of the FLOW-3D models. While the modeled conditions may vary from field applications, the setup in the physical model that leads to a free flow condition out of the storm drain inlet is considered conservative and the CFD model is setup to mimic the physical model conditions. Two designs were initially modeled: one with a 48-in storm drain inlet and one with a 30-in storm drain inlet. Both storm drain inlets sit at 0.5-ft from bottom of the upstream rectangular approach channel. The upstream approach channel has a width of 20-ft with a zero longitudinal slope. Downstream of the storm drain inlets, the longitudinal slope of the exit channel is 12.6% to allow free outflow from the exit channel.

Subsequent modeling of the storm drain inlet involving adding a falling object (human body dummy) and analysis was completed on the 48-in storm drain inlet, 30-in storm drain inlet and added storm drain inlet sizes of 60-in, 18-in, and 12-in. Two body dummies were created for the simulation. One body dummy was based on a typical 6-ft adult and the second body dummy was based on a 50-in child. The entrance conditions at the storm drain inlets included a MHFD grate, a vertical grate, a flared entrance grate, and smaller storm drain inlets of 12-in and 18-in, no grates were modeled or the MHFD grate was modeled only. The shapes and dimensions of the MHFD grate, vertical, grate, and flared grate were provided by the CSU physical modeling team.

2.2 Model Domain

A three-dimensional view of the storm drain inlet system is illustrated on Figure 2-1. The model domain varies between models as the modeling conditions change (such as channel width, inlet size, flow rate, and grate type). Changes to the domain were made to optimize the computational time.

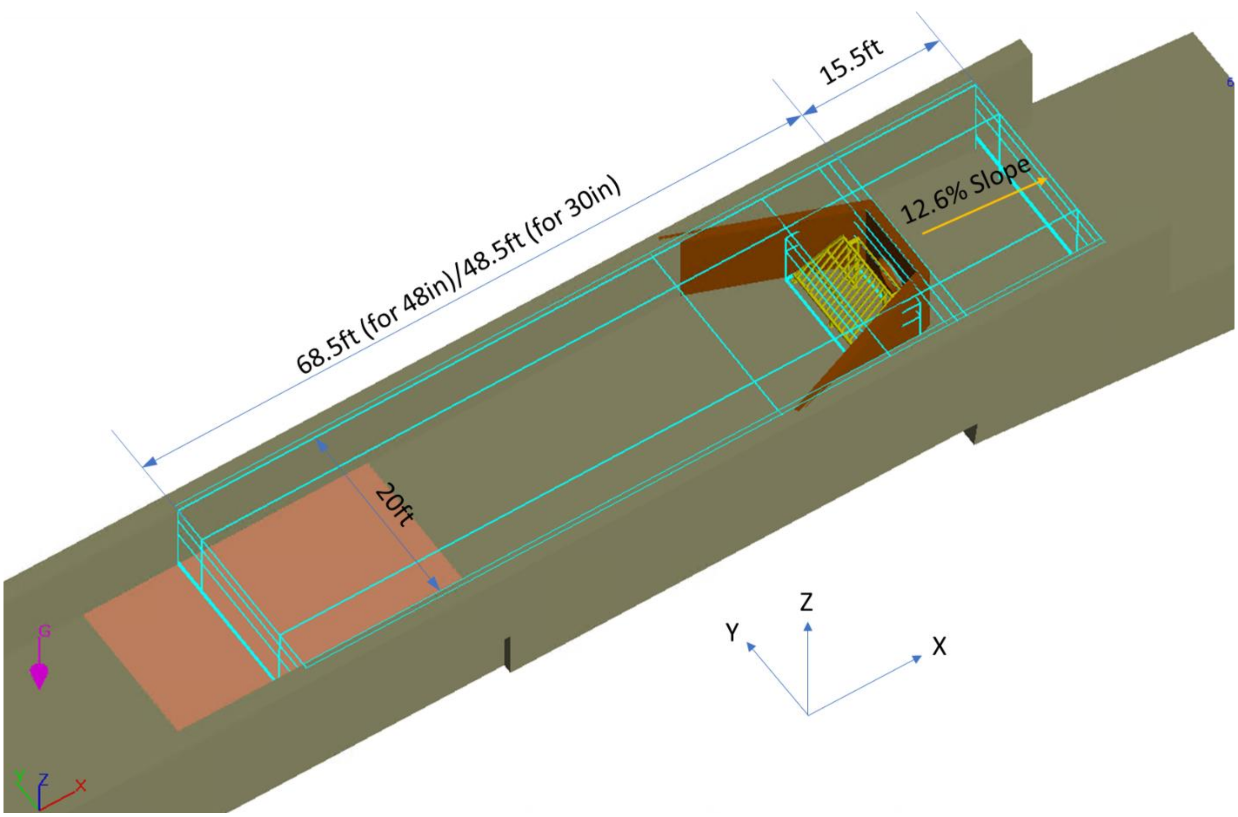

Figure 2-1. 3D View of Storm Drain Inlets and CFD General Modeling Domain

The FLOW-3D model domain, as shown on Figure 2-1 also, consists of a reach of the approach channel upstream of the storm drain inlet, the wing walls, the grates, and a short reach of the downstream exit channel. The upstream end of the model starts at a sufficiently long distance (at least 10-times of the storm drain inlet size) upstream of the storm drain inlet and grate if equipped so any boundary effects would be minimized.

The upstream boundary condition was set with a preset design flow and the starting water depth for each flow condition was estimated from a trial-and-error procedure. The downstream boundary condition was set with an “outflow” boundary condition. The right and left boundary conditions for the CFD model were set beyond the channel walls and were specified as “no-flow” boundary conditions.

The multi-block technique was used to define the mesh for the computation domain when the grates are included in the model. Models without a grate used a single block modeling technique with varying mesh sizes. The finest mesh was set at the storm drain inlet and around the grates so the geometry of the storm drain inlet, and the shape of the grates could be properly rendered. Away from the storm drain inlets and grates, the mesh size becomes larger, so the total number of mesh cells is managed for efficient computations. The smallest mesh size is about 0.0625 ft x 0.0625 ft x 0.0625 ft when the grates are included. The largest mesh has a resolution of 0.5 ft x 0.2 ft x 0.2 ft for mesh cells away from the storm drain inlets.

2.3 Assumptions and Pertinent Input Parameters

The CFD models also requires defined parameters to run. The input parameters regarding fluid properties, air entrainment and turbulence adopted and specified in the modeling files are presented in Table 2-1

The surface roughness for the concrete surface of the spillway chute was assumed to be 0.005 ft and the grates were assigned with a surface roughness of 0.003 ft, per guidance in Chow (1959). In general, FLOW-3D results are insensitive to the surface roughness coefficients.

Table 2-1. Summary of Adopted Model Input Parameters

	Value	Comments
Acceleration of Gravity (ft/s^2)	- 32.2	Standard value
Water Density (slugs/ft^3)	1.94	Standard value
Water Temperature (°C)	20	Adopted value
Viscosity of Water (lbf-sec/ft^2)	2.09 x 10^{-5}	Standard value
Viscosity of Air (lbf-sec/ft^2)	3.8 x 10^{-7}	Standard value
Turbulence Models	Renormalized Group (RNG)	
Air Entrainment	No air entrainment was model since air entrainment upstream of the inlet is not expected.	
Momentum Advection	Second order or Second order with monotonicity preserving	Typical choice for hydraulic applications with secondary flow.

2.4 CFD Model Scenarios

Table 2-2 supplies a summary of the initial model runs that do not include an object that has fallen against the grate in the form of a body dummy, for the two storm drain inlet conditions of 30-in and 48-in.

Table 2-2. Summary of Initial CFD Runs without a Body Dummy

Run No.	Inlet Size (inches)	Grate Presence	Flow Rate (cfs)	Run Name
1	48	No	150	StormDrain_48in_NoGrate_150cfs_Run03
2	48	No	125	StormDrain_48in_NoGrate_125cfs_Run03
3	48	No	100	StormDrain_48in_NoGrate_100cfs_Run03
4	48	No	75	StormDrain_48in_NoGrate_75cfs_Run03
5	48	No	50	StormDrain_48in_NoGrate_50cfs_Run03
6	30	No	50	StormDrain_30in_NoGrate_50cfs_Run01
7	30	No	45	StormDrain_30in_NoGrate_45cfs_Run01
8	30	No	40	StormDrain_30in_NoGrate_40cfs_Run01
9	30	No	35	StormDrain_30in_NoGrate_35cfs_Run01
10	30	No	25	StormDrain_30in_NoGrate_25cfs_Run01
11	48	MHFD Grate	150	StormDrain_48in_WithGrate_150cfs_Run02
12	48	MHFD Grate	100	StormDrain_48in_WithGrate_100cfs_Run02
13	48	MHFD Grate	50	StormDrain_48in_WithGrate_50cfs_Run02
14	30	MHFD Grate	50	StormDrain_30in_WithGrate_50cfs_Run02
15	30	MHFD Grate	40	StormDrain_30in_WithGrate_40cfs_Run02
16	30	MHFD Grate	25	StormDrain_30in_WithGrate_25cfs_Run02
17	48	Vertical Grate	75	StormDrain_48in_VerticalGrate_AsBuilt_75cfs_Hydro_Run2
18	48	Vertical Grate	90	StormDrain_48in_VerticalGrate_AsBuilt_90cfs_Hydro
19	48	Vertical Grate	115	StormDrain_48in_VerticalGrate_AsBuilt_115cfs_Hydro_Run2

Table 2-3 supplies a summary of the grate and storm drain inlet sizes for the expanded runs that include an object that has fallen against the grate (body dummy) for all the storm drain inlet sizes investigated. Details of the flow conditions modeled will be presented in Section 5.

Table 2-3. Summary of Initial CFD Runs with a Body Dummy

Inlet Size	Grate Type				Range of Flow
	MHFD*	Vertical**	Flared Entrance	No Grate	(cfs)
60-in	Yes	Yes	Yes	No	100 - 200
48-in	Yes	Yes	Yes	No	35 - 175
30-in	Yes	Yes	Yes	No	25 - 75
18-in	Yes	No	Yes	Yes	10 - 22
12-in	Yes	No	Yes	Yes	6 - 10

*) MHFD grates were initially modeled with 12-in offset from the culvert entrance but final runs with body dummy were without offset. Also, MHFD grates has a 12-in top bench for 48-in and 60-in culverts and no top bench for 30-in or smaller culverts.
**) Vertical grates were conducted with both 0-in and 12-in offset from the culvert entrance.

2.5 Model Run Procedure

All CFD model runs were setup as unsteady flow models with an initial starting water depth throughout the entire model domain and the boundary conditions discussed above for each of the runs. Each FLOW-3D model was then run until a near-steady-state condition was achieved with the outflow reaching a near-constant over the duration of the simulation time.

3. CFD Model Results without Grates, Falling Objects

3.1 48-in Storm Drain Inlet without a Grate at 50 cfs

This scenario simulates a steady-state flow of 50 cfs. Figure 3-1 and Figure 3-2 are 3D view and plan view of the simulated surface flow velocity and vectors, respectively. Figure 3-3 is a profile view of the velocity and flow vectors along the centerline of the storm drain inlet. At this flow, the modeling shows that the storm drain inlet is partially full. The simulated flow depth upstream of the wingwall is 3.22 ft with an average velocity of 0.78 ft/s.

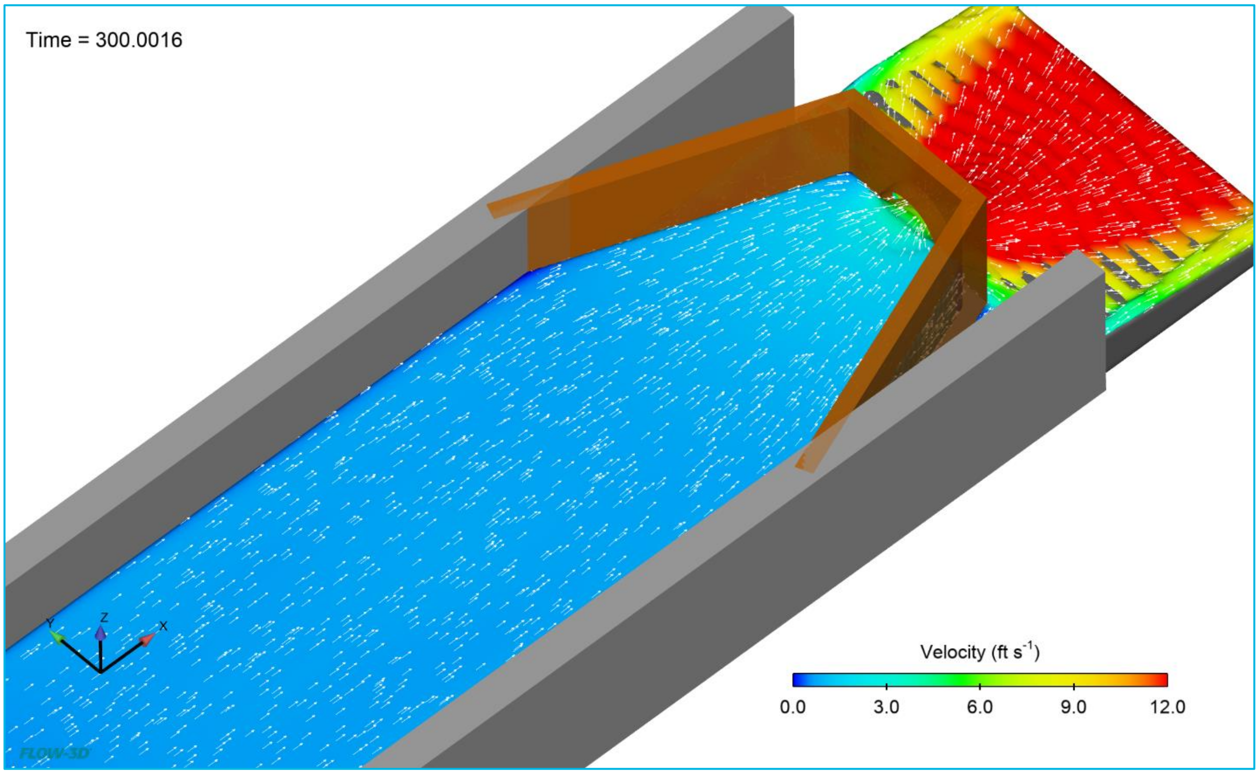

Figure 3-1. 3D View of Simulated Flow Velocity and Vectors for 48-in Inlet without Grate at 50 cfs

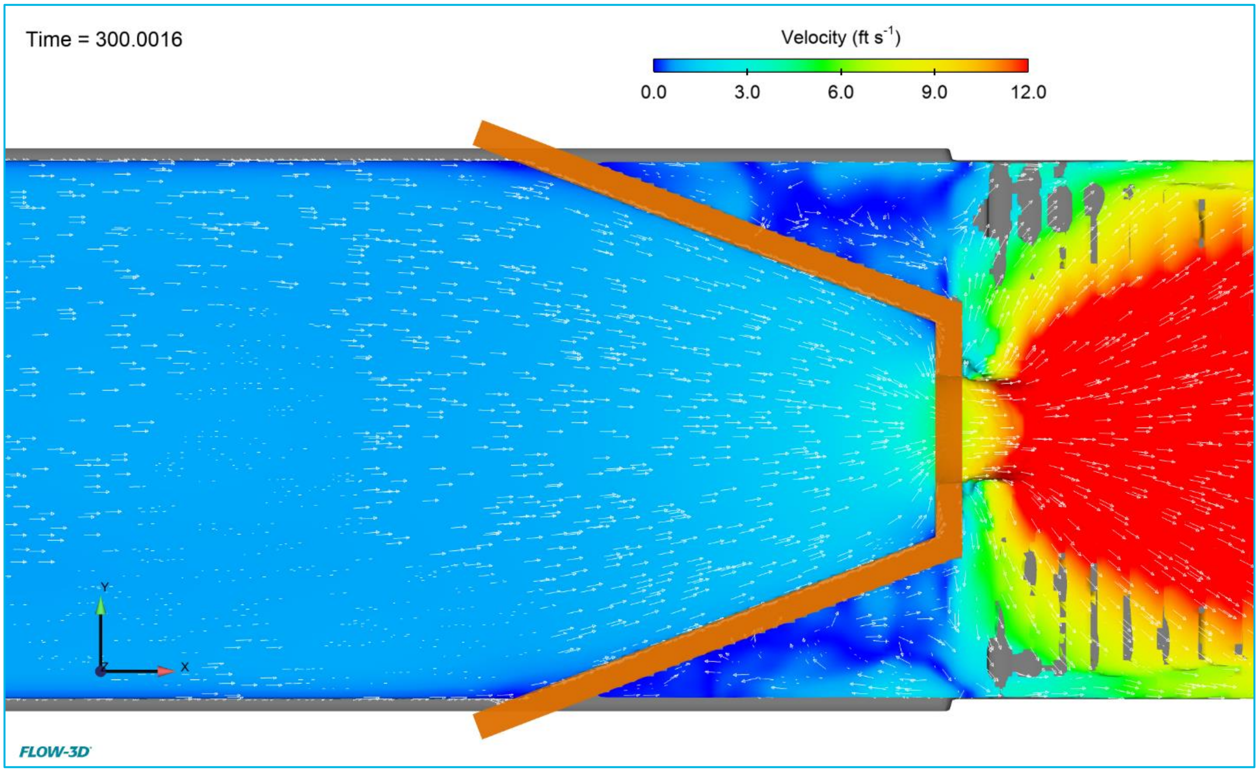

Figure 3-2. Plan View of Simulated Flow Velocity and Vectors for 48-in Inlet without Grate at 50 cfs

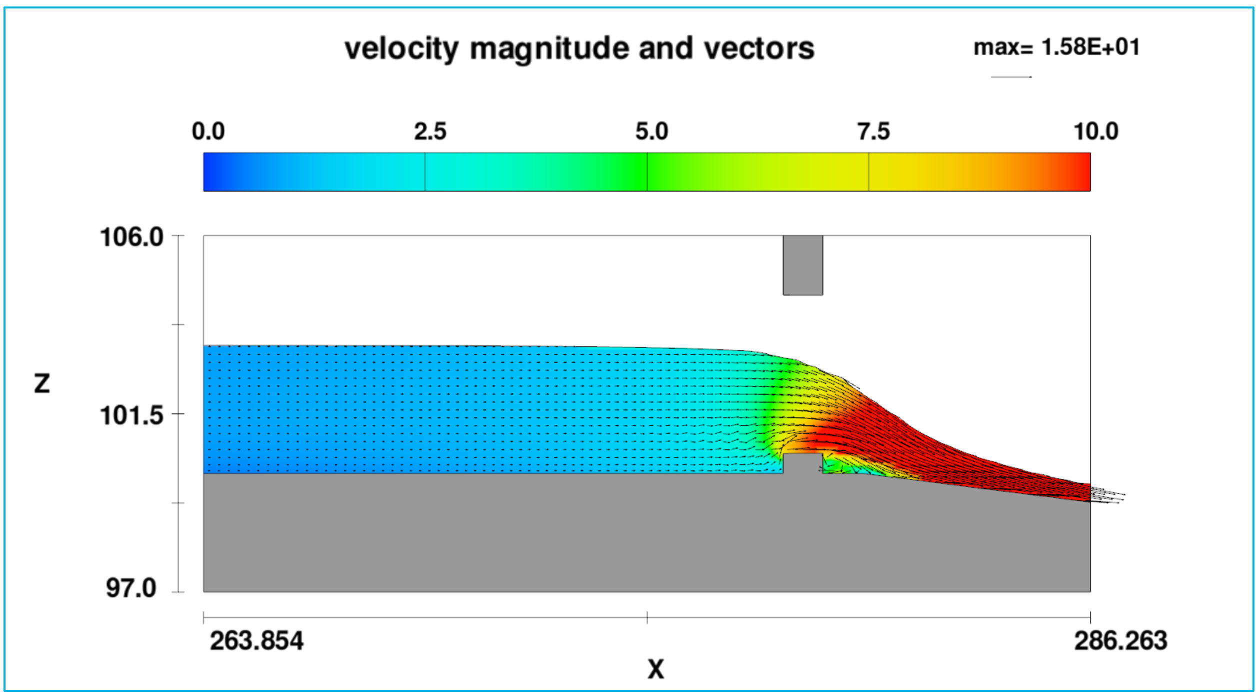

Figure 3-3. Profile View of Simulated Flow Velocity and Vectors along Inlet Centerline for 48-in Inlet without Grate at 50 cfs

3.2 48-in Storm Drain Inlet without a Grate at 75 cfs

This scenario simulates a steady-state flow of 75 cfs. Figure 3-4 and Figure 3-5 are 3D view and plan view of the simulated surface flow velocity and vectors, respectively. Figure 3-6 is a profile view of the velocity and flow vectors along the centerline of the storm drain inlet. At this flow, the modeling shows that the storm drain inlet is partially full. The simulated flow depth upstream of the wingwall is 3.89 ft with an average velocity of 0.96 ft/s.

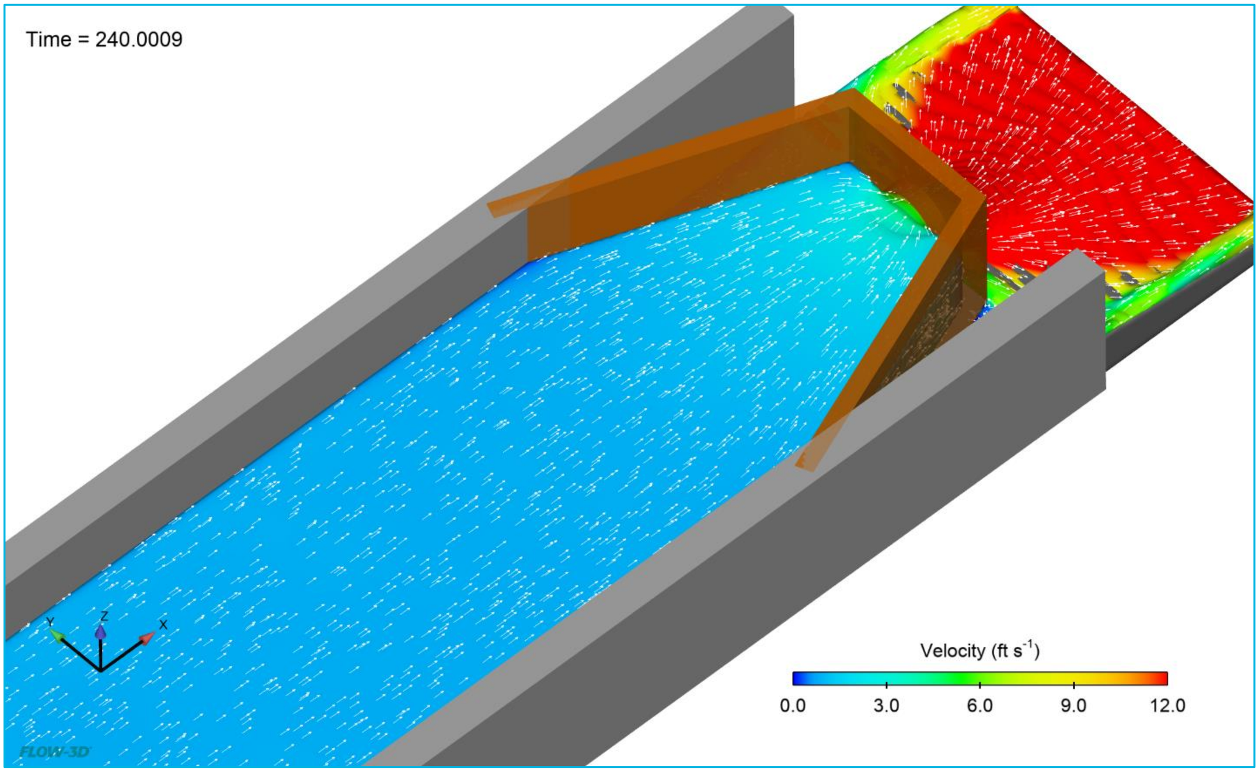

Figure 3-4. 3D View of Simulated Flow Velocity and Vectors for 48-in Inlet without Grate at 75 cfs

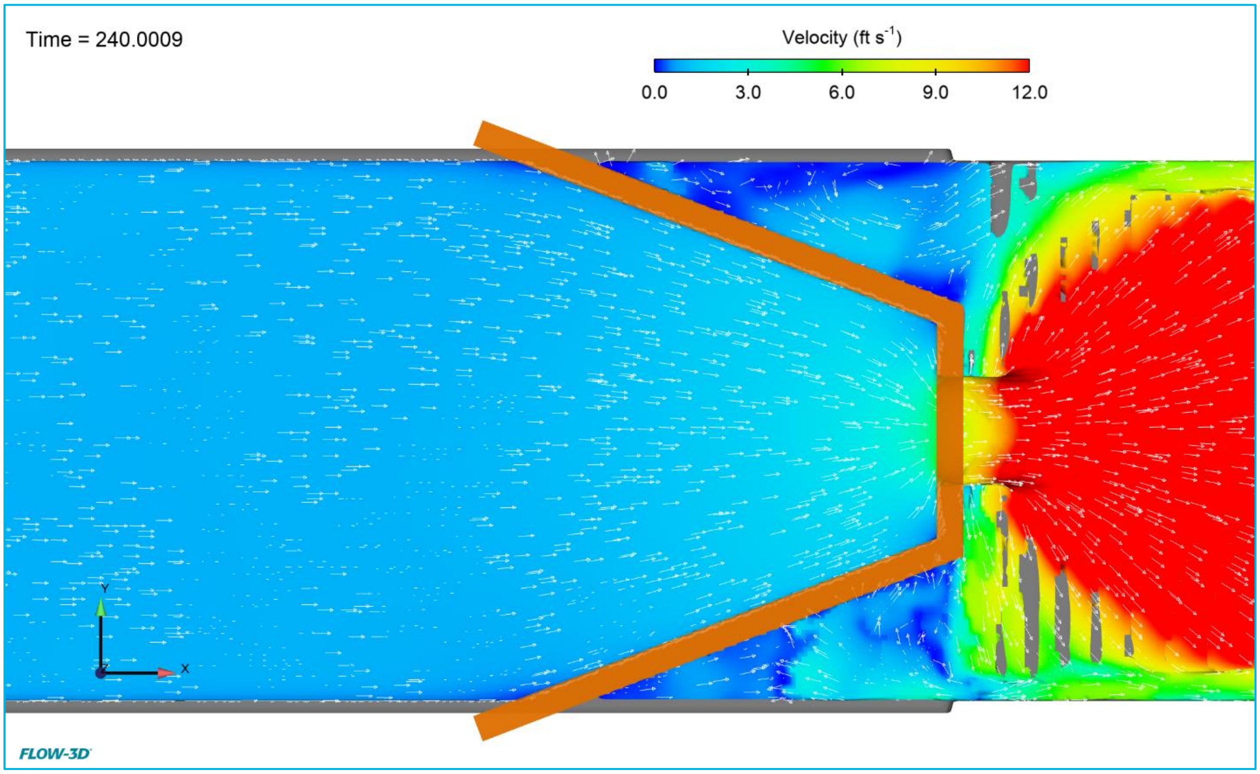

Figure 3-5. Plan View of Simulated Flow Velocity and Vectors for 48-in Inlet without Grate at 75 cfs

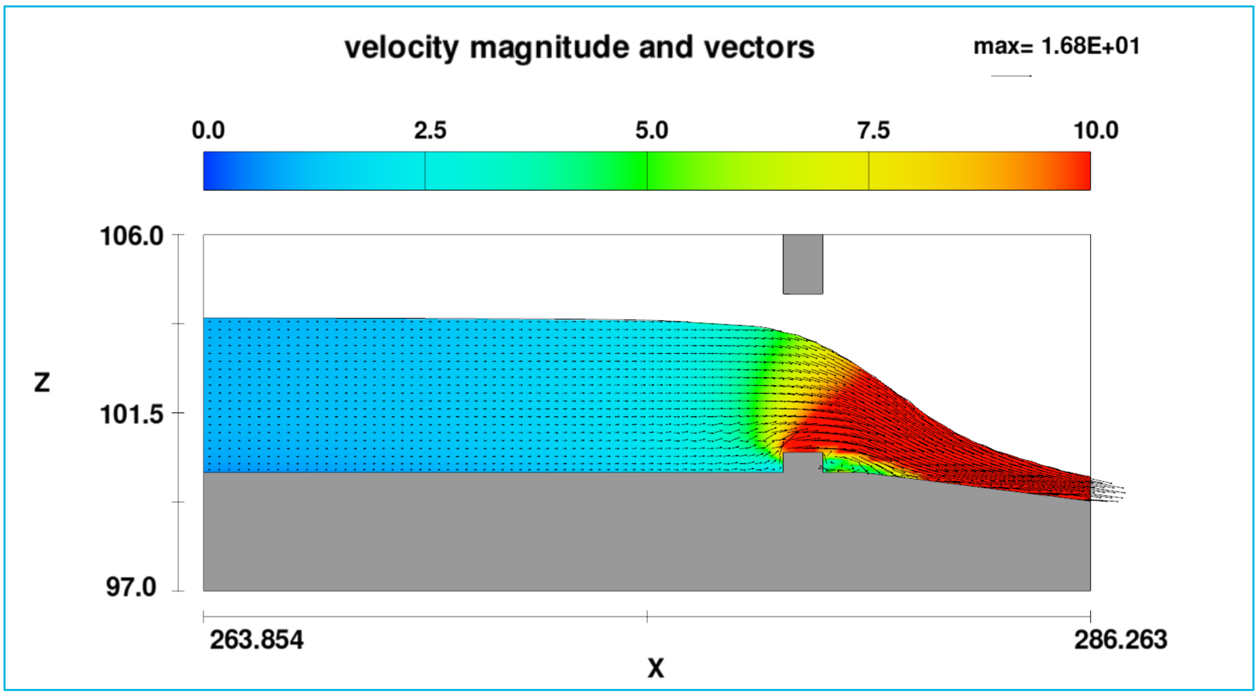

Figure 3-6. Profile View of Simulated Flow Velocity and Vectors along Inlet Centerline for 48-in Inlet without Grate at 75 cfs

3.3 48-in Storm Drain Inlet without a Grate at 100 cfs

This scenario simulates a steady-state flow of 100 cfs. Figure 3-7and Figure 3-8 are 3D view and plan view of the simulated surface flow velocity and flow vectors, respectively. Figure 3-9is a profile view of the velocity and vectors along the centerline of the storm drain inlet. At this flow, the modeling shows that the storm drain inlet is partially full. The simulated flow depth upstream of the wingwall is 4.55 ft with an average velocity of 1.10 ft/s.

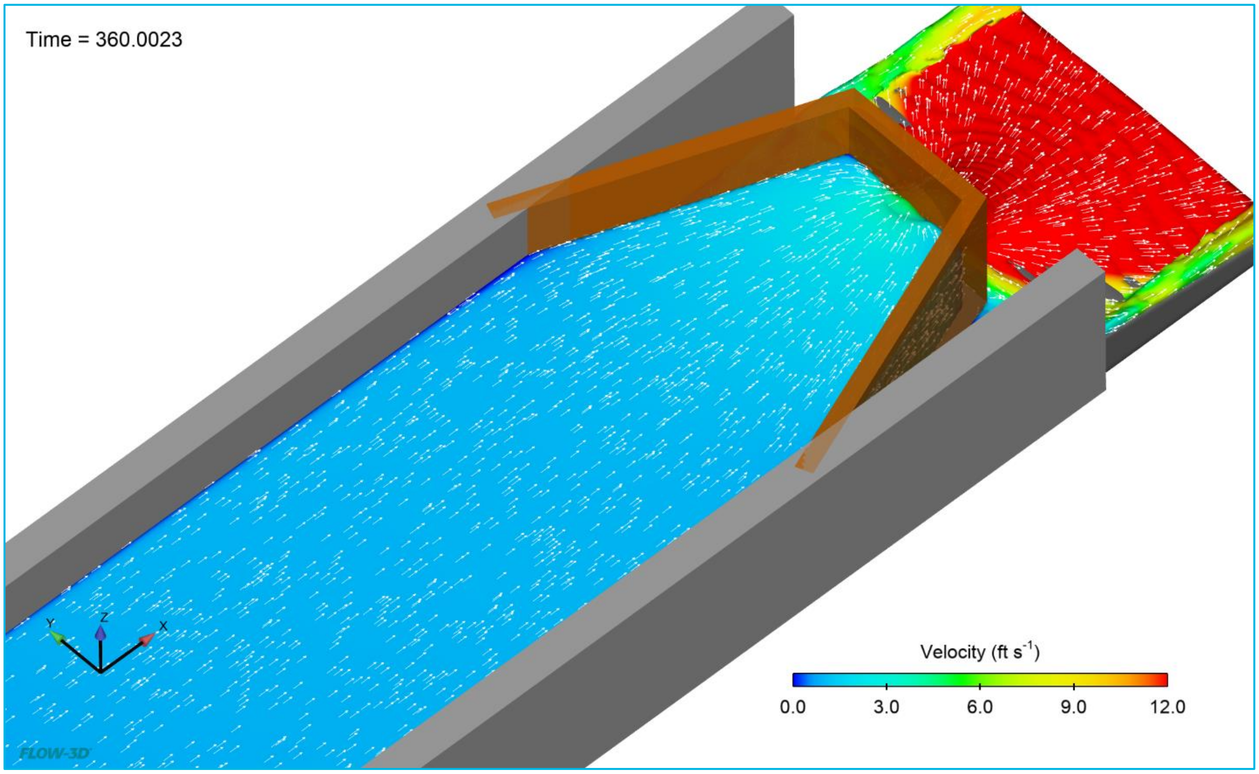

Figure 3-7. 3D View of Simulated Flow Velocity and Vectors for 48-in Inlet without Grate at 100 cfs

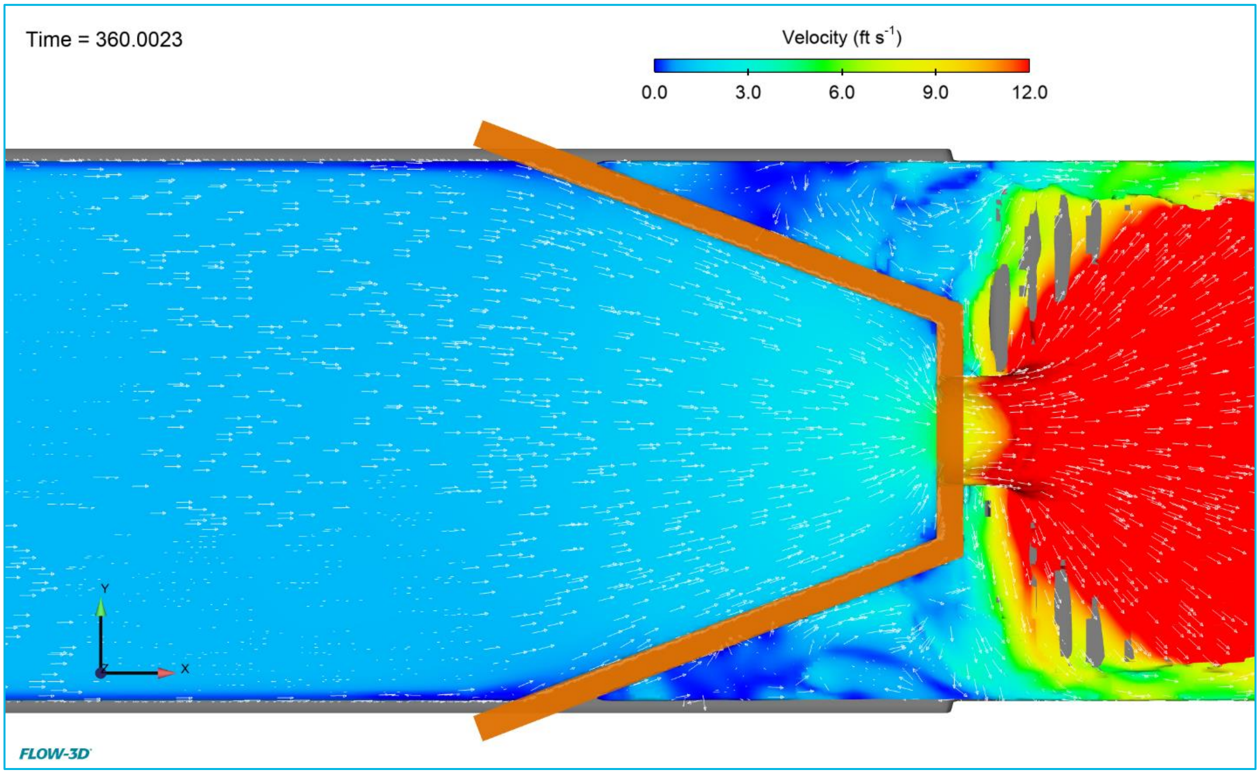

Figure 3-8. Plan View of Simulated Flow Velocity and Vectors for 48-in Inlet without Grate at 100 cfs

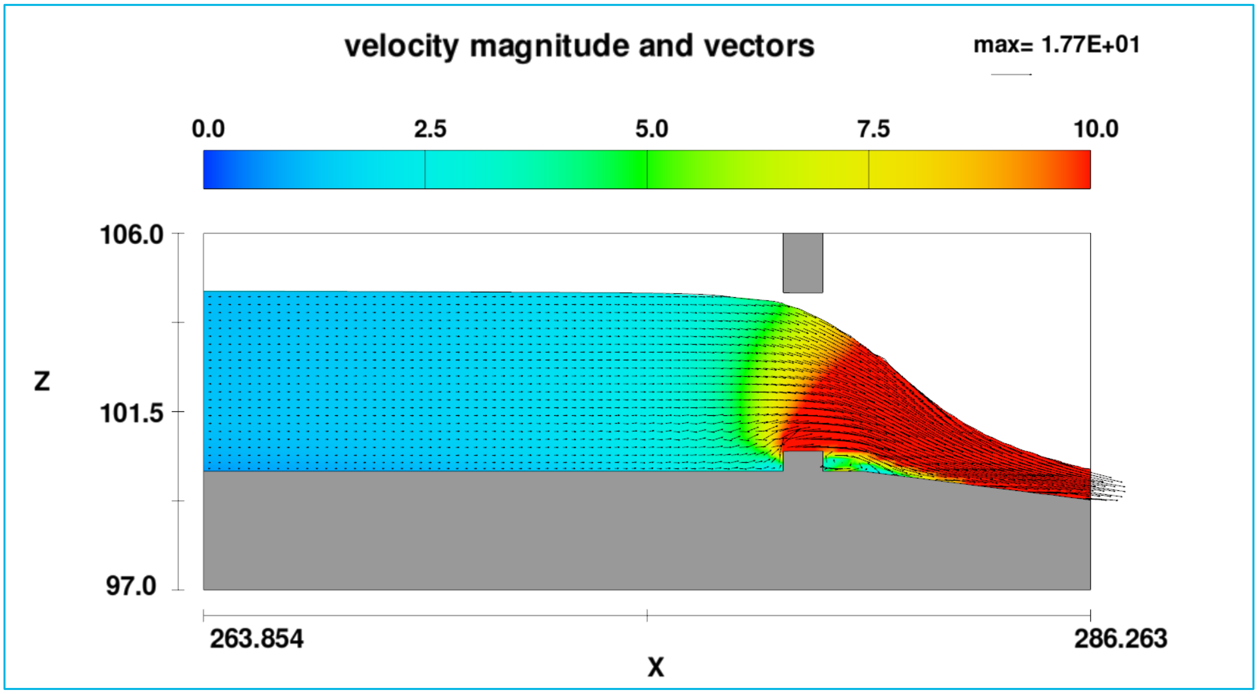

Figure 3-9. Profile View of Simulated Flow Velocity and Vectors along Inlet Centerline for 48-in Inlet without Grate at 100 cfs

3.4 48-in Storm Drain Inlet without a Grate at 125 cfs

This scenario simulates a steady-state flow of 125 cfs. Figure 3-10 and Figure 3-11 are 3D view and plan view of the simulated surface flow velocity and vectors, respectively. Figure 3-12 is a profile view of the velocity and vectors along the centerline of the storm drain inlet. At this flow, the modeling shows that the storm drain inlet is submerged. The simulated flow depth upstream of the wingwall is 5.25 ft with an average velocity of 1.19 ft/s.

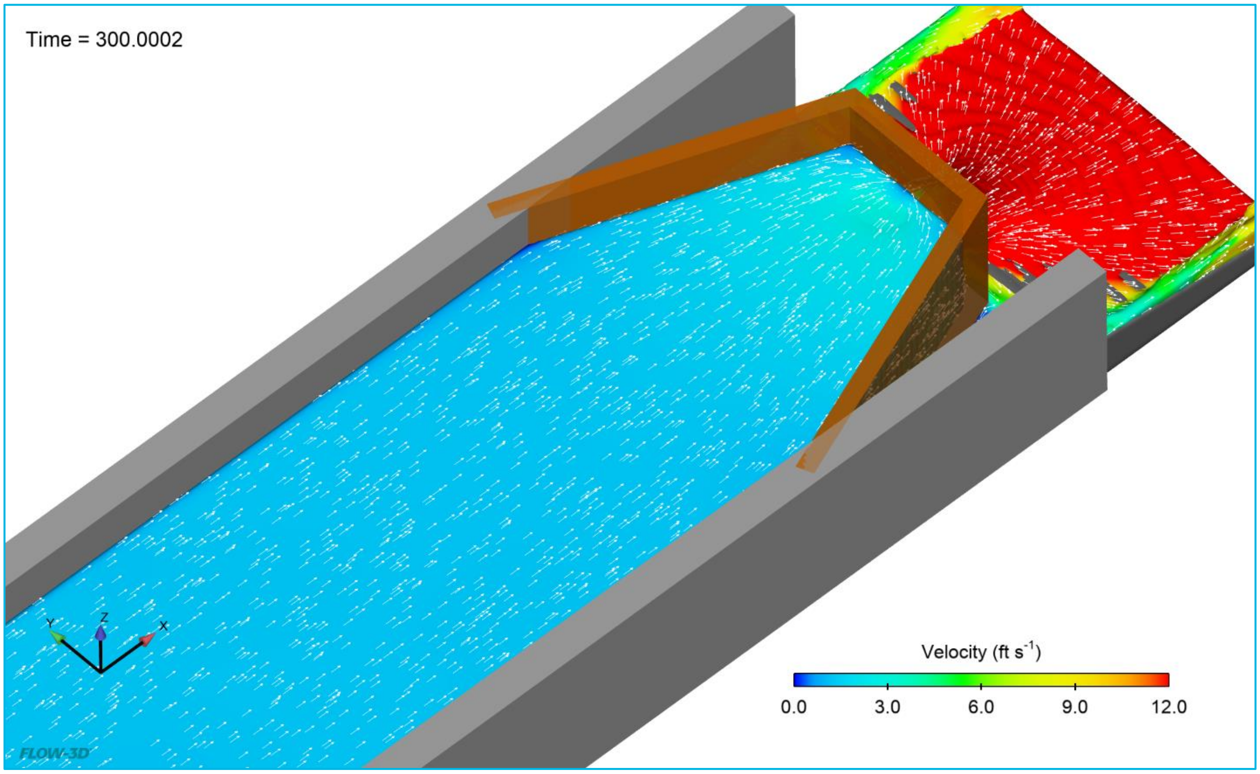

Figure 3-10. 3D View of Simulated Flow Velocity and Vectors for 48-in Inlet without Grate at 125 cfs

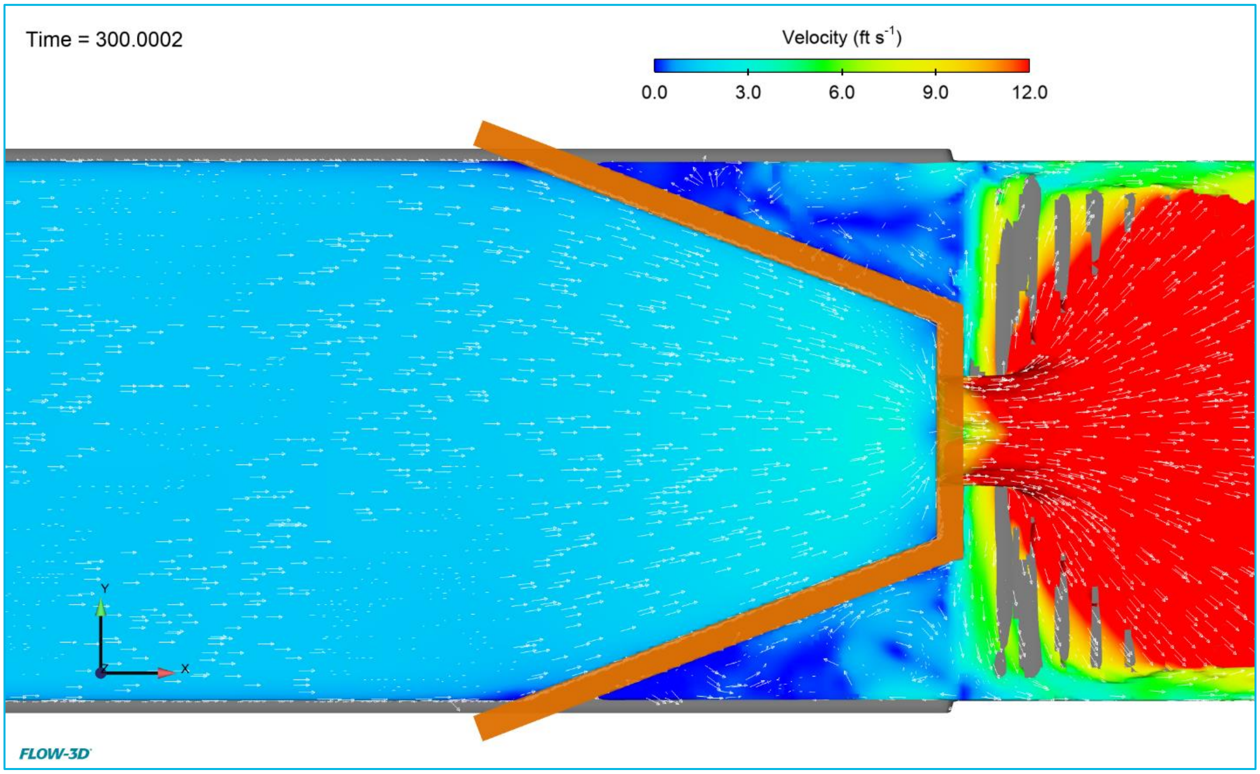

Figure 3-11. Plan View of Simulated Flow Velocity and Vectors for 48-in Inlet without Grate at 125 cfs

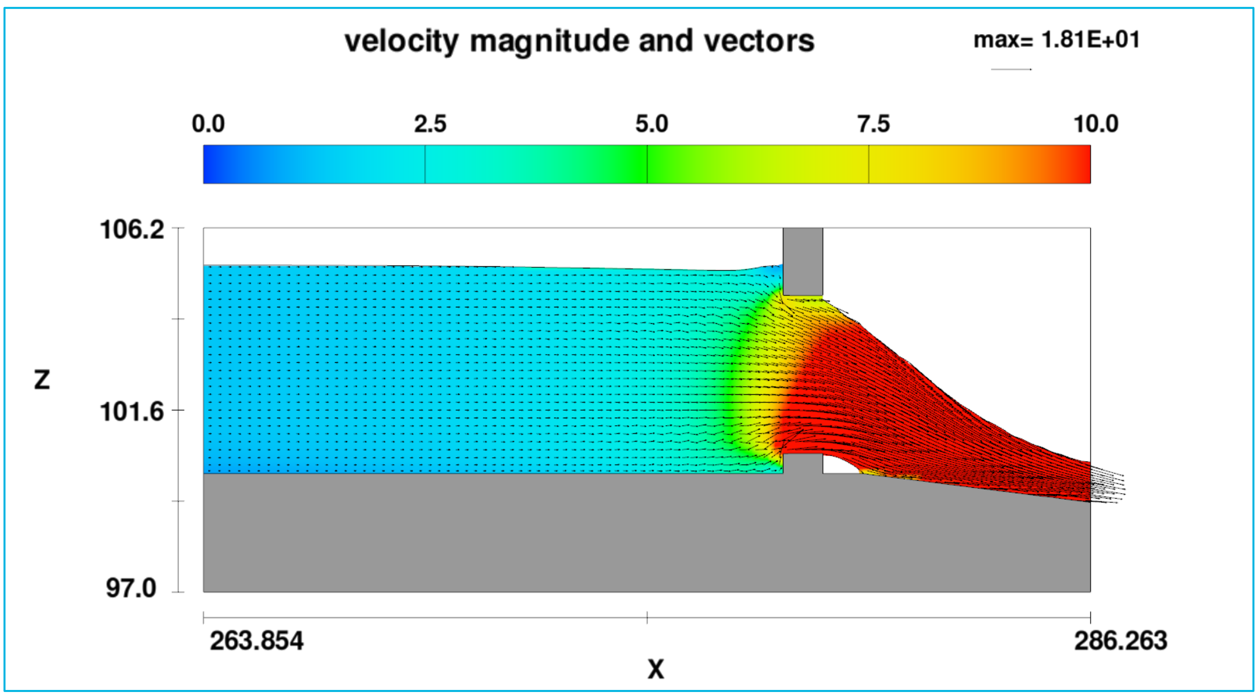

Figure 3-12. Profile View of Simulated Flow Velocity and Vectors along Inlet Centerline for 48-in Inlet without Grate at 125 cfs

3.5 48-in Storm Drain Inlet without a Grate at 150 cfs

This scenario simulates a steady-state flow of 150 cfs. Figure 3-13 and Figure 3-14 are 3D view and plan view of the simulated surface flow velocity and vectors, respectively. Figure 3-15 is a profile view of the velocity and vectors along the centerline of the storm drain inlet. At this flow, the modeling shows that the storm drain inlet is submerged. The simulated flow depth upstream of the wingwall is 6.29 ft with an average velocity of 1.19 ft/s.

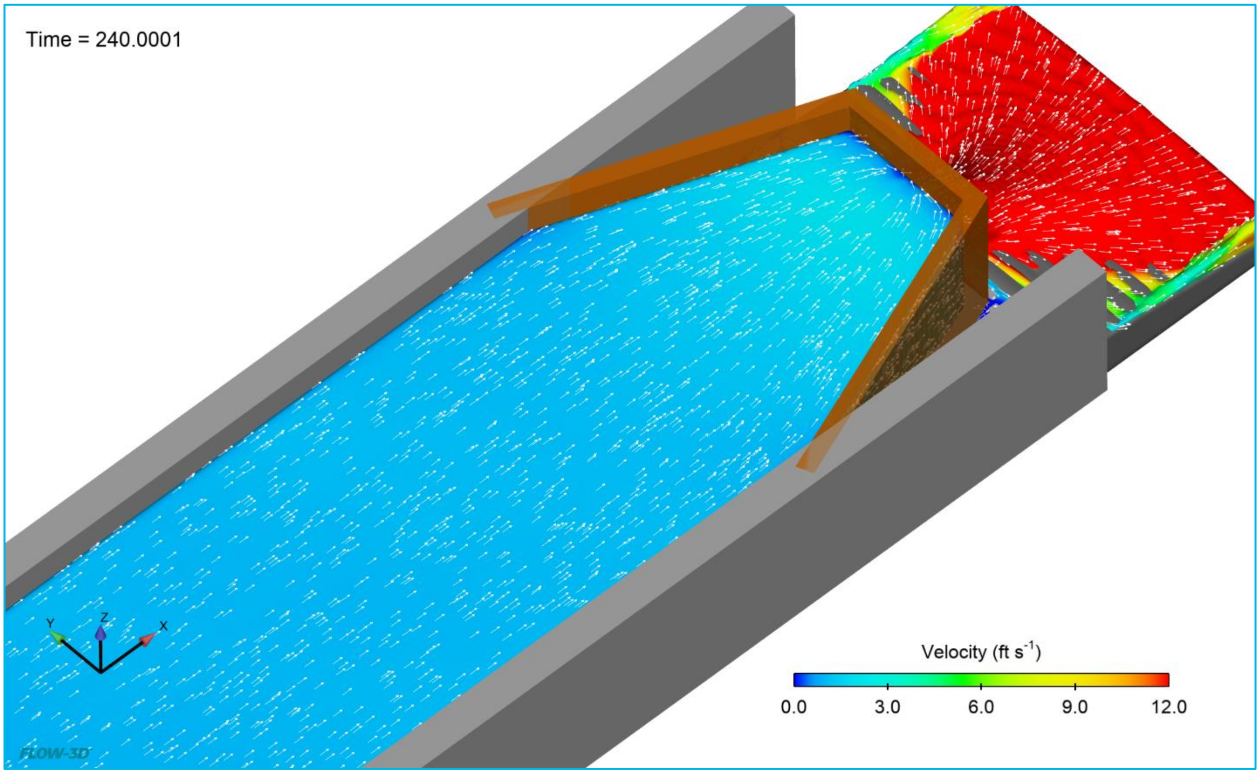

Figure 3-13. 3D View of Simulated Flow Velocity and Vectors for 48-in Inlet at 150 cfs

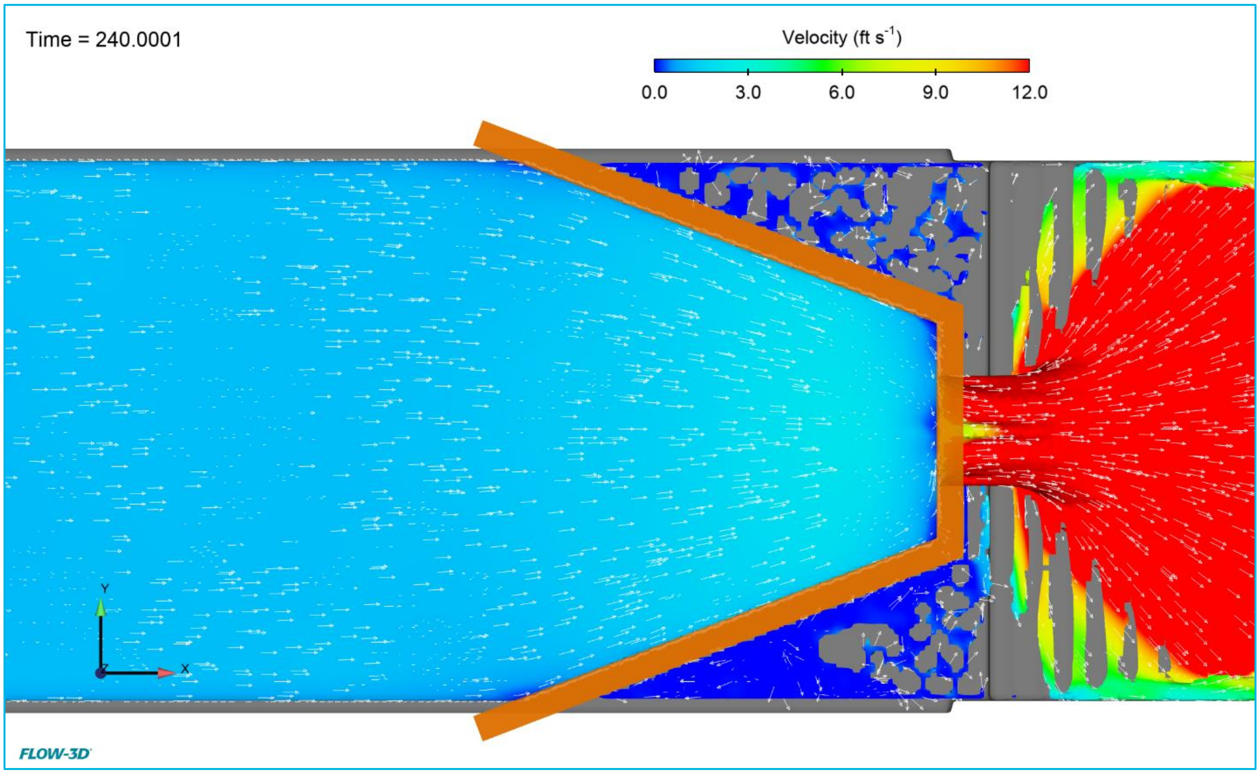

Figure 3-14. Plan View of Simulated Flow Velocity and Vectors for 48-in Inlet at 150 cfs

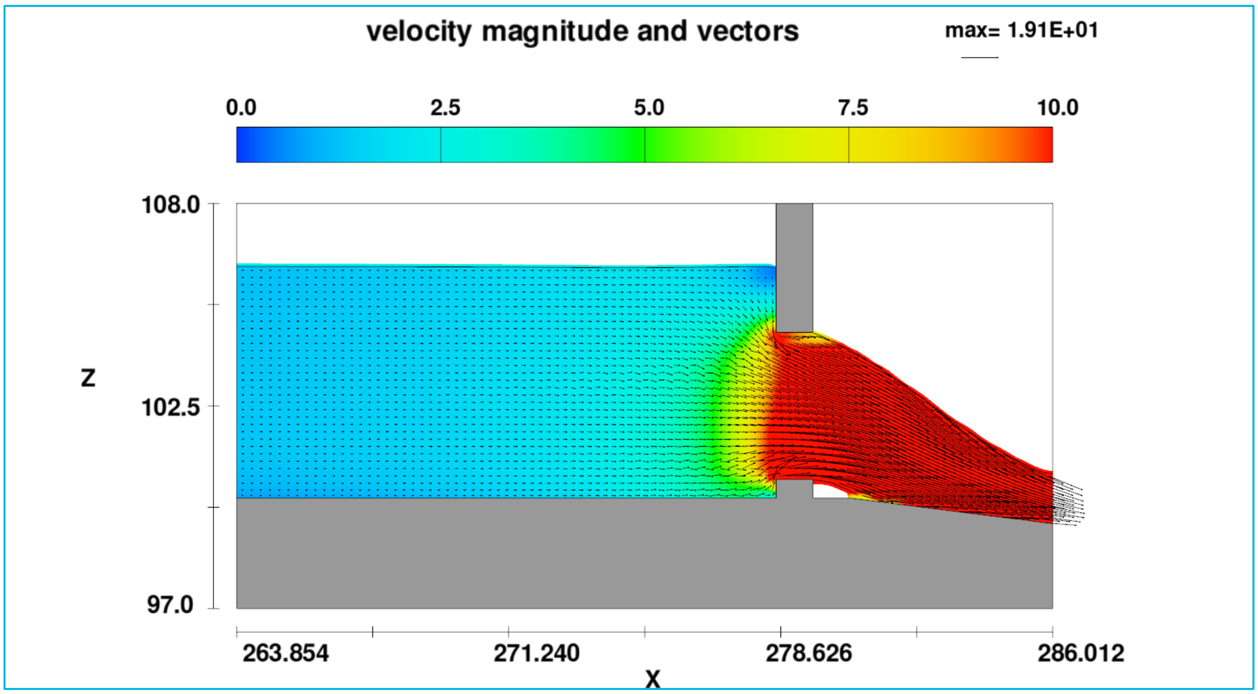

Figure 3-15. Profile View of Simulated Flow Velocity and Vectors along Inlet Centerline for 48-in Inlet at 150 cfs

3.6 30-in Storm Drain Inlet without Grate at 25 cfs

This scenario simulates a steady-state flow of 25 cfs for the 30-in inlet. Figure 3-16 and Figure 3-17 are 3D view and plan view of the simulated surface flow velocity and vectors, respectively. Figure 3-18 is a profile view of the velocity and vectors along the centerline of the storm drain inlet. At this flow, the modeling shows that the storm drain inlet is partially full. The simulated flow depth upstream of the wingwalls is 2.84 ft with an average velocity of 0.44 ft/s.

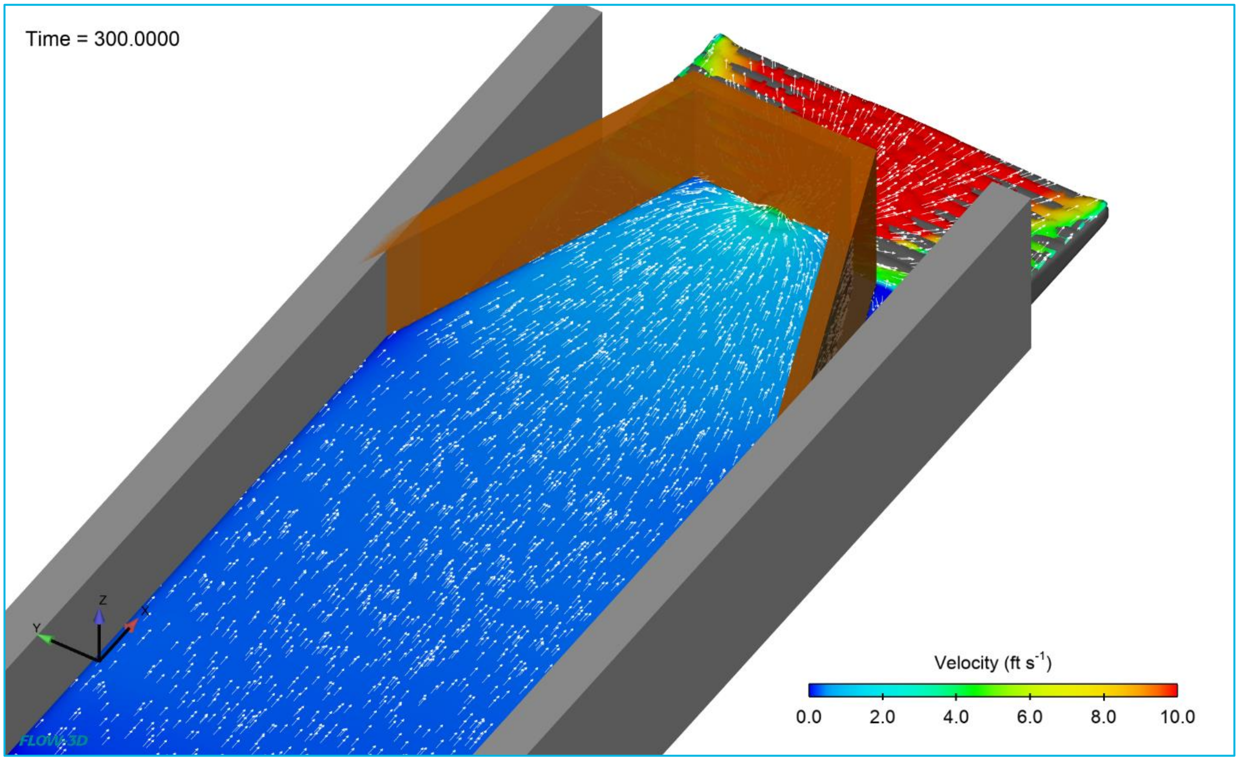

Figure 3-16. 3D View of Simulated Flow Velocity and Vectors for 30-in Inlet without Grate at 25 cfs

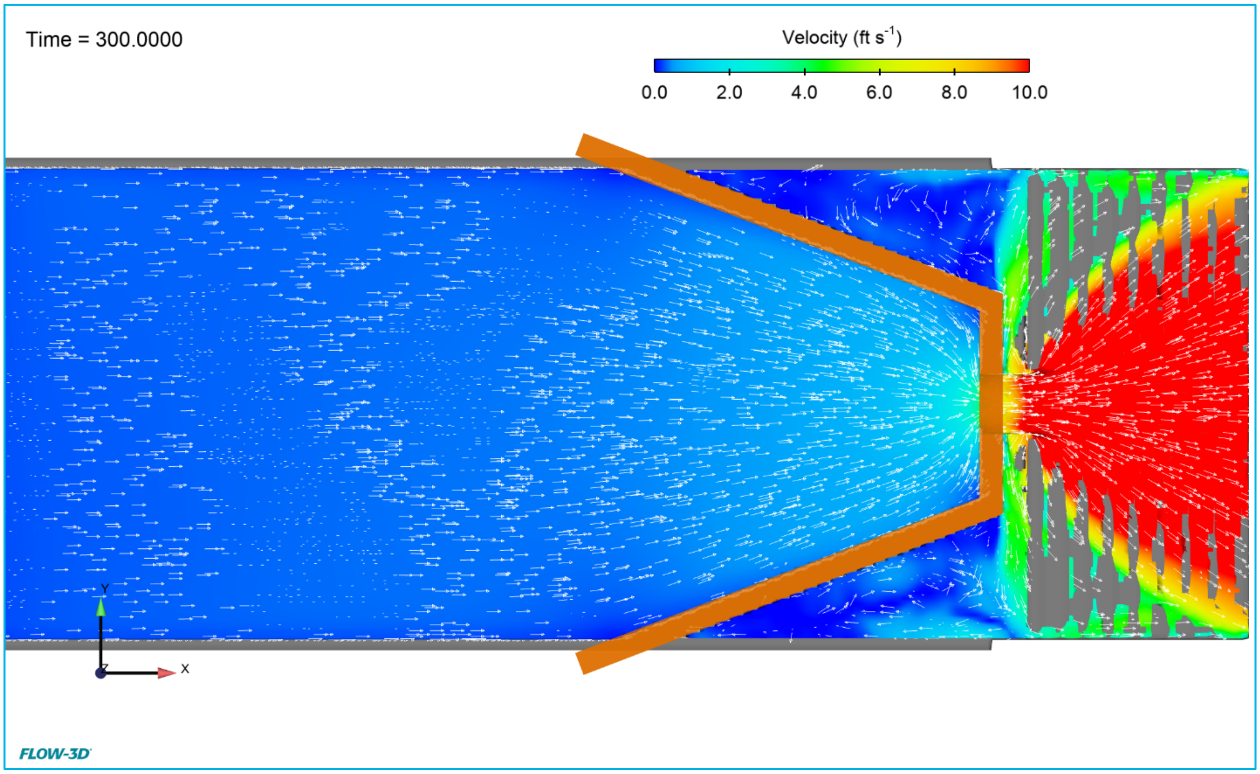

Figure 3-17. Plan View of Simulated Flow Velocity and Vectors for 30-in Inlet without Grate at 25 cfs

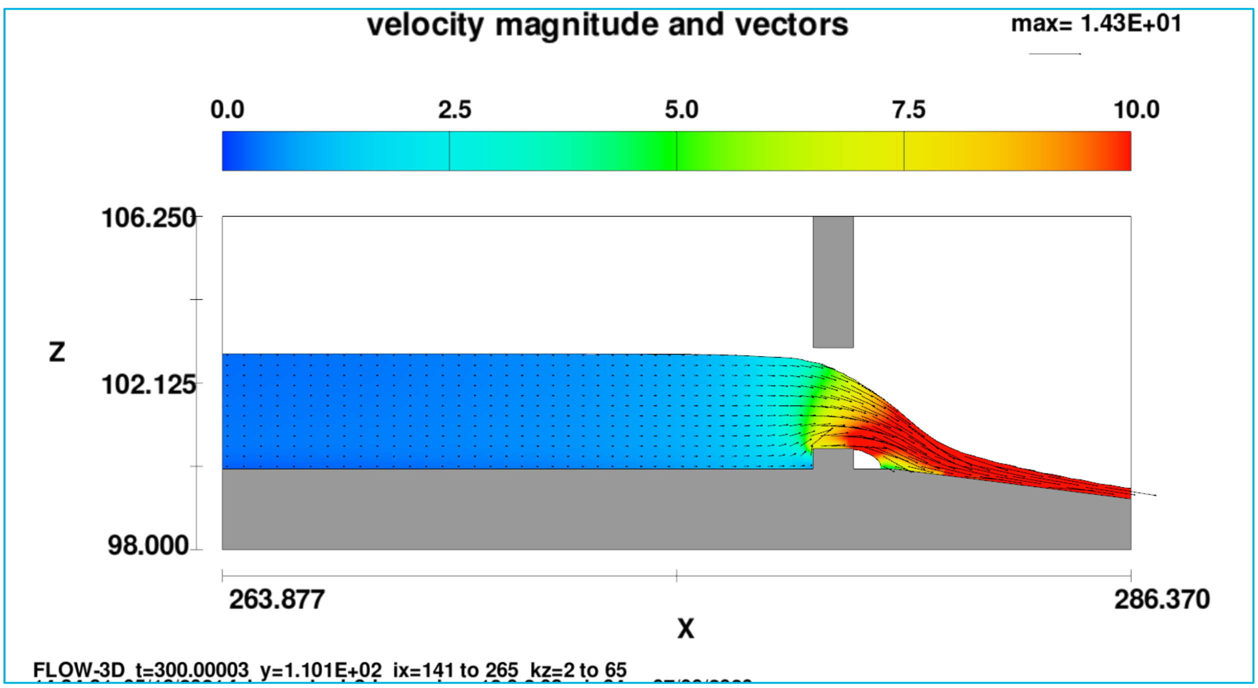

Figure 3-18. Profile View of Simulated Flow Velocity and Vectors along Inlet Centerline for 30-in Inlet without Grate at 25 cfs

3.7 30-in Storm Drain Inlet without Grate at 35 cfs

This scenario simulates a steady-state flow of 35 cfs for the 30-in inlet. Figure 3-19 and Figure 3-20 are 3D view and plan view of the simulated surface flow velocity and vectors, respectively. Figure 3-21 is a profile view of the velocity and vectors along the centerline of the storm drain inlet. At this flow, the modeling shows that the storm drain inlet is submerged. The simulated flow depth upstream of the wingwalls is 3.42 ft with an average velocity of 0.51 ft/s.

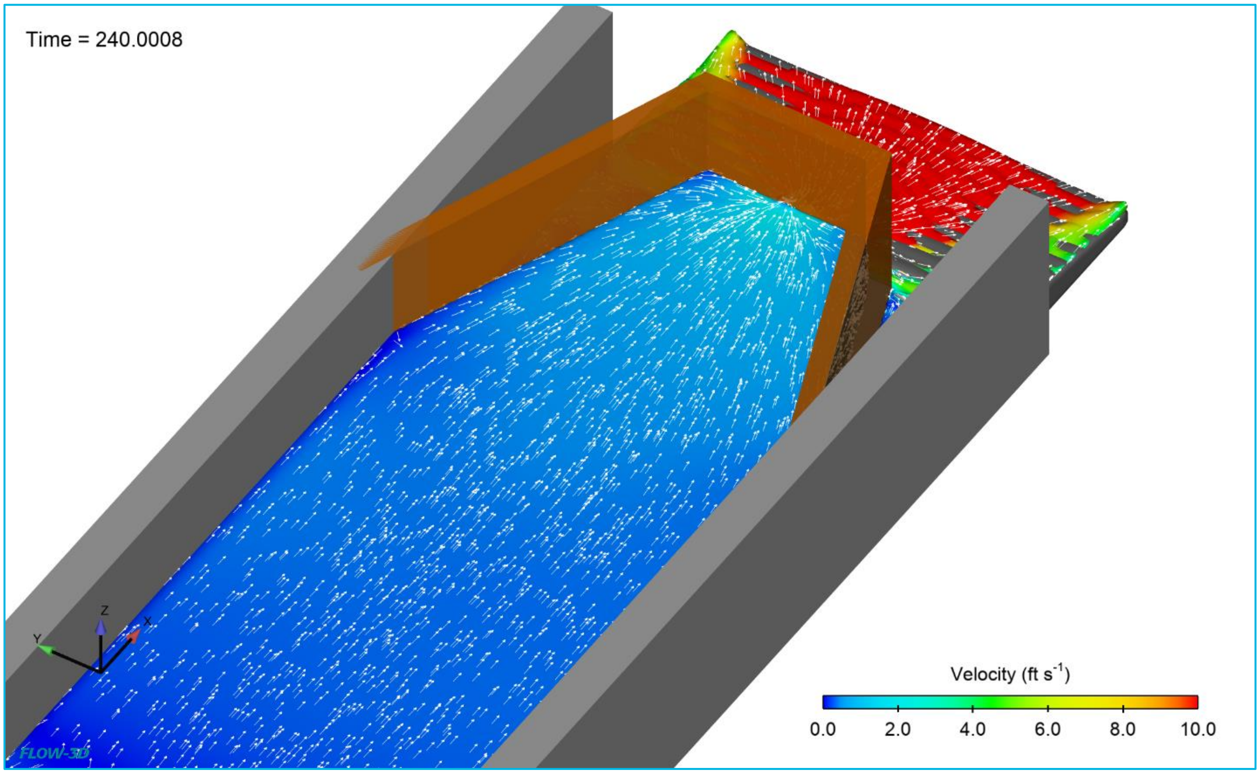

Figure 3-19. 3D View of Simulated Flow Velocity and Vectors for 30-in Inlet without Grate at 35 cfs

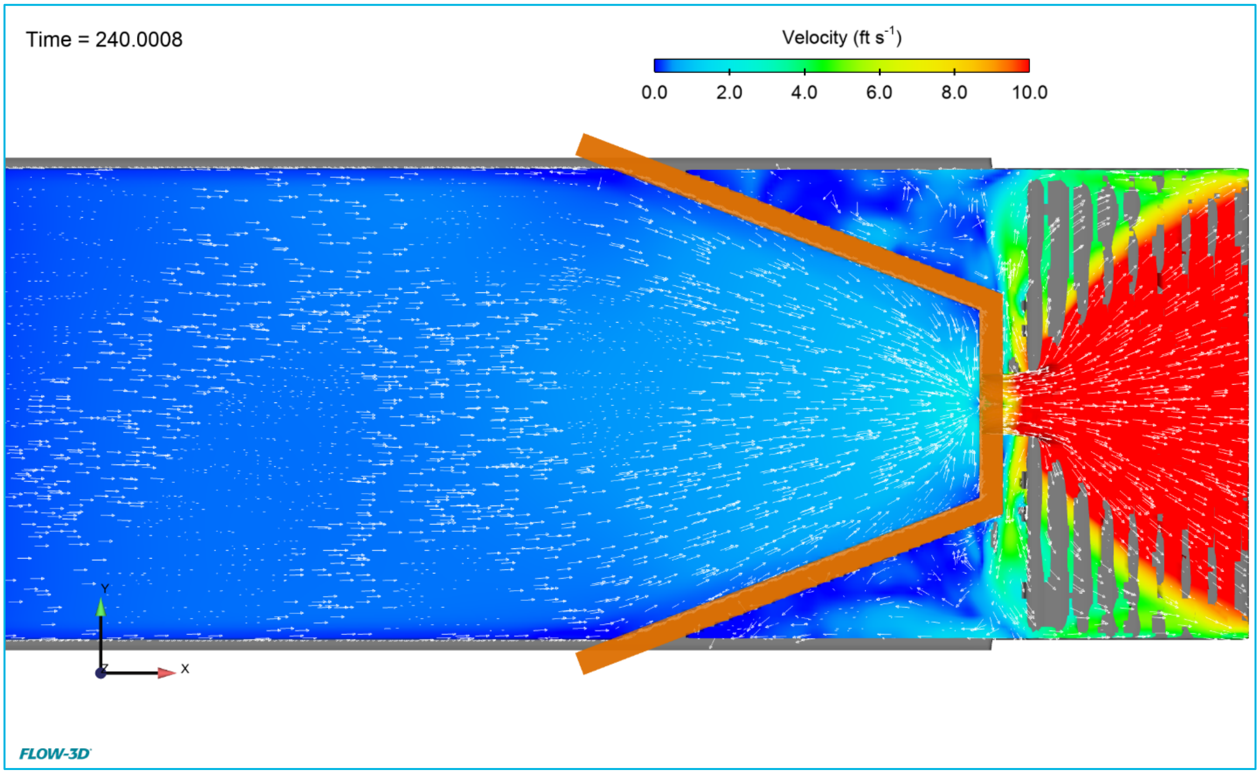

Figure 3-20. Plan View of Simulated Flow Velocity and Vectors for 30-in Inlet without Grate at 35 cfs

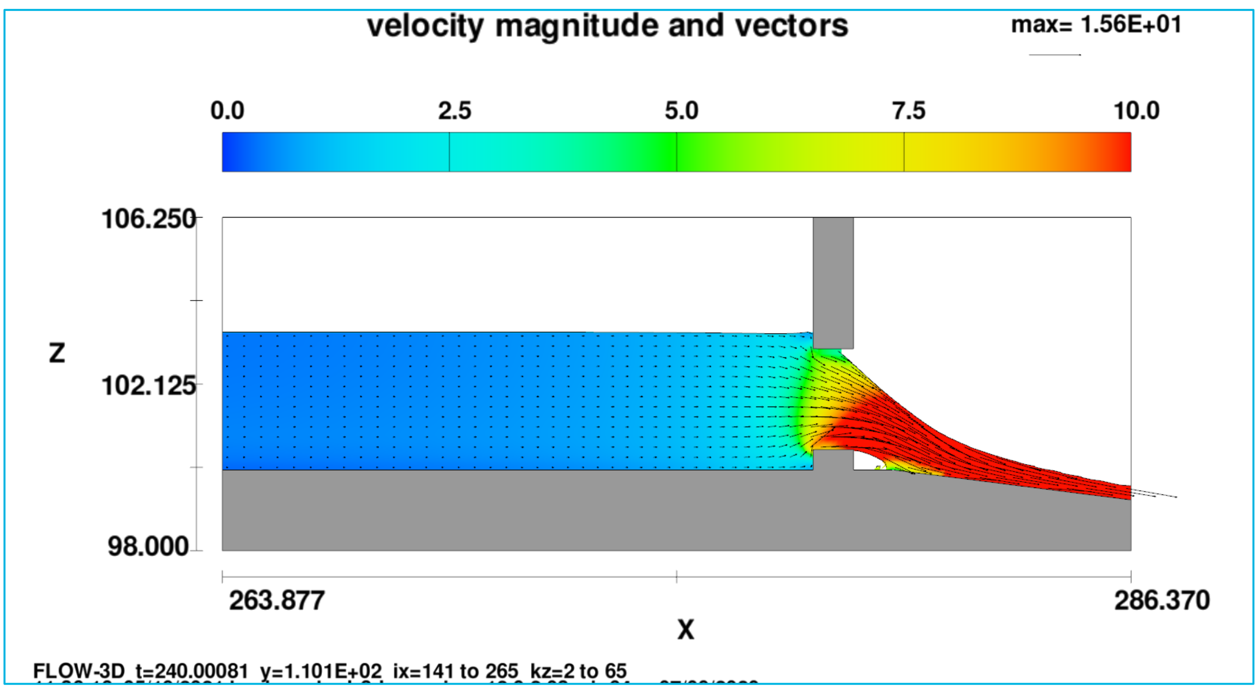

Figure 3-21. Profile View of Simulated Flow Velocity and Vectors along Inlet Centerline for 30-in Inlet without Grate at 35 cfs

3.8 30-in Storm Drain Inlet without Grate at 40 cfs

This scenario simulates a steady-state flow of 40 cfs for the 30-in inlet. Figure 3-22 and Figure 3-23 are 3D view and plan view of the simulated surface flow velocity and vectors, respectively. Figure 3-24 is a profile view of the velocity and vectors along the centerline of the storm drain inlet. At this flow, the modeling shows that the storm drain inlet is submerged. The simulated flow depth upstream of the wingwalls is 3.82 ft with an average velocity of 0.52 ft/s.

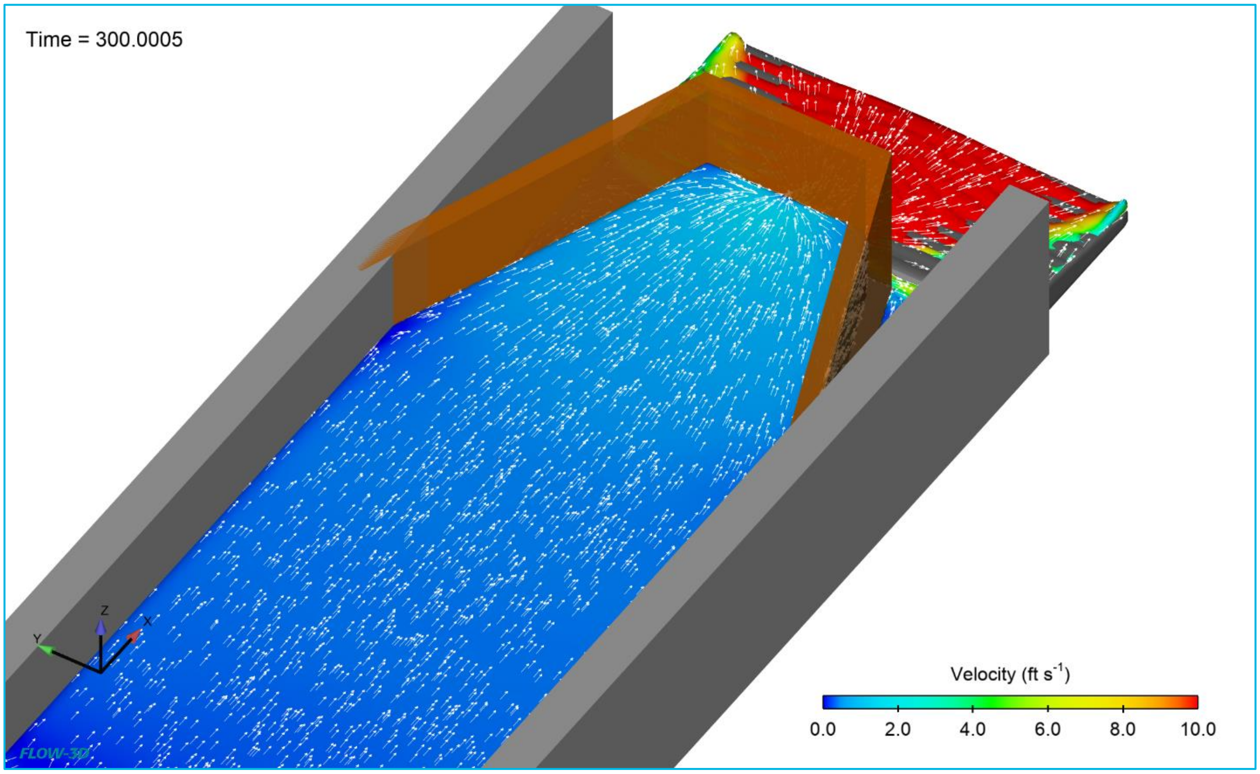

Figure 3-22. 3D View of Simulated Flow Velocity and Vectors for 30-in Inlet without Grate at 40 cfs

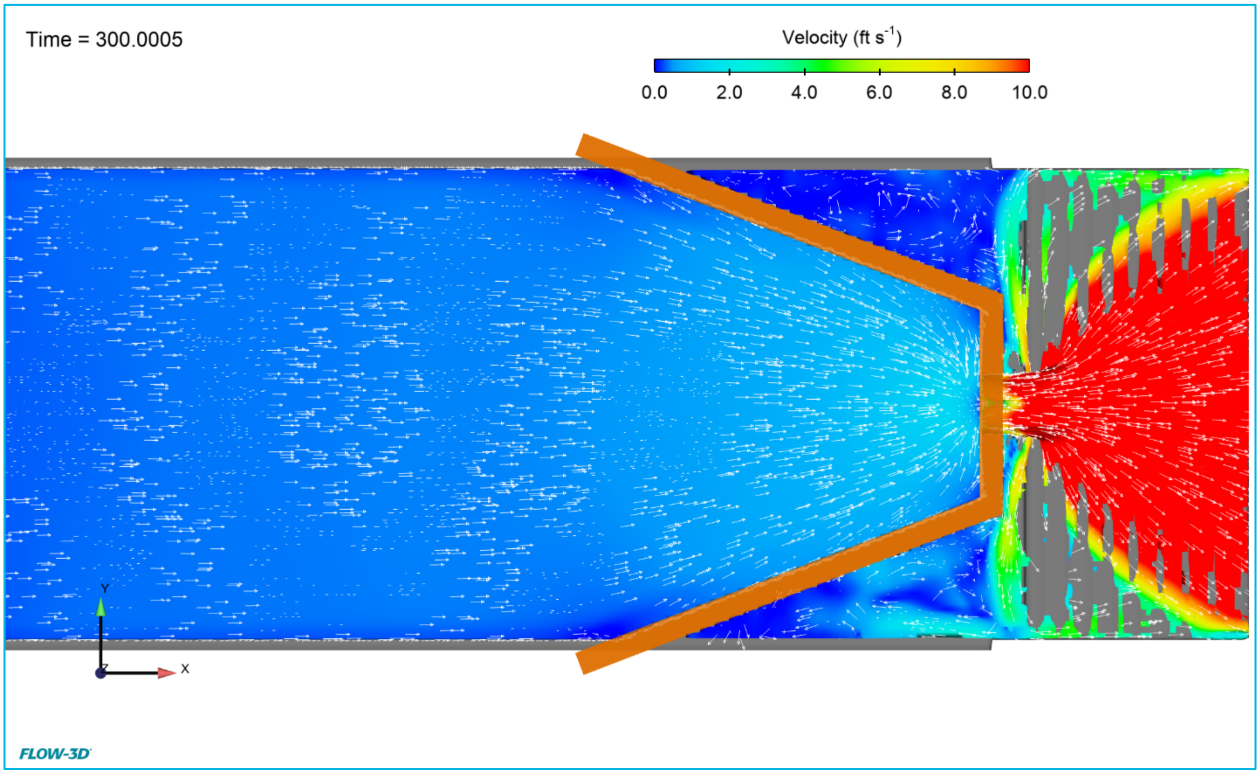

Figure 3-23. Plan View of Simulated Flow Velocity and Vectors for 30-in Inlet without Grate at 40 cfs

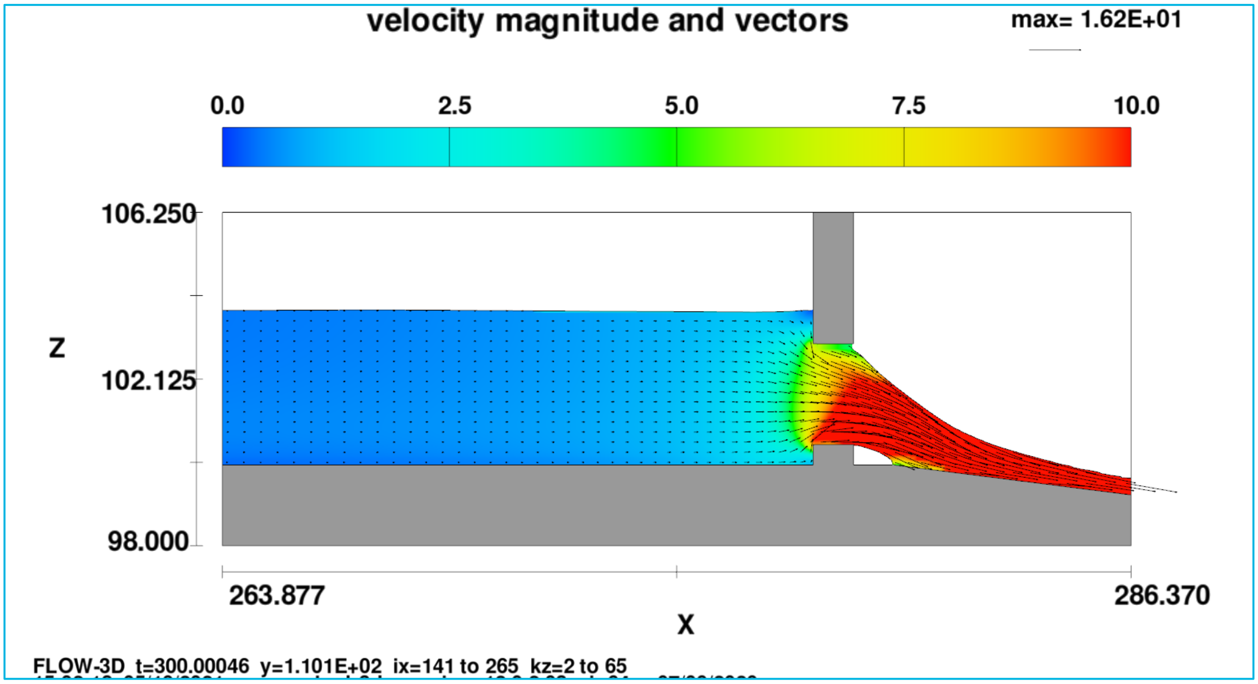

Figure 3-24. Profile View of Simulated Flow Velocity and Vectors along Inlet Centerline for 30-in Inlet without Grate at 40 cfs

3.9 30-in Storm Drain Inlet without Grate at 45 cfs

This scenario simulates a steady-state flow of 45 cfs for the 30-in inlet. Figure 3-25 and Figure 3-26 are 3D view and plan view of the simulated surface flow velocity and vectors, respectively. Figure 3-27 is a profile view of the velocity and vectors along the centerline of the storm drain inlet. At this flow, the modeling shows that the storm drain inlet is submerged. The simulated flow depth upstream of the wingwalls is 4.33 ft with an average velocity of 0.52 ft/s.

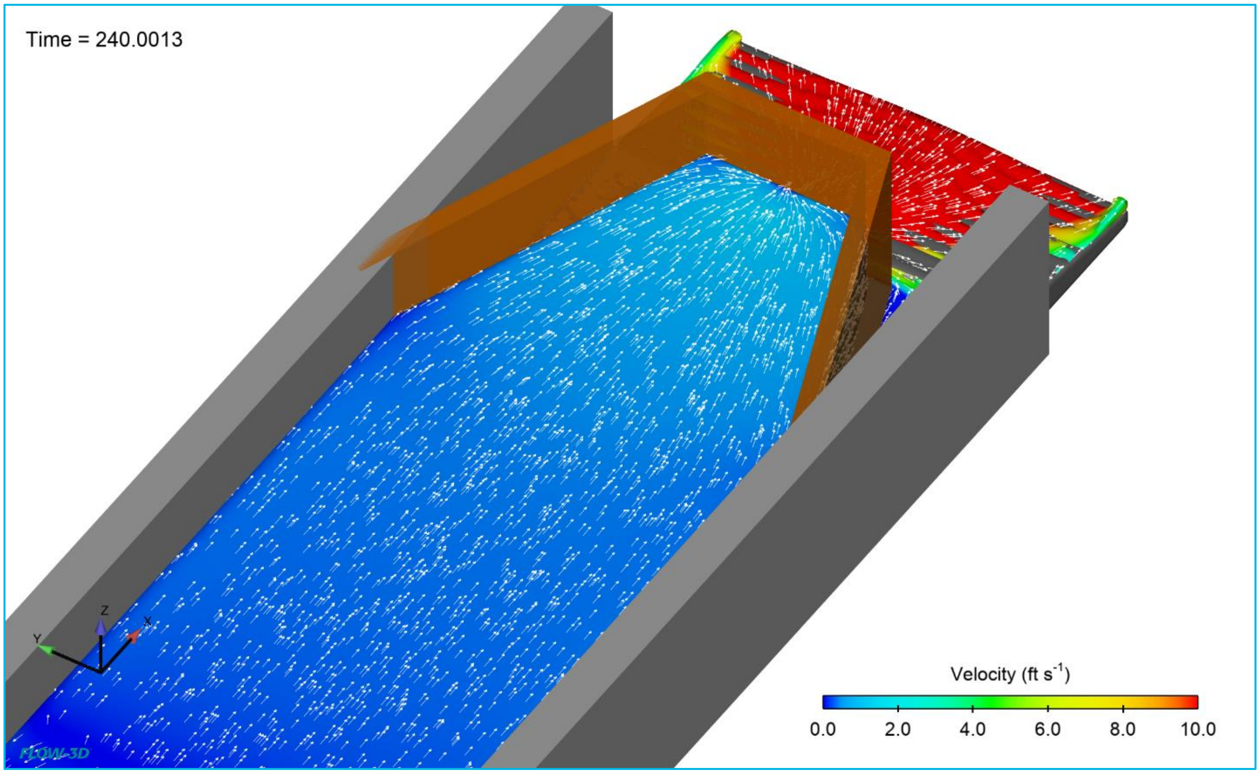

Figure 3-25. 3D View of Simulated Flow Velocity and Vectors for 30-in Inlet without Grate at 45 cfs

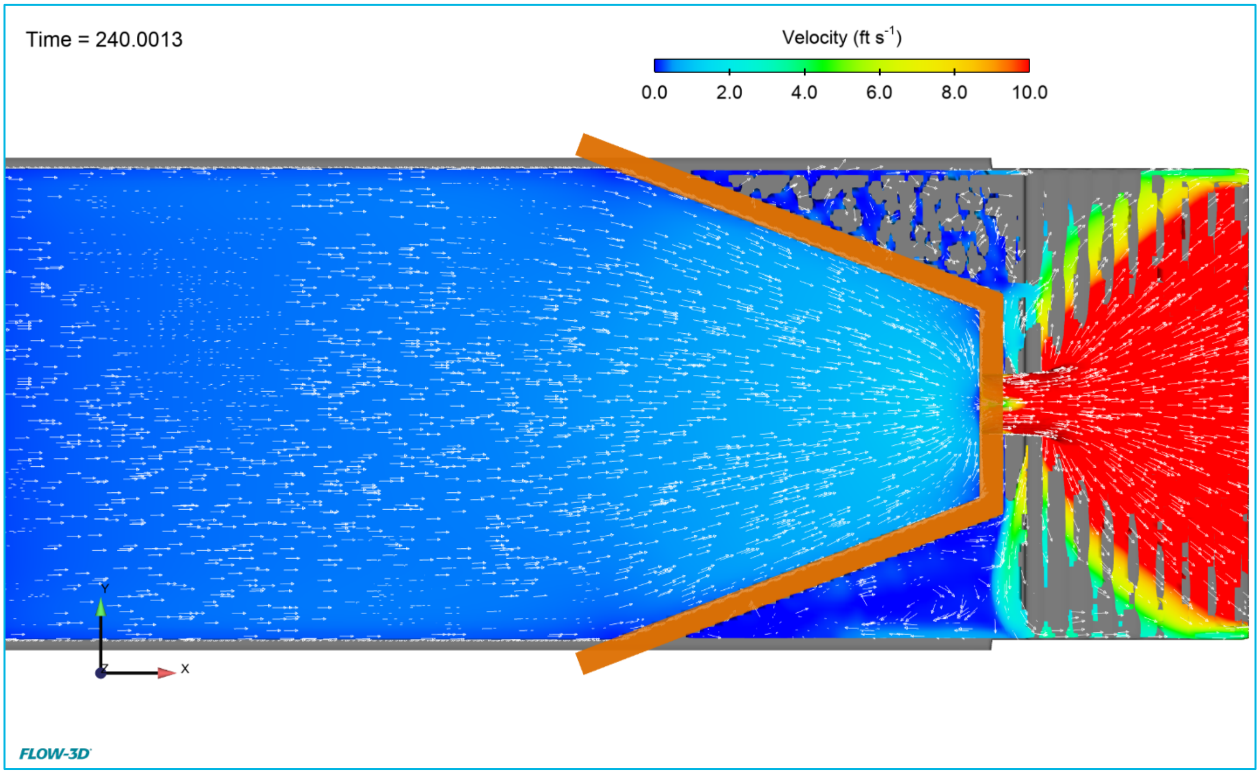

Figure 3-26. Plan View of Simulated Flow Velocity and Vectors for 30-in Inlet without Grate at 45 cfs

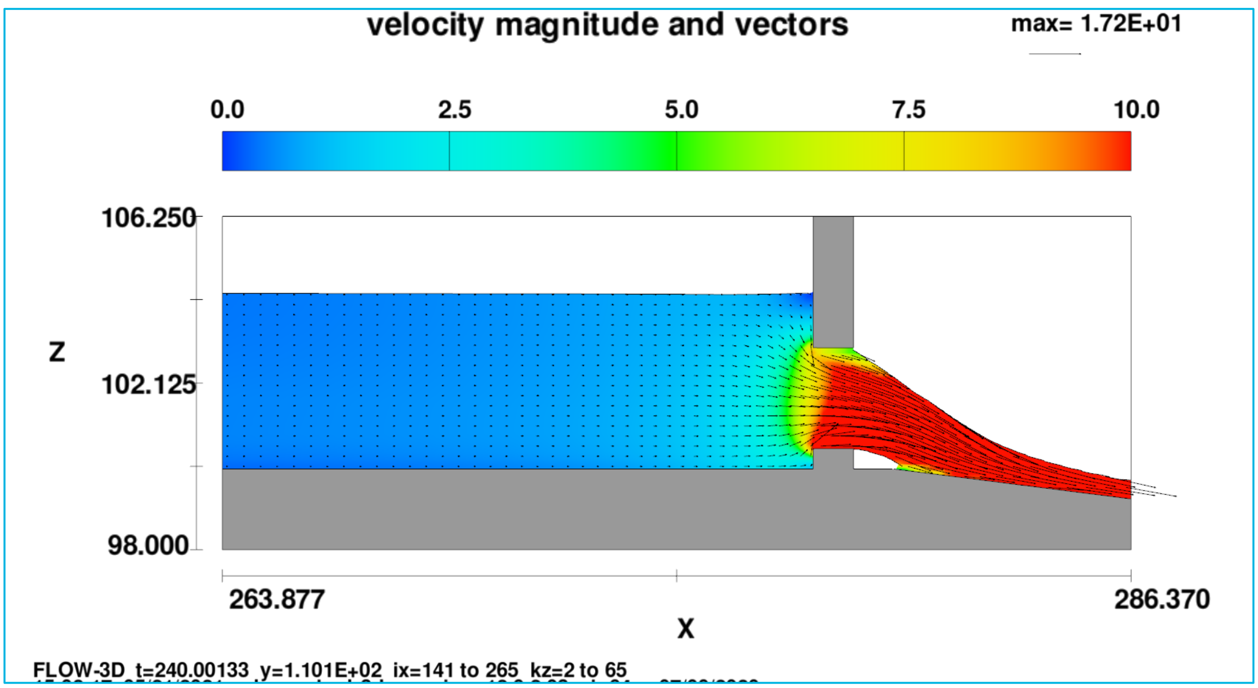

Figure 3-27. Profile View of Simulated Flow Velocity and Vectors along Inlet Centerline for 30-in Inlet without Grate at 45 cfs

3.10 30-in Storm Drain Inlet without Grate at 50 cfs

This scenario simulates a steady-state flow of 50 cfs for the 30-in inlet. Figure 3-28 and Figure 3-29 are 3D view and plan view of the simulated surface flow velocity and vectors, respectively. Figure 3-30 is a profile view of the velocity and vectors along the centerline of the storm drain inlet. At this flow, the modeling shows that the storm drain inlet is submerged. The simulated flow depth upstream of the wingwalls is 4.74 ft with an average velocity of 0.53 ft/s.

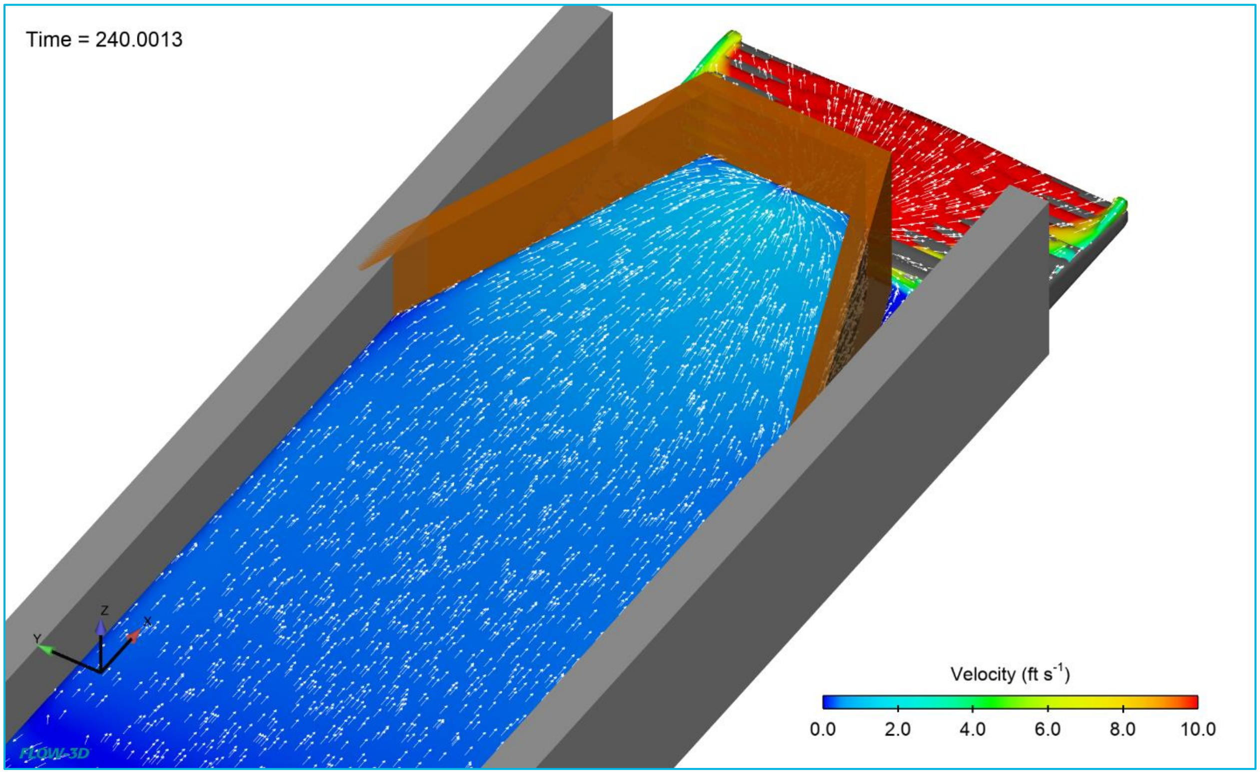

Figure 3-28. 3D View of Simulated Flow Velocity and Vectors for 30-in Inlet without Grate at 50 cfs

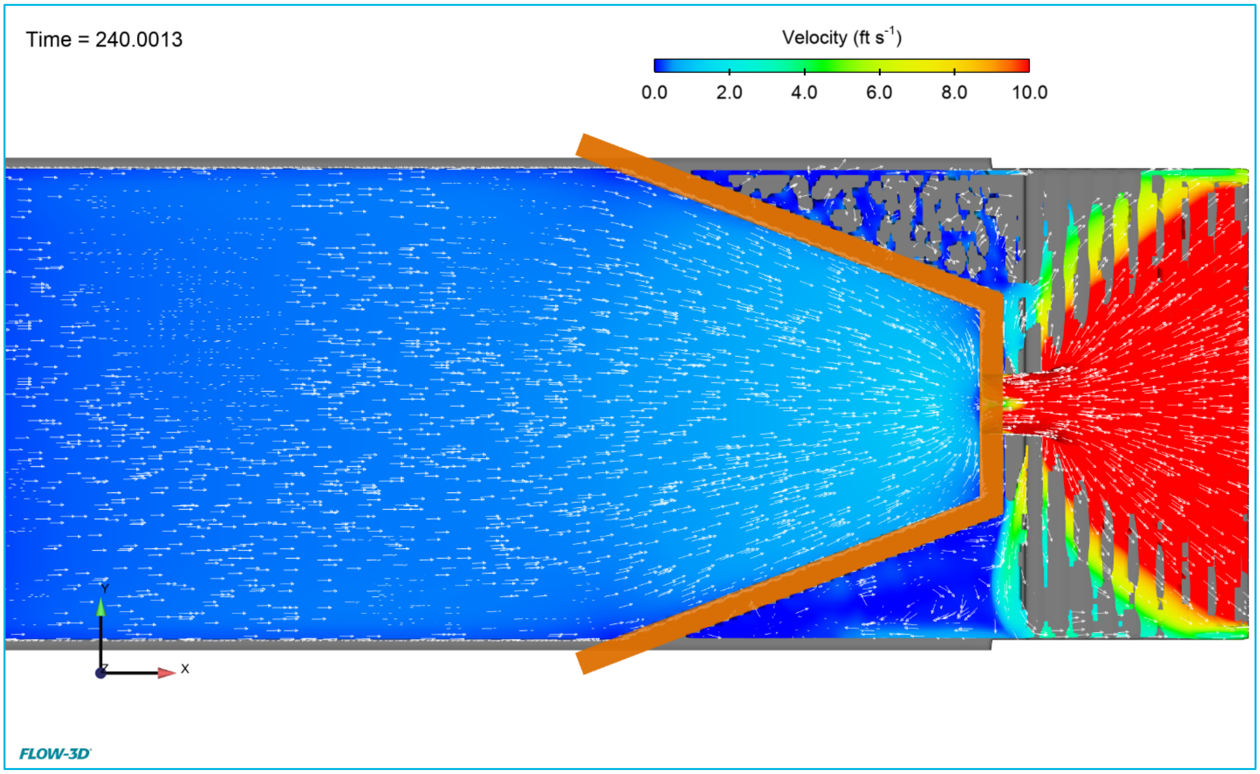

Figure 3-29. Plan View of Simulated Flow Velocity and Vectors for 30-in Inlet without Grate at 50 cfs

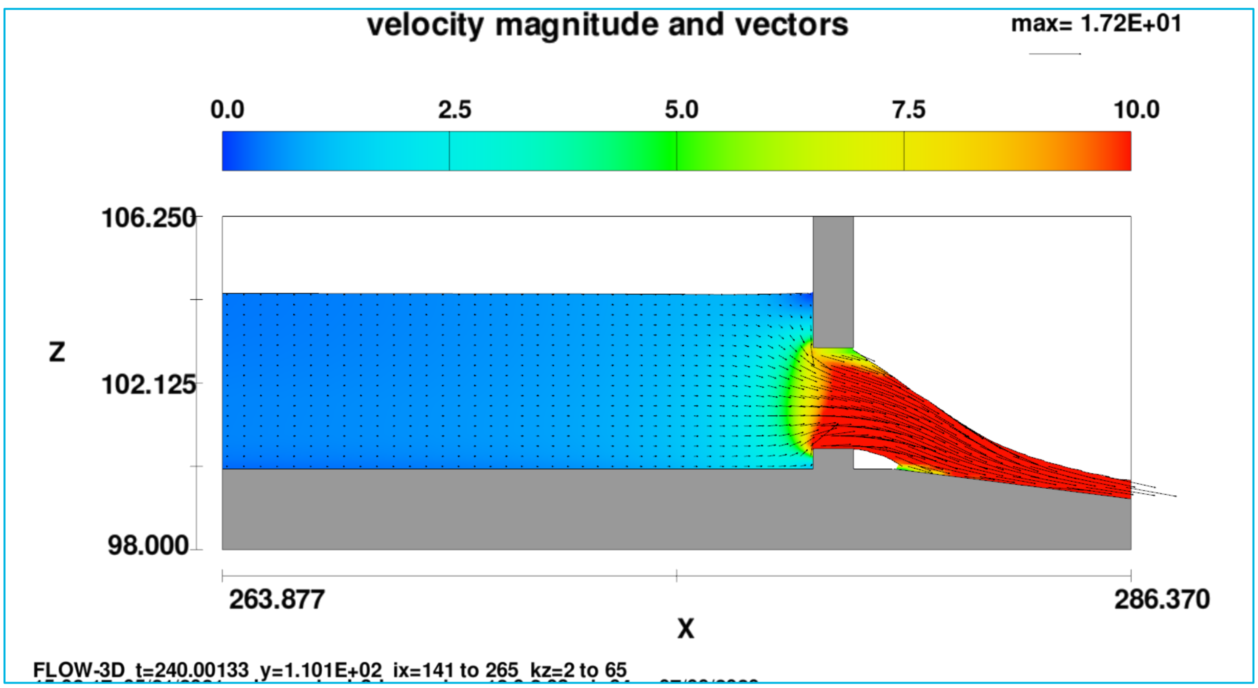

Figure 3-30. Profile View of Simulated Flow Velocity and Vectors along Inlet Centerline for 30-in Inlet without Grate at 50 cfs

4. CFD Model Results with MHFD Grates without an Object Against the Grate

This section presents the initial CFD modeling results for the MHFD grates without an object against the grate. The modeling was conducted with initial layouts of the grates provided by MHFD that have an offset of 12-in upstream from the culvert entrance. This is slightly different from the final layout that is without this offset as presented in Section 5. The modeled grates also have a 12-in horizontal top that is located downstream of the sloping upstream face of the grates. The same grate was used for all culvert sizes modeled in this section. The purpose of the CFD modeling detailed in this section was conducted to evaluate the hydraulics upstream of the culvert entrance only.

4.1 48-in Inlet with Grate at 50 cfs

This scenario simulates a steady-state flow of 50 cfs with the proposed MHFD grate installed. Figure 4-1 and Figure 4-2 are 3D view and plan view of the simulated surface flow velocity and vectors, respectively. Figure 4-3 is a profile view of the velocity and vectors along the centerline of the inlet.

At this flow, the modeling shows that the storm drain inlet remains partially full, with the water level in the approach channel increasing by 0.01 ft from the non-grate scenario. The approach velocity for the grate itself is generally less than 3 ft/s.

The total net force acting on the grates, including pressure and shear, was simulated to be about 85 lbs.

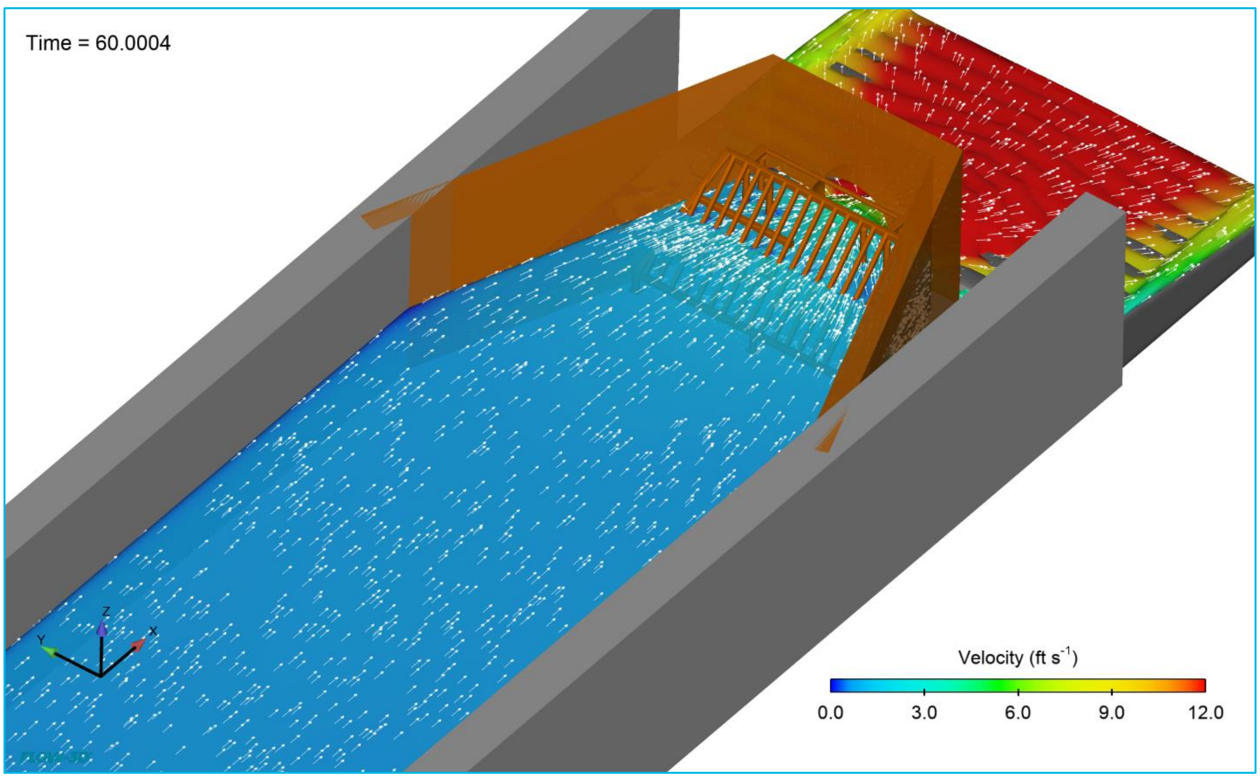

Figure 4-1. 3D View of Simulated Flow Velocity and Vectors for 48-in Inlet with Grate at 50 cfs

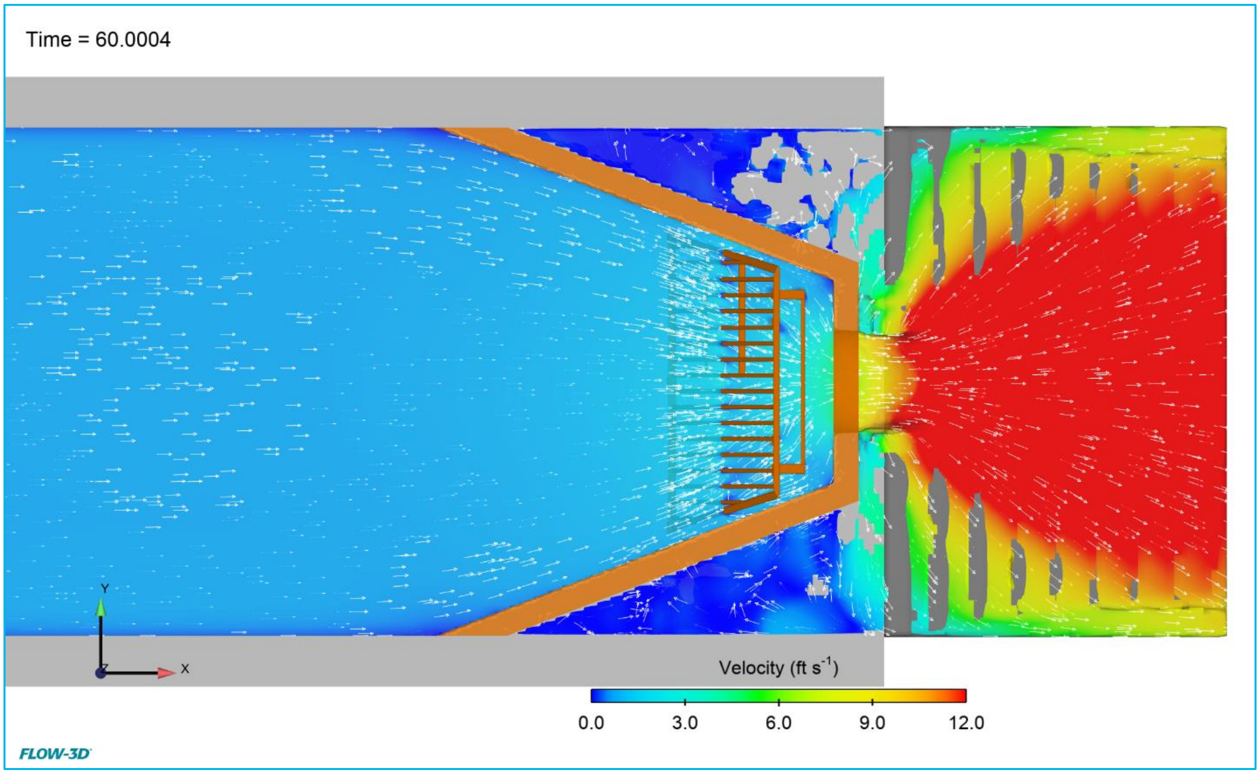

Figure 4-2. Plan View of Simulated Flow Velocity and Vectors for 48-in Inlet with Grate at 50 cfs

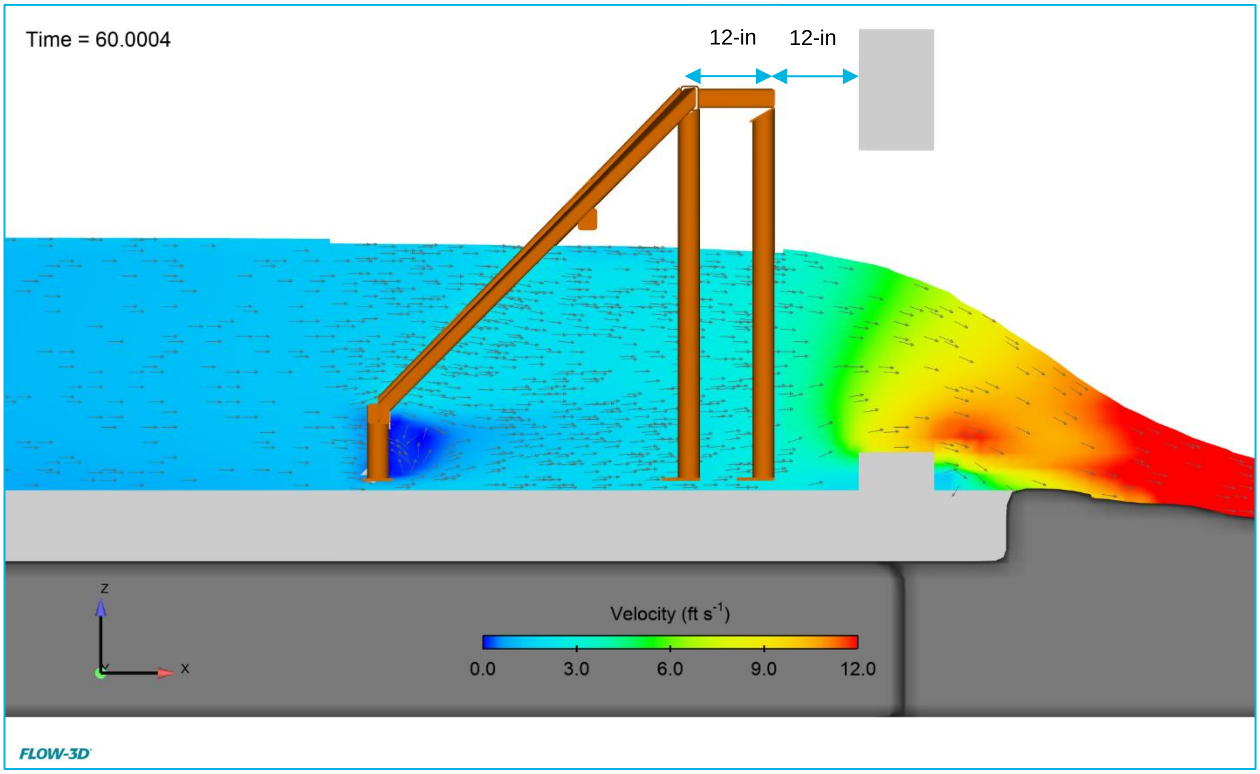

Figure 4-3. Profile View of Simulated Flow Velocity and Vectors along Inlet Centerline for 48-in Inlet with Grate at 50 cfs

4.2 48-in Storm Drain Inlet with Grate at 100 cfs

This scenario simulates a steady-state flow of 100 cfs with the proposed MHFD grate installed. Figure 4-4 and Figure 4-5 are 3D view and plan view of the simulated surface flow velocity and vectors, respectively. Figure 4-6 is a profile view of the velocity and vectors along the centerline of the storm drain inlet.

At this flow, the modeling shows that the storm drain inlet remains partially full, with the water level in the approach channel increasing by 0.08 ft from the non-grate scenario. The approach velocity for the grate itself is generally less than 3 ft/s.

The total net force acting on the grates, including pressure and shear, was simulated to be about 121 lbs.

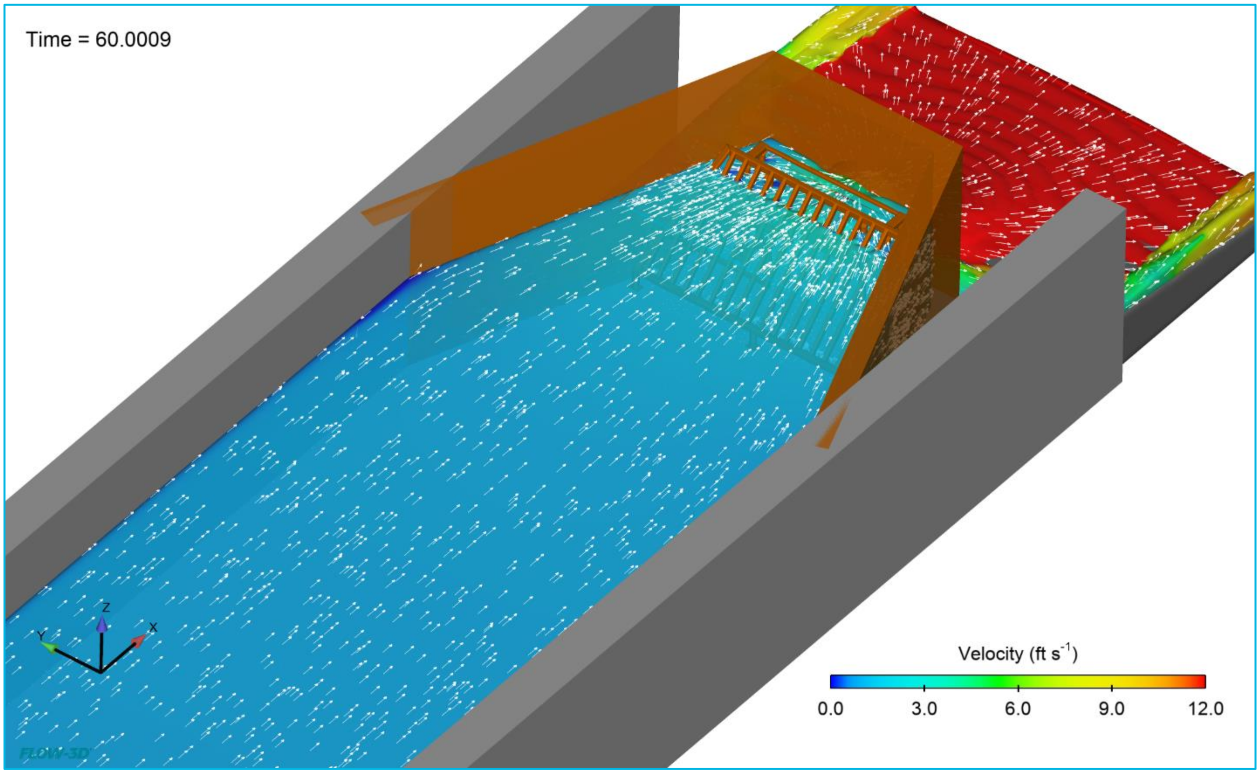

Figure 4-4. 3D View of Simulated Flow Velocity and Vectors for 48-in Inlet with Grate at 100 cfs

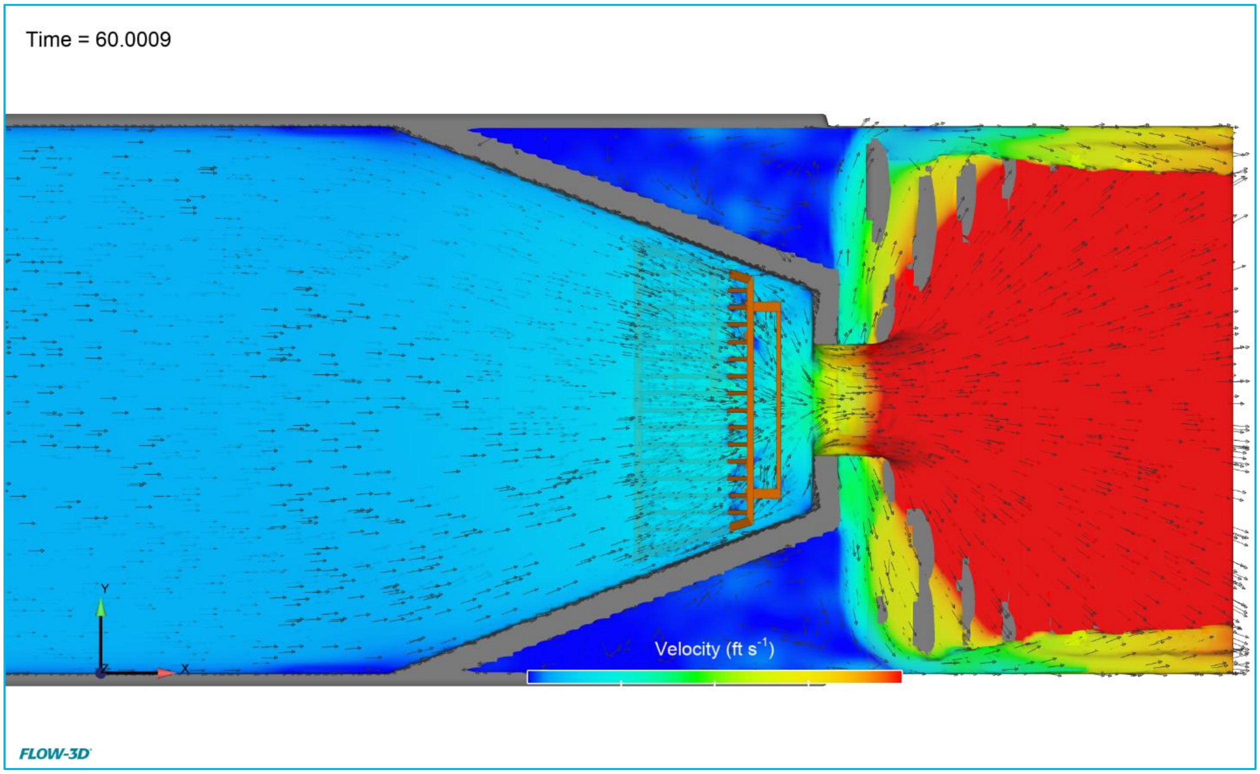

Figure 4-5. Plan View of Simulated Flow Velocity and Vectors for 48-in Inlet with Grate at 100 cfs

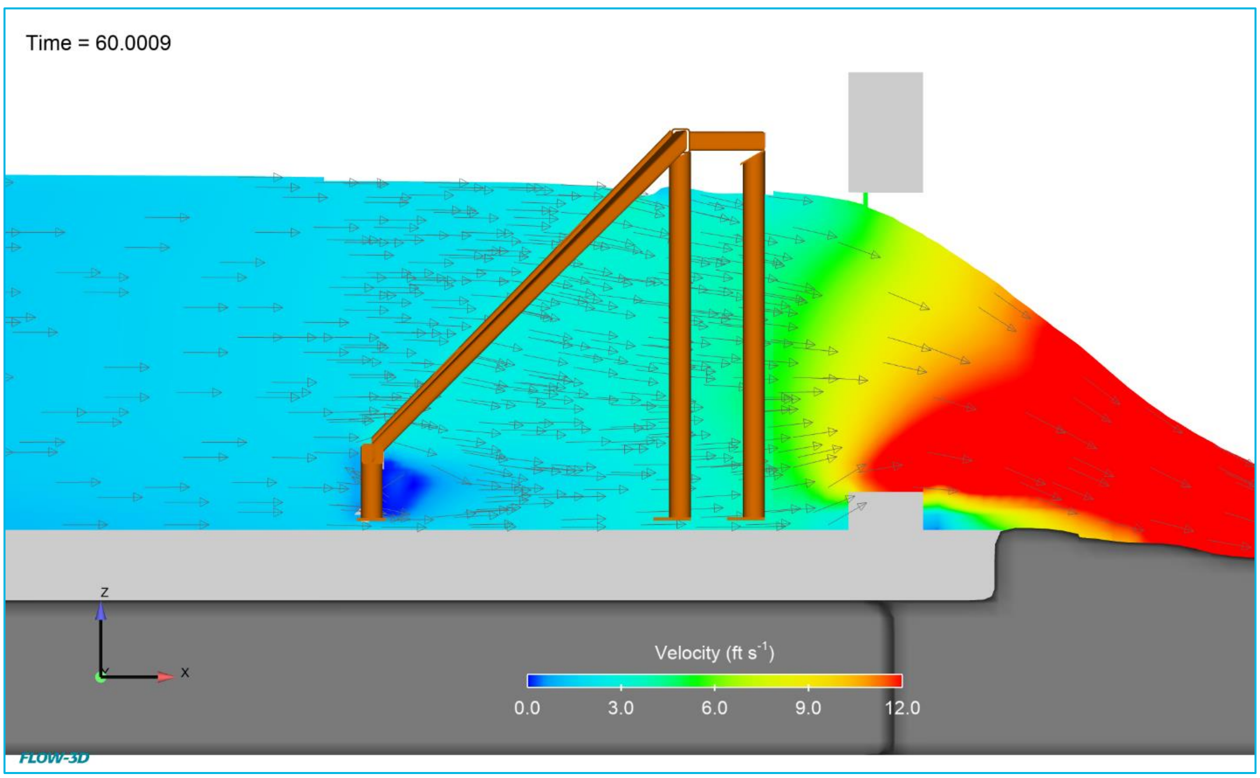

Figure 4-6. Profile View of Simulated Flow Velocity and Vectors along Inlet Centerline for 48-in Inlet with Grate at 100 cfs

4.3 48-in Storm Drain Inlet with Grate at 150 cfs

This scenario simulates a steady-state flow of 150 cfs with the proposed MHFD grate installed. Figure 4-7 and Figure 4-8 are 3D view and plan view of the simulated surface flow velocity and vectors, respectively. Figure 4-9 is a profile view of the velocity and vectors along the centerline of the storm drain inlet.

At this flow, the modeling shows that the inlet remains submerged with the water level in the approach channel increased by 0.08 ft from the non-grate scenario. The approach velocity for the grate itself is generally less than 3 ft/s.

The total net force acting on the grates, including pressure and shear, was simulated to be about 145 lbs.

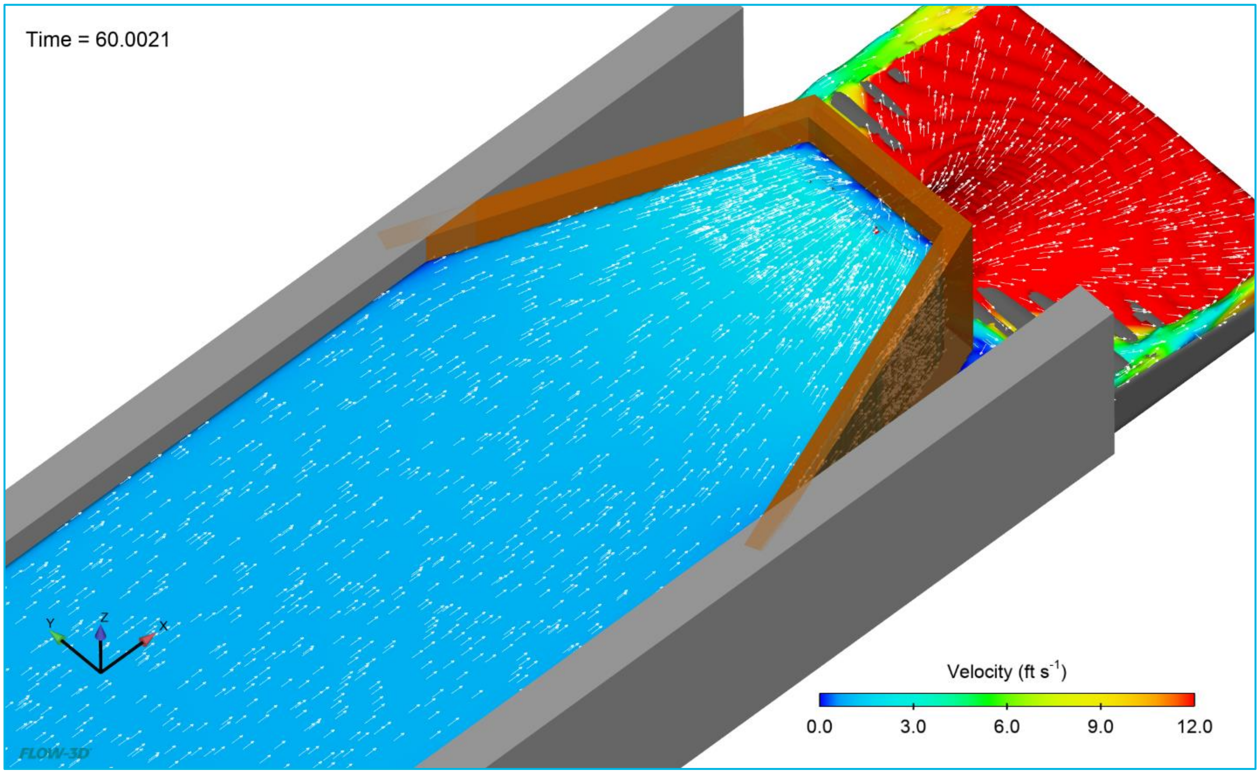

Figure 4-7. 3D View of Simulated Flow Velocity and Vectors for 48-in Inlet with Grate at 150 cfs

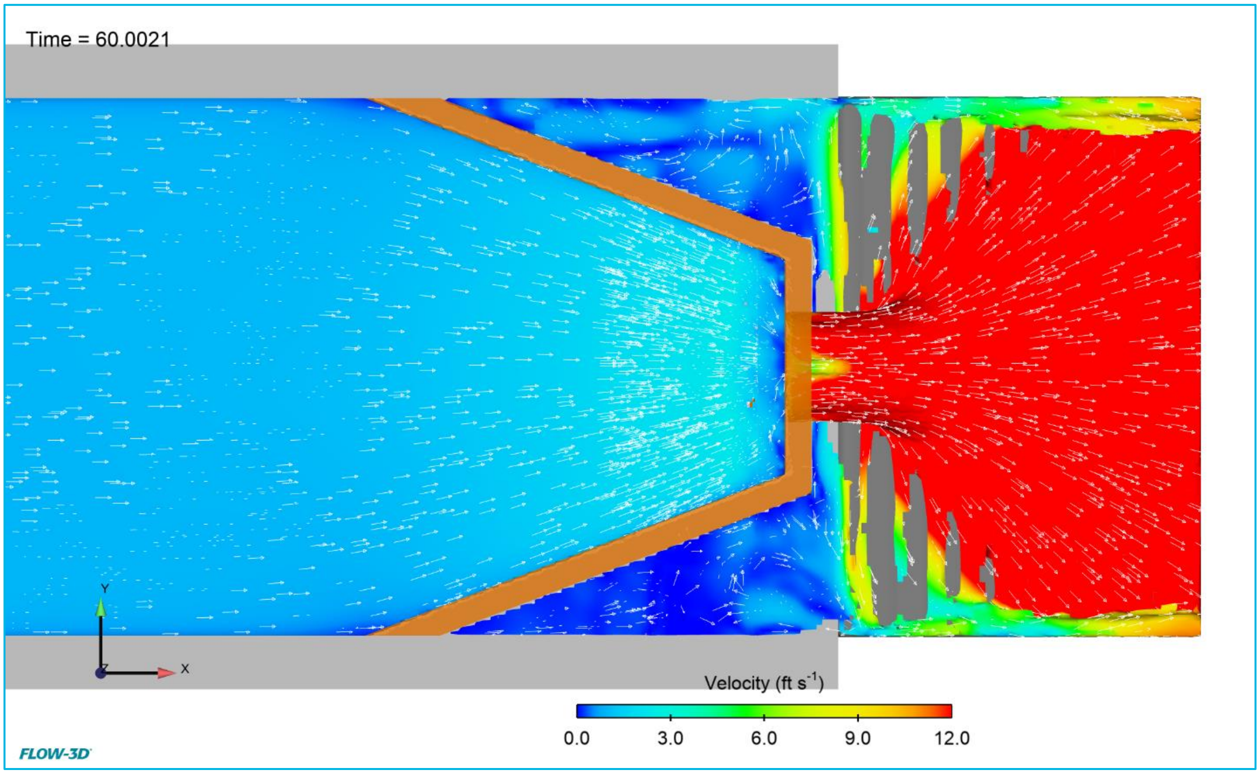

Figure 4-8. Plan View of Simulated Flow Velocity and Vectors for 48-in Inlet with Grate at 150 cfs

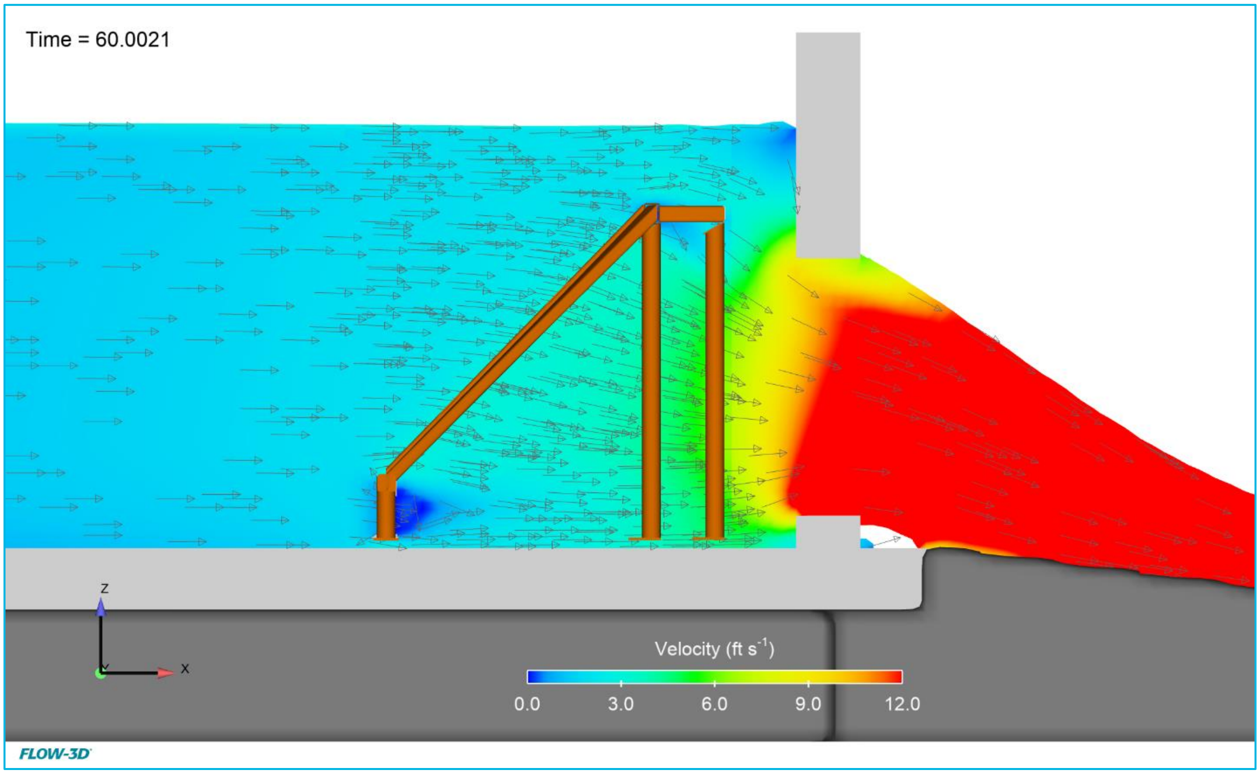

Figure 4-9. Profile View of Simulated Flow Velocity and Vectors along Inlet Centerline for 48-in Inlet with Grate at 150 cfs

4.4 30-in Storm Drain Inlet with Grate at 25 cfs

This scenario simulates a steady-state flow of 25 cfs with the proposed MHFD grate installed. Figure 4-10 and Figure 4-11 are 3D view and plan view of the simulated surface flow velocity and vectors, respectively. Figure 4-12 is a profile view of the velocity and vectors along the centerline of the inlet.

At this flow, the modeling shows that the inlet remains partially full, with the water level in the approach channel increased by 0.01 ft from the non-grate scenario. The approach velocity for the grate itself is generally less than 3 ft/s.

The total net force acting on the grates, including pressure and shear, was simulated to be about 94 lbs.

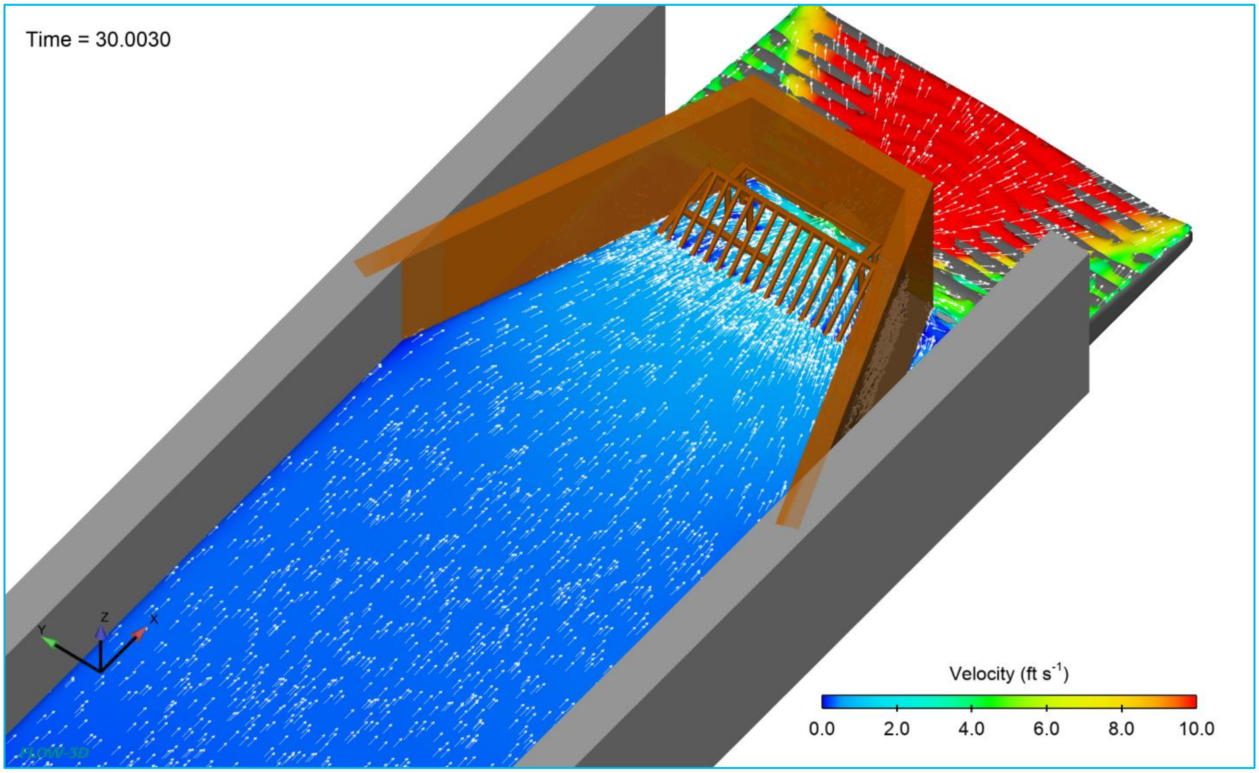

Figure 4-10. 3D View of Simulated Flow Velocity and Vectors for 30-in Inlet with Grate at 25 cfs

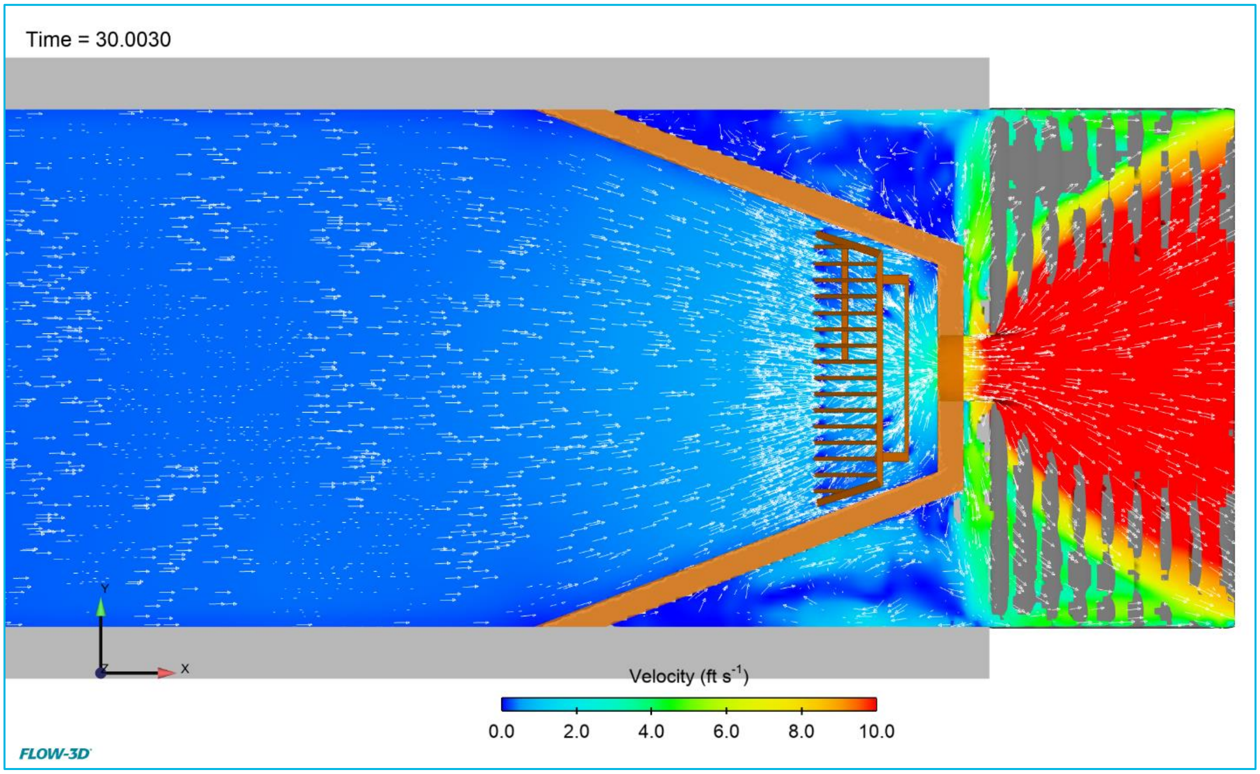

Figure 4-11. Plan View of Simulated Flow Velocity and Vectors for 30-in Inlet with Grate at 25 cfs

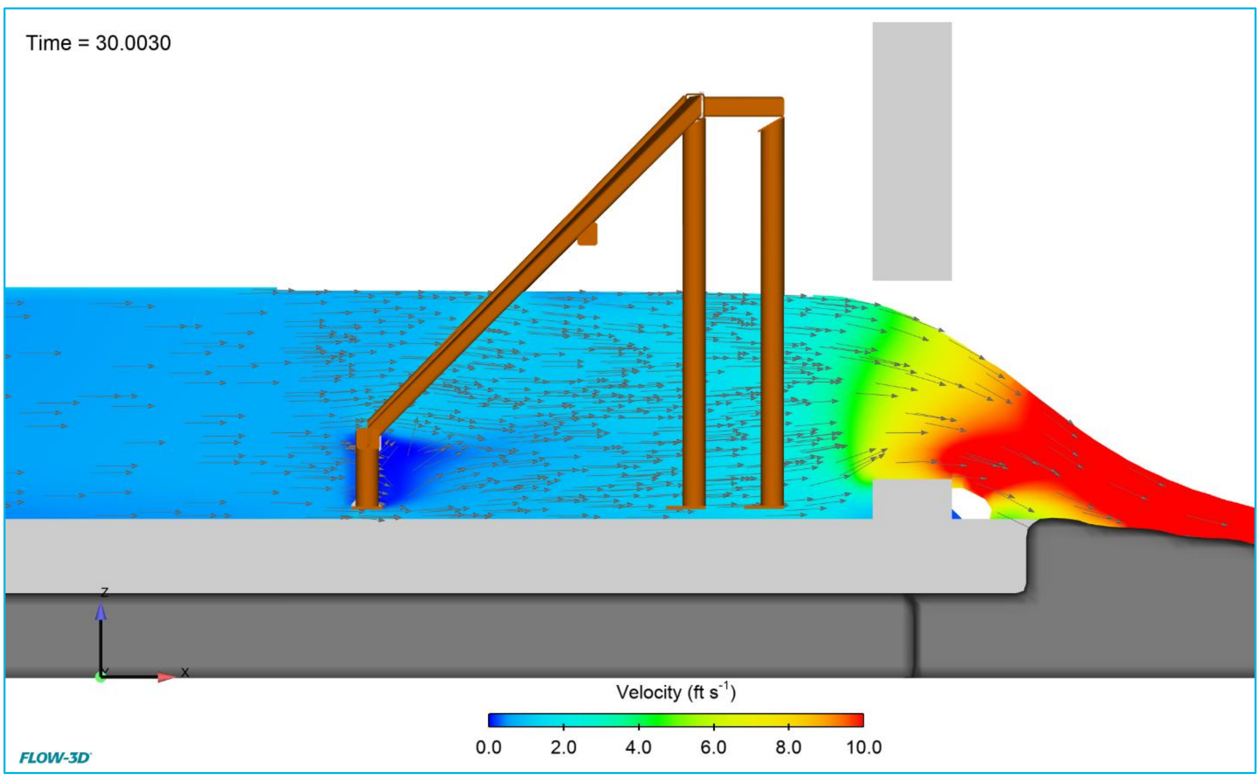

Figure 4-12. Profile View of Simulated Flow Velocity and Vectors along Inlet Centerline for 30-in Inlet with Grate at 25 cfs

4.5 30-in Storm Drain Inlet with Grate at 40 cfs

This scenario simulates a steady-state flow of 40 cfs with the proposed MHFD grate installed. Figure 4-13 and Figure 4-14 are 3D view and plan view of the simulated surface flow velocity and vectors, respectively. Figure 4-15 is a profile view of the velocity and vectors along the centerline of the inlet.

At this flow, the modeling shows that the inlet remains completely submerged with the water level in the approach channel increased by 0.01 ft from the non-grate scenario. The approach velocity for the grate itself is generally less than 3 ft/s.

The total net force acting on the grates, including pressure and shear, was simulated to be about 130 lbs.

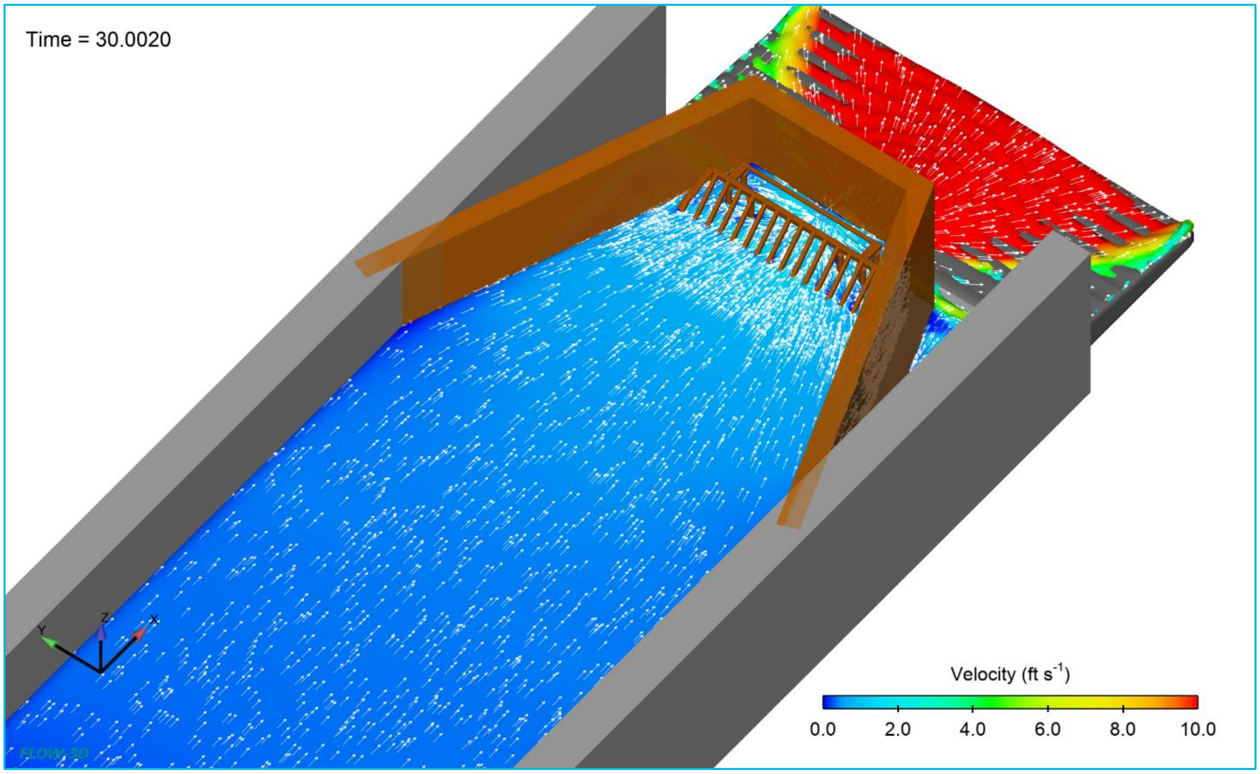

Figure 4-13. 3D View of Simulated Flow Velocity and Vectors for 30-in Inlet with Grate at 40 cfs

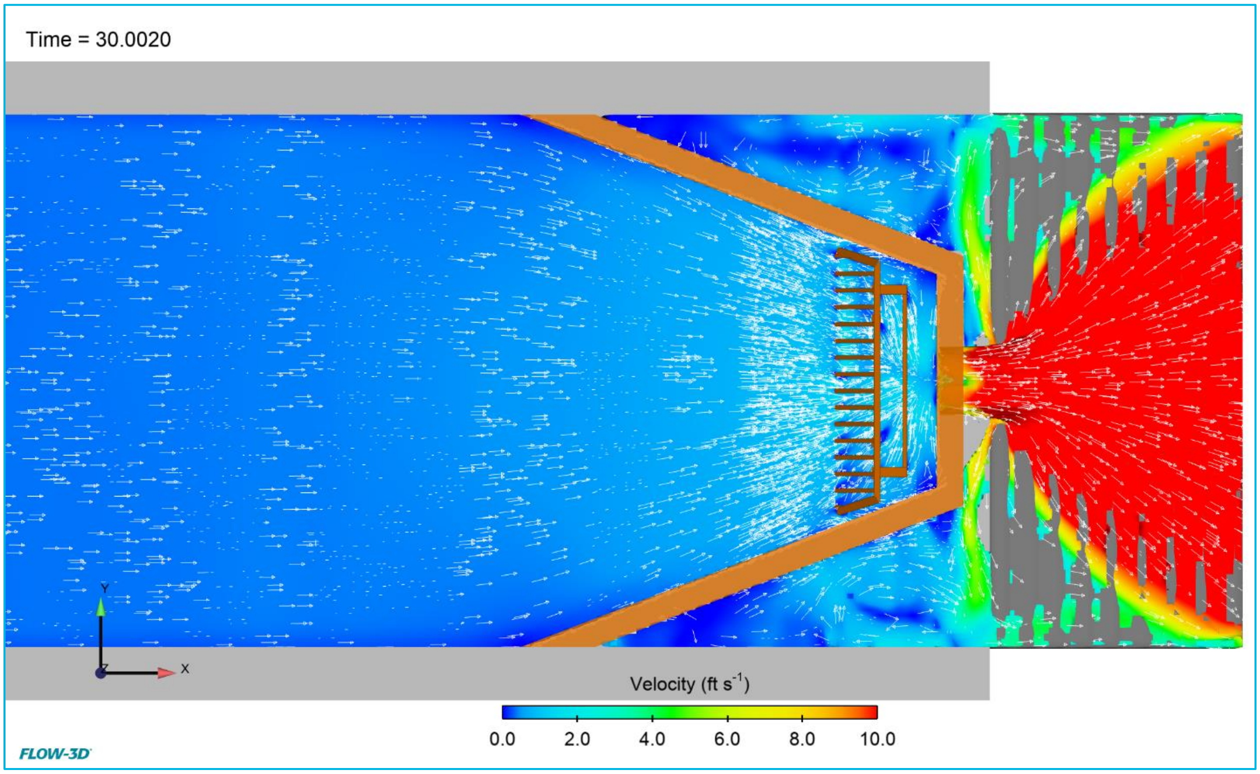

Figure 4-14. Plan View of Simulated Flow Velocity and Vectors for 30-in Inlet with Grate at 40 cfs

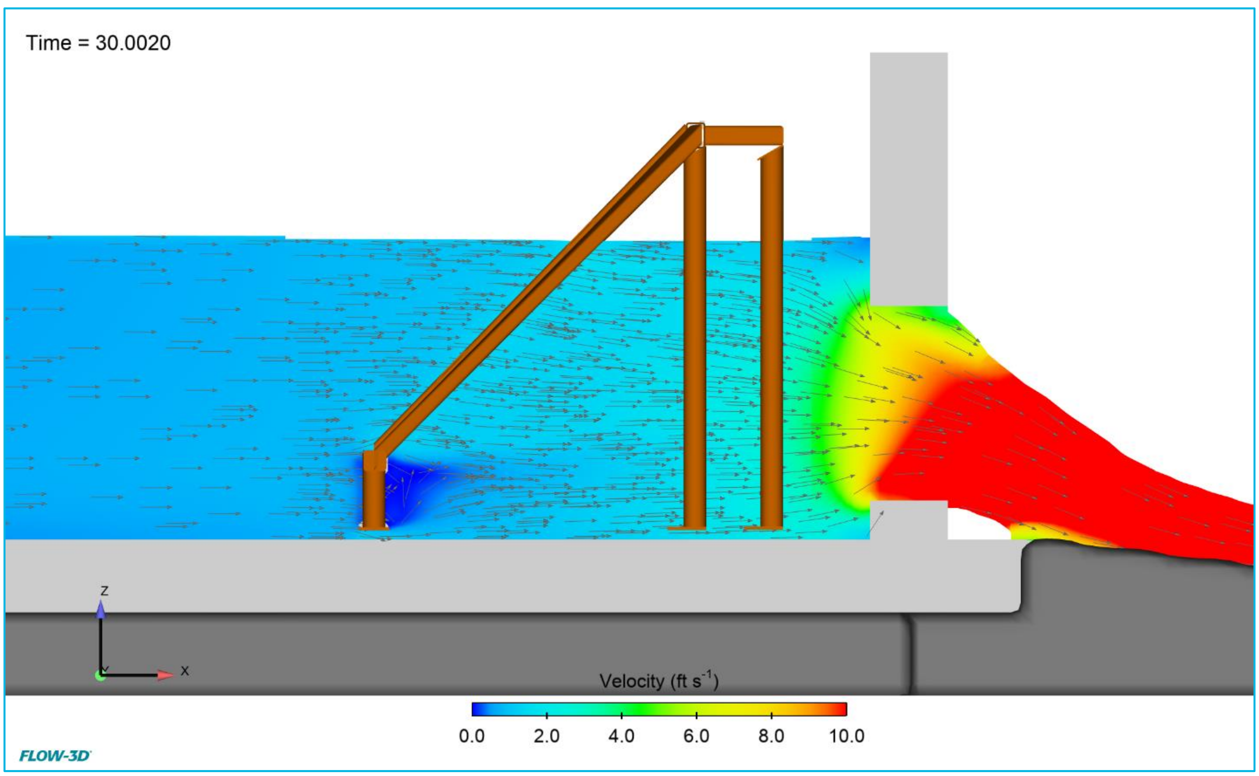

Figure 4-15. Profile View of Simulated Flow Velocity and Vectors along Inlet Centerline for 30-in Inlet with Grate at 40 cfs

4.6 30-in Storm Drain Inlet with Grate at 50 cfs

This scenario simulates a steady-state flow of 50 cfs with the proposed MHFD grate installed. Figure 4-16 and Figure 4-17 are 3D view and plan view of the simulated surface flow velocity and vectors, respectively. Figure 4-18 is a profile view of the velocity and vectors along the centerline of the inlet.

At this flow, the modeling shows that the inlet remains completely submerged with the water level in the approach channel increased by 0.01 ft from the non-grate scenario. The approach velocity for the grate itself is generally less than 3 ft/s.

The total net force acting on the grates, including pressure and shear, was simulated to be about 145 lbs.

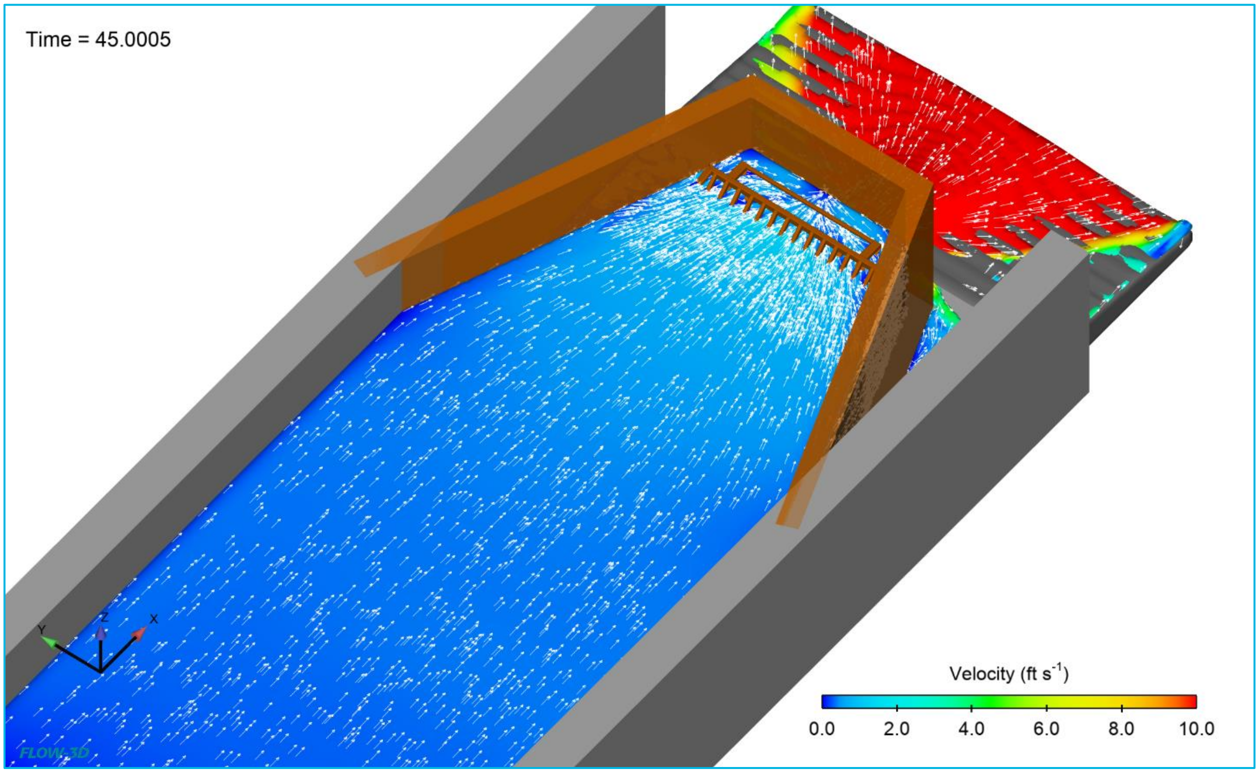

Figure 4-16. 3D View of Simulated Flow Velocity and Vectors for 30-in Inlet with Grate at 50 cfs

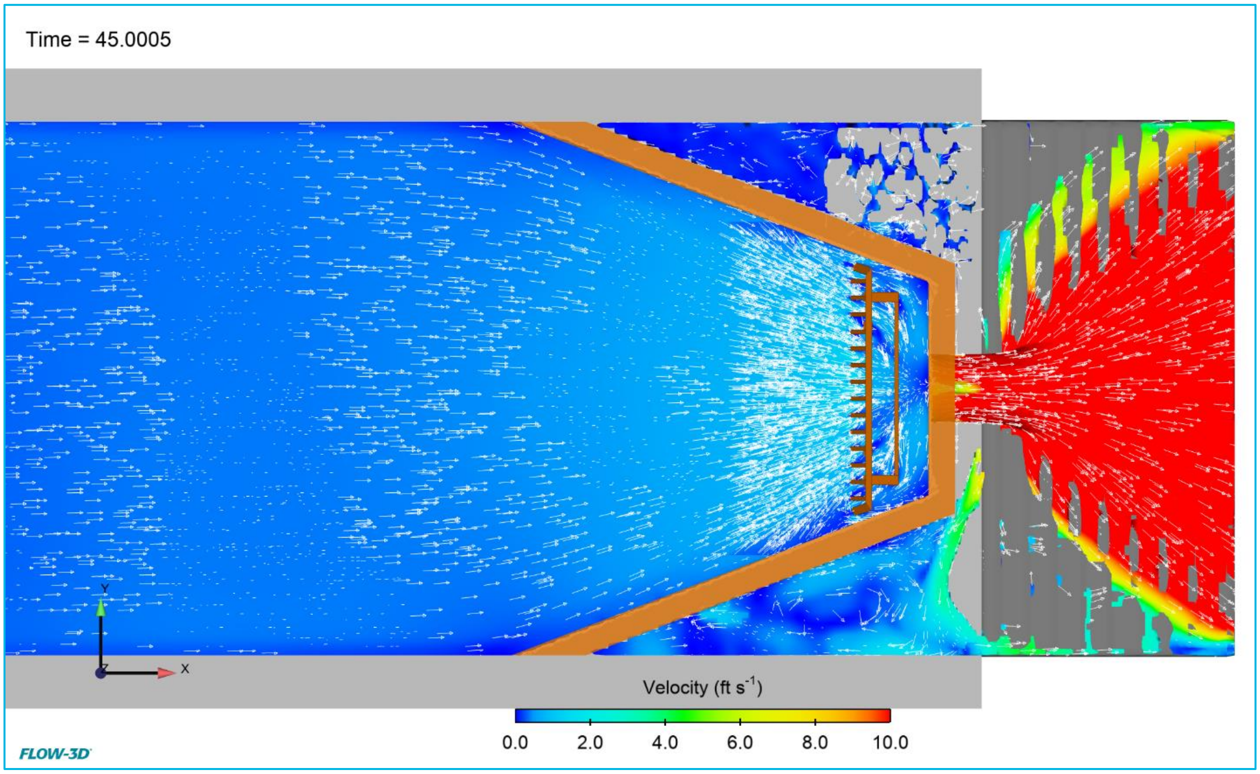

Figure 4-17. Plan View of Simulated Flow Velocity and Vectors for 30-in Inlet with Grate at 50 cfs

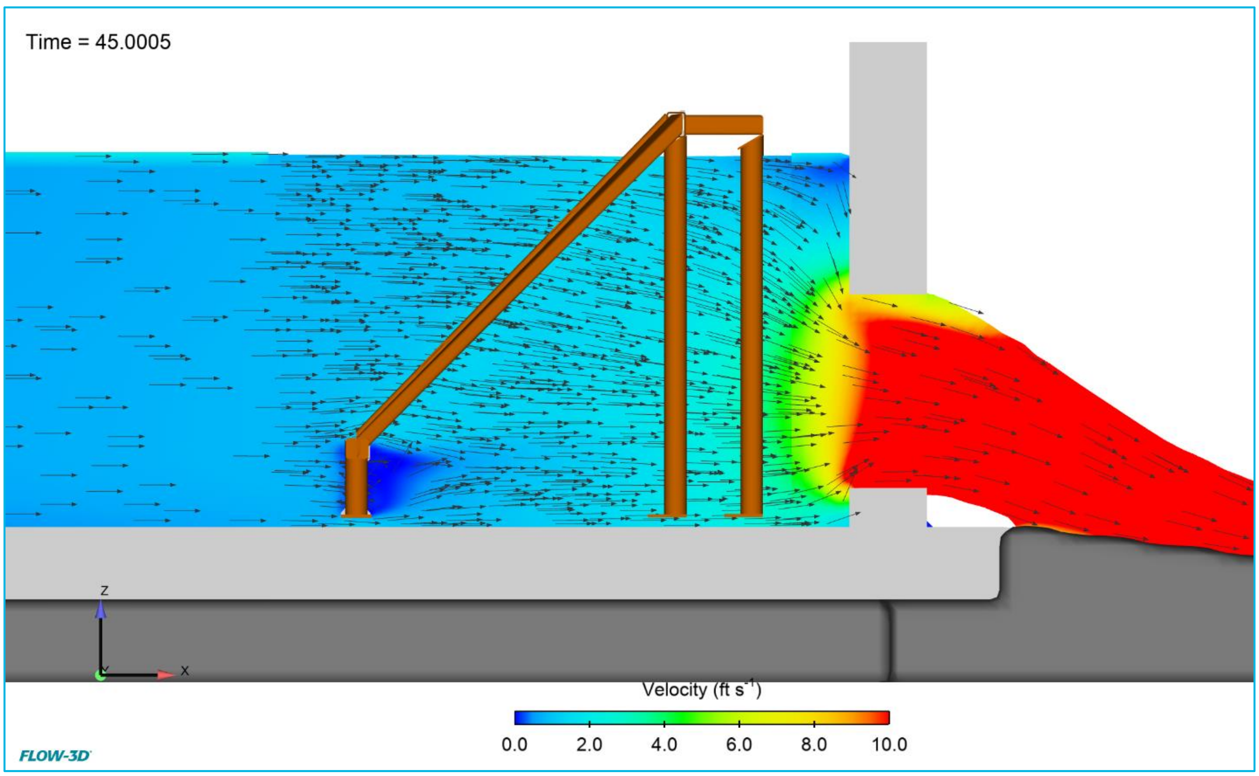

Figure 4-18. Profile View of Simulated Flow Velocity and Vectors along Inlet Centerline for 30-in Inlet with Grate at 50 cfs

5. CFD Model Results with Falling Objects with an Object Against the Grate

With the earlier CFD modeling results completed to help design the MHFD inclined grate, subsequent CFD modeling was focused on estimating the dynamic forces acting on an object that has fallen on the grate. The modeling was also used to estimate the dynamic forces acting on an object that stands immediately at the entrance of the storm drain inlet without a grate for small size storm drain inlets such as the 18-in and 12-in storm drain inlets. A range of CFD modeling was conducted for this study summarized as follows:

- 60-in Storm drain inlet
  - Vertical Grate
  - MHFD Grate
  - Flared Entrance and grate
- 48-in Storm drain inlet
  - Vertical Grate
  - MHFD Grate
  - Flared Entrance and grate
- 30-in Storm drain inlet
  - Vertical Grate
  - MHFD Grate
  - Flared Entrance and grate
- 24-in Storm drain inlet
  - Flared Entrance and grate
- 18-in Storm drain inlet
  - MHFD Grate
  - Flared Entrance and grate
  - No Grate
- 12-in Storm drain inlet
  - MHFD Grate
  - Flared Entrance and Grate
  - No grate

For this CFD modeling, an adult size body dummy or a child size body dummy was used as the object that had fallen against the grate. The adult body dummy was used for the 30-in to 60-in storm drain inlet modeling while the child body dummy was used for the modeling of the smaller storm drain inlet sizes (12 in and 18 in).

5.1 Grate Type

5.1.1 Vertical Grate

A vertical rectangular grate of various dimensions was assumed to fit the size of the storm drain inlet, as it is illustrated on Figure 5-1. The grate is placed typically at a distance from the storm drain inlet. In this study, two positions were investigated, one at zero distance to the storm drain inlet and another at 18-in upstream of the storm drain inlet.

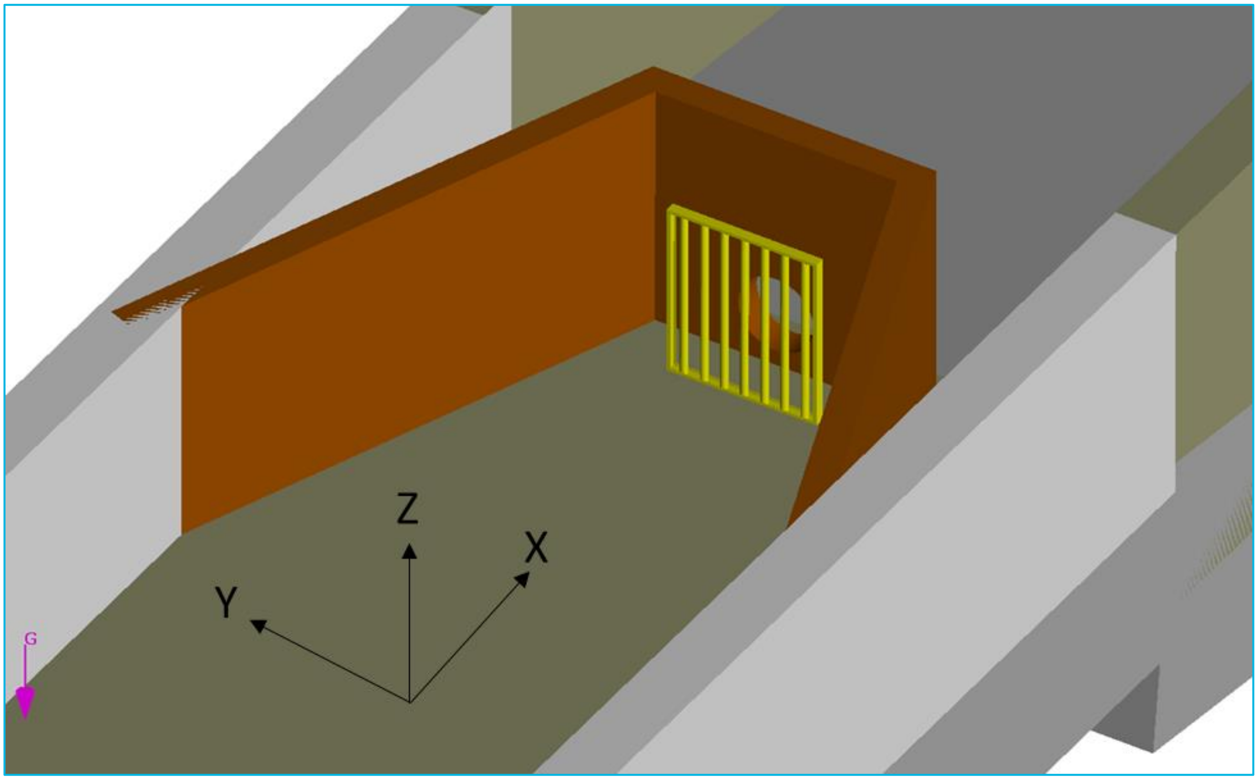

Figure 5-1. 3D Illustration of Vertical Grate at 18-in Away from the Storm drain inlet

5.1.2 MHFD Grate

The MHFD grate is an inclined grate at a 1:1 slope that is set immediately upstream of the storm drain inlet, as illustrated in Figure 5-2 for a MHFD inclined grate placed on a 60-in storm drain inlet. The size of the grate varies with the storm drain inlet size. For this modeling, a 12-in long square support is assumed to be located between the inclined section of the grate and the entrance to the storm drain inlet. Note that no square support was used in the modeling described in Section 4. The square support was assumed to be used for the grates designed for 48-in and 60-in culverts only. For 30-in and smaller culverts, the square support is assumed to be absent, leaving the 1:1 inclined grate to sit directly at the culvert entrance, as illustrated in Figure 5-3.

The object that has fallen against the grate (body dummy) was assumed to lay on the inclined grate with its toes touching the ground as shown in Figure 5-3.

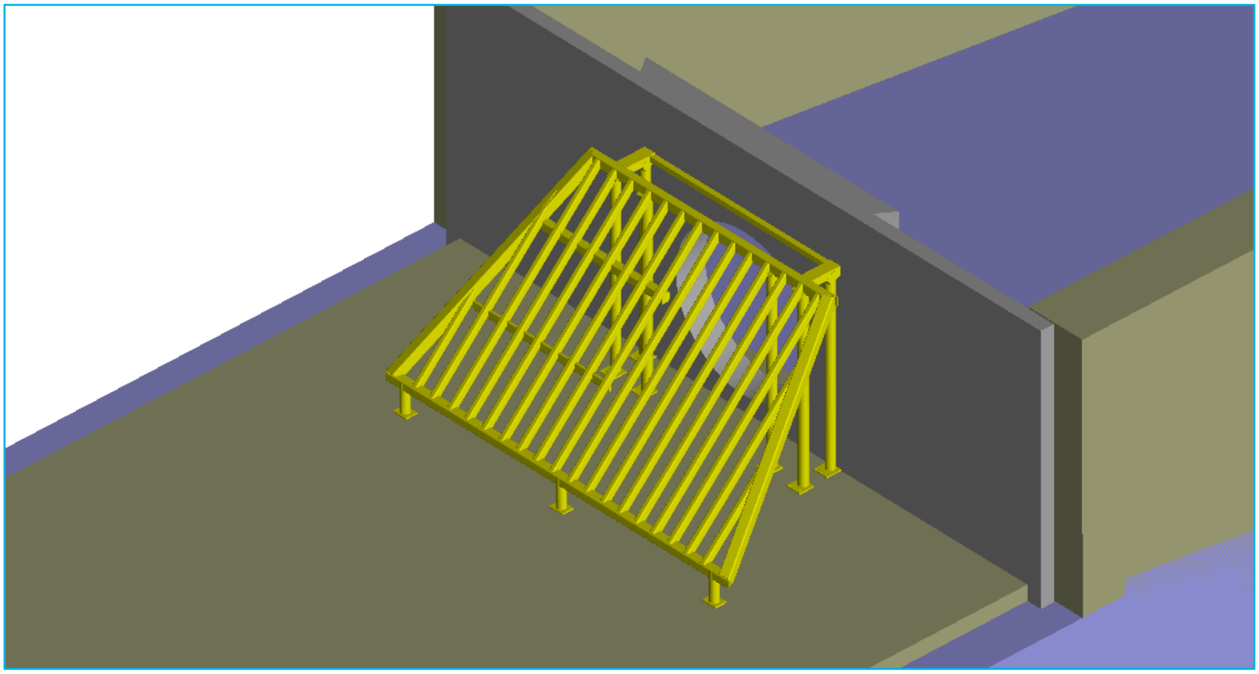

Figure 5-2. 3D Illustration of MHFD Grate (60-In Culvert)

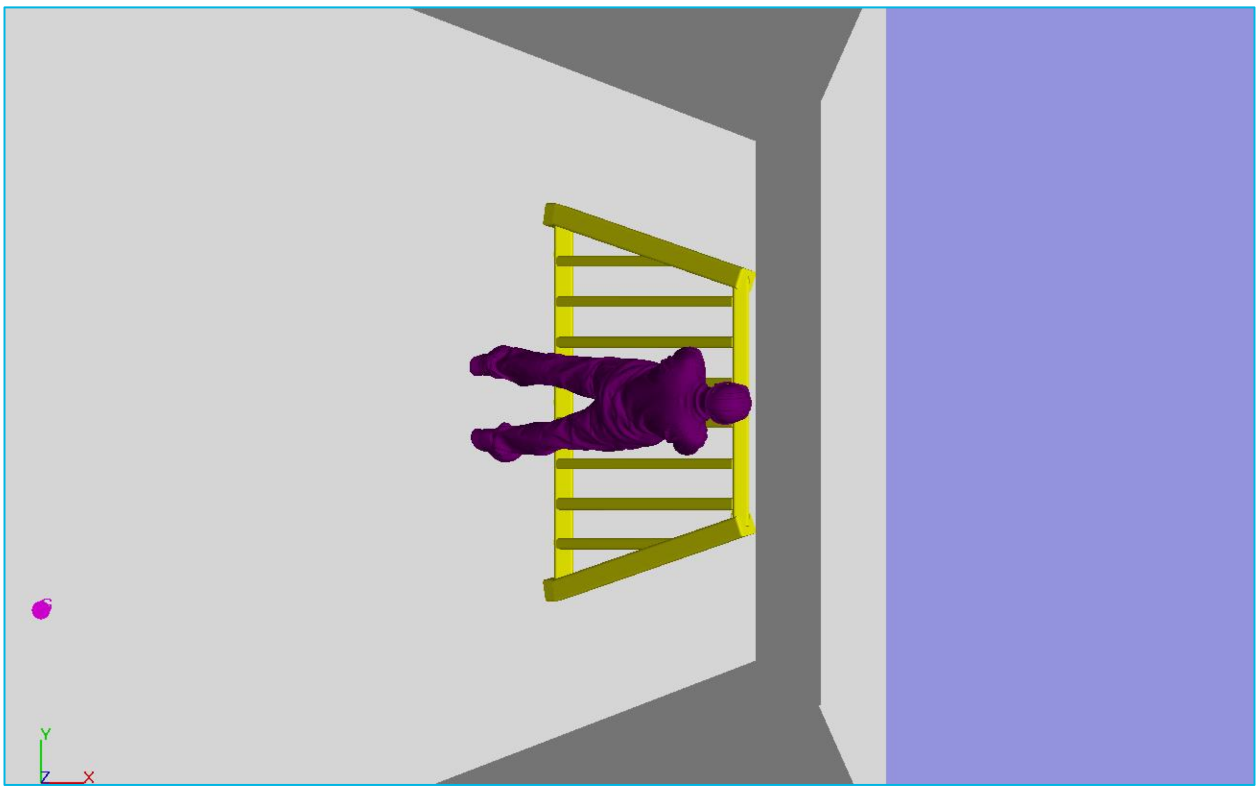

Figure 5-3. 3D Illustration of MHFD Grate (30-in Culvert)

5.1.3 Flared Storm Drain Inlet and Grate

The flared grate is an inclined grate at various slopes for different storm drain inlet sizes that has a flared entrance to the storm drain inlet. The size of the grate varies with the storm drain inlet size. For this modeling, the object that has fallen against the grate (body dummy) was assumed to fall onto the inclined grate. The dimensions modeled for each drain inlet size in this study are shown in Figure 5-4 for the 60-inch culverts, Figure 5-5 for the 48-in culverts, Figure 5-6 for the 30-in culverts, Figure 5-7 for the 24-in culverts, Figure 5-8 for the 18-in culverts, and Figure 5-9 for the 12-in culverts.

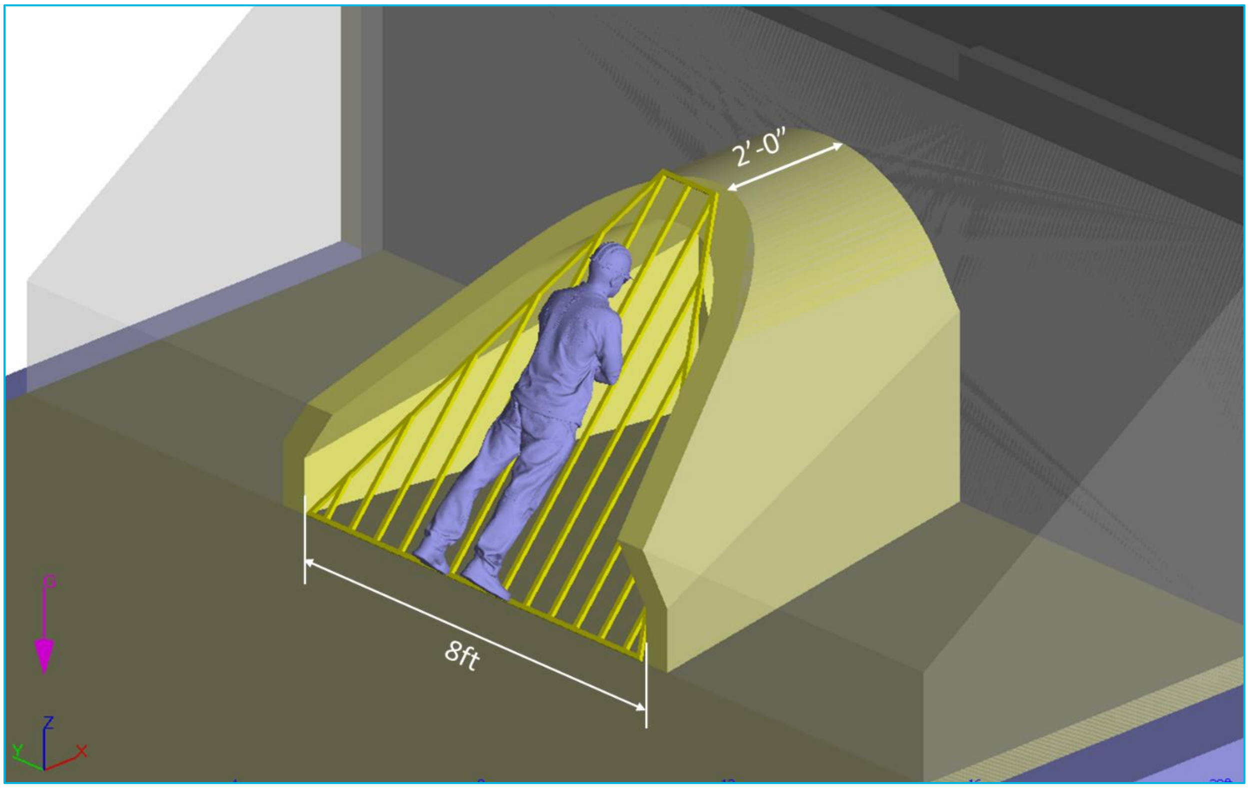

Figure 5-4. 3D Illustration of Flared Entrance Grate for 60-In Culverts

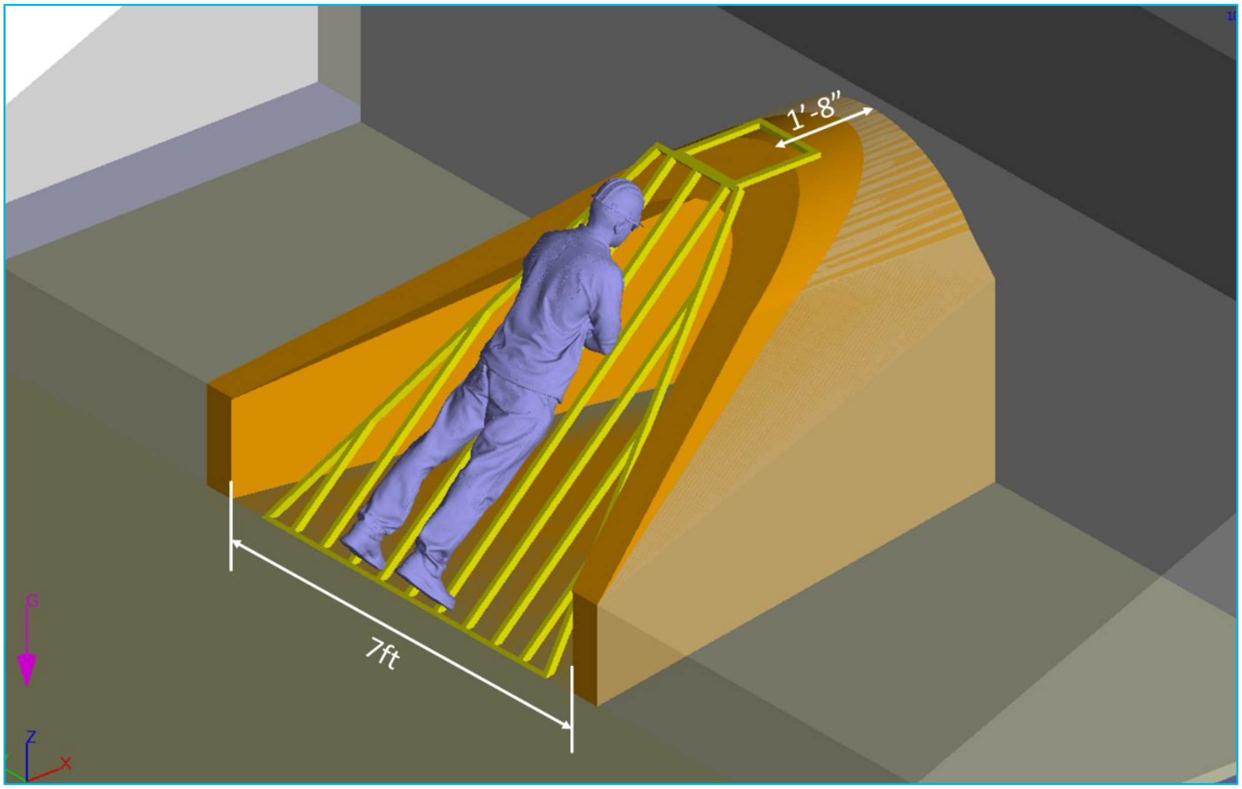

Figure 5-5. 3D Illustration of Flared Entrance Grate for 48-In Culverts

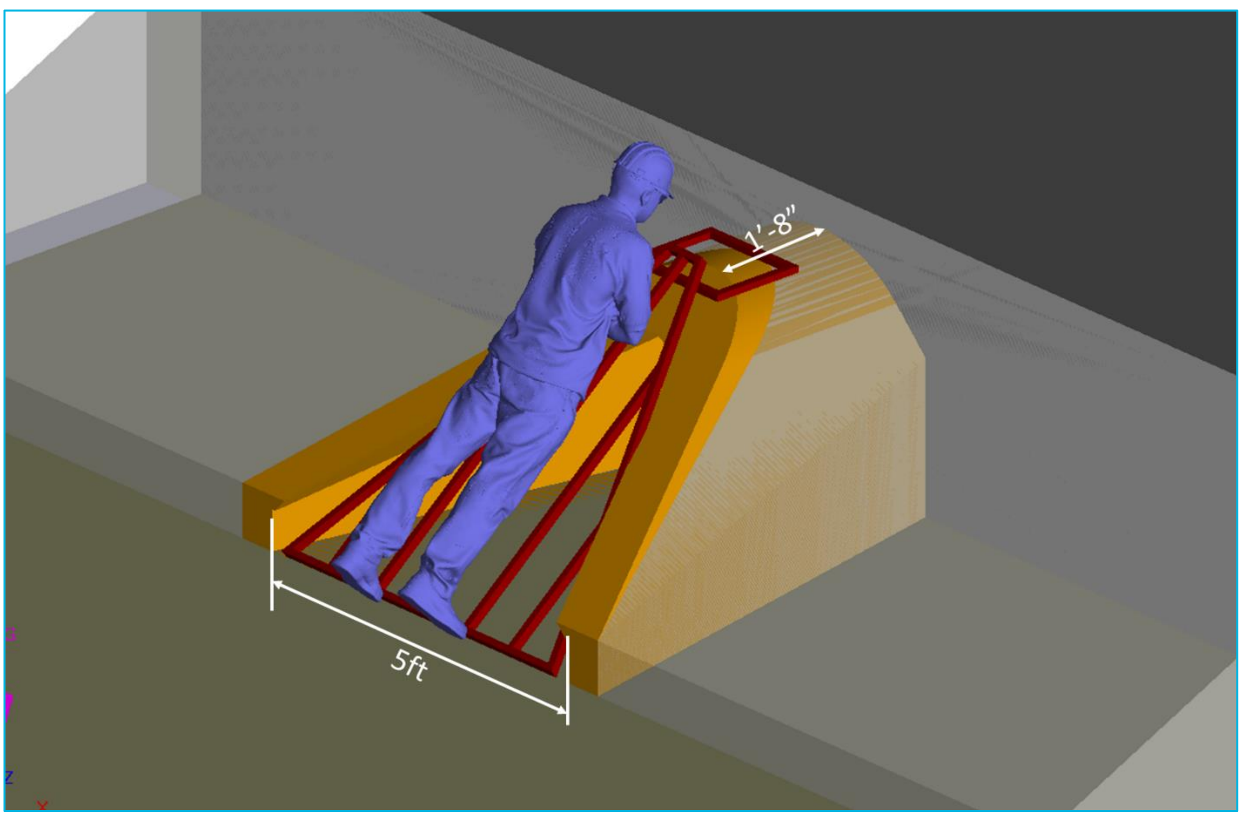

Figure 5-6. 3D Illustration of Flared Entrance Grate for 30-In Culverts

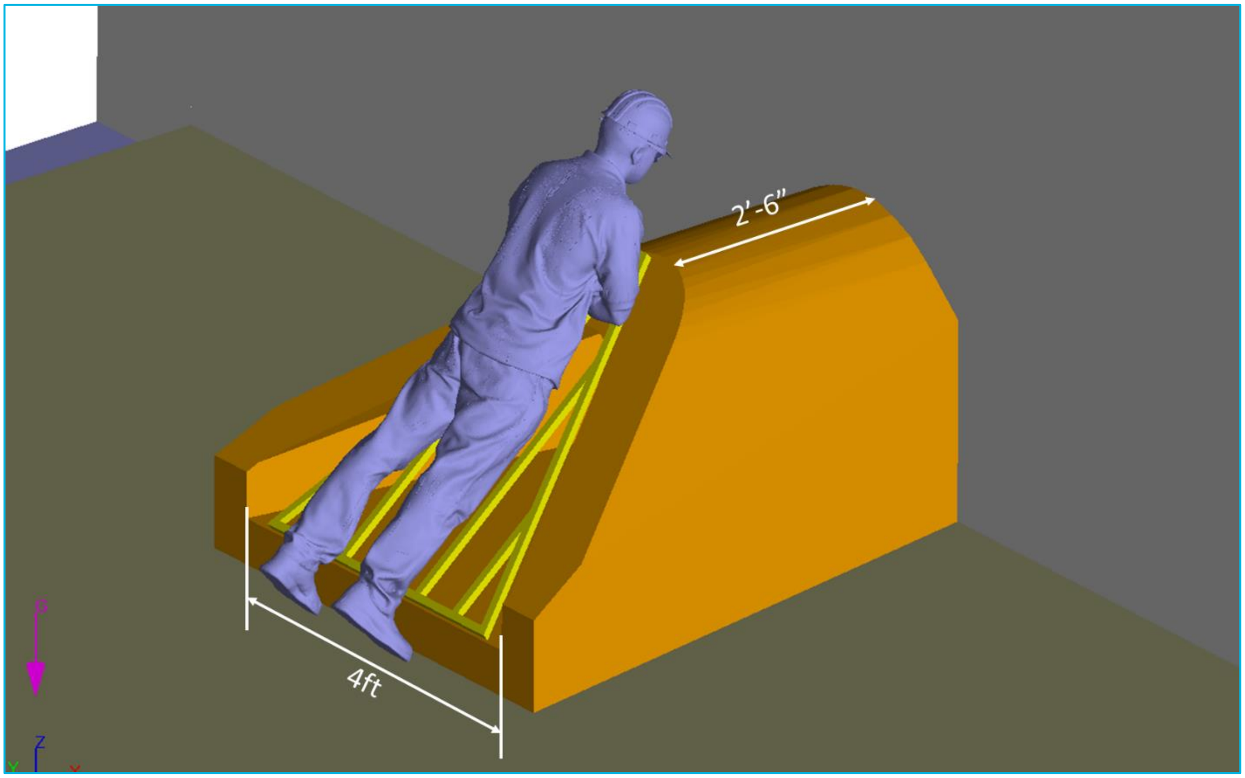

Figure 5-7. 3D Illustration of Flared Entrance Grate for 24-In Culverts

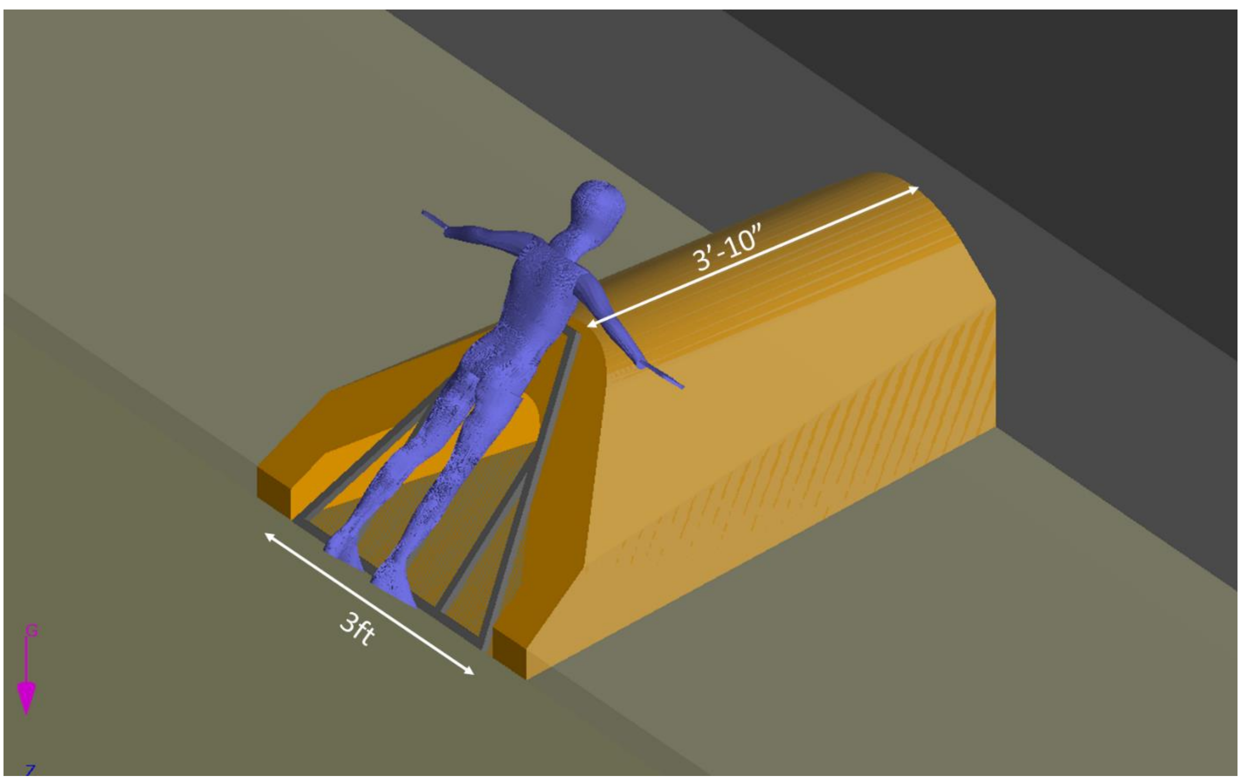

Figure 5-8. 3D Illustration of Flared Entrance Grate for 18-In Culverts

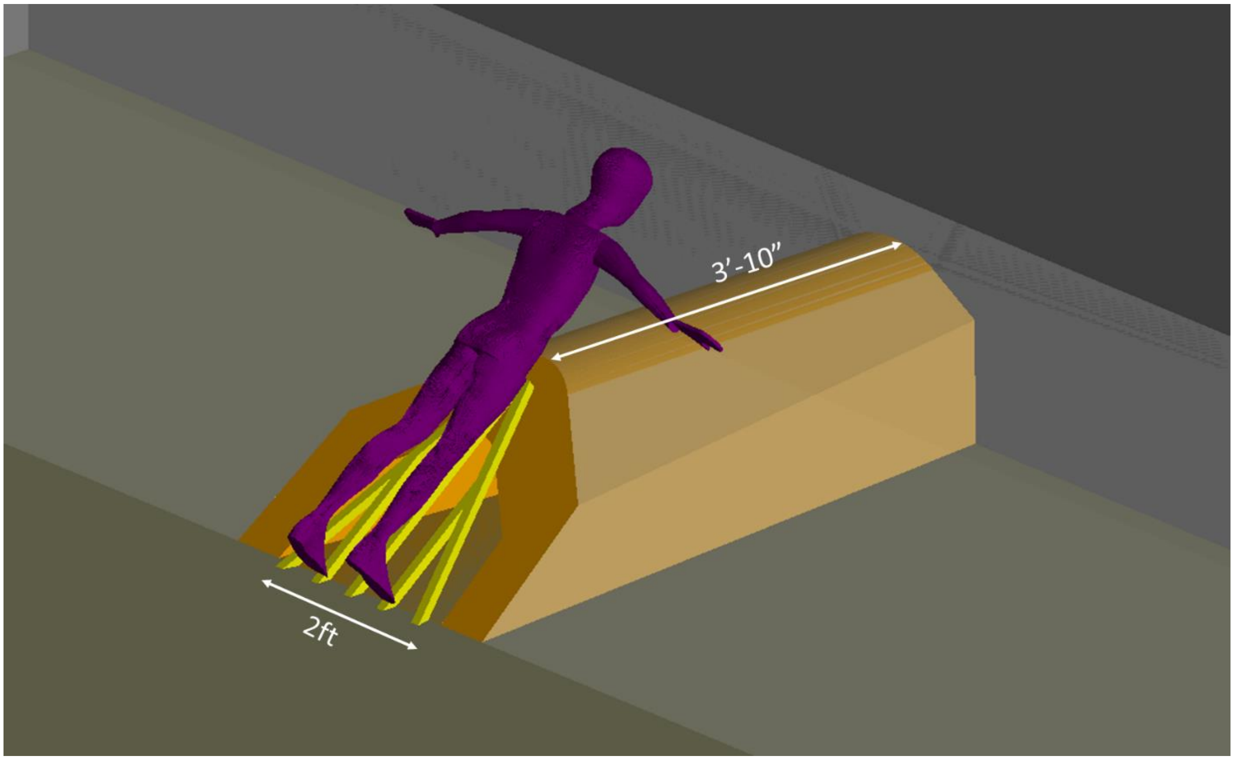

Figure 5-9. 3D Illustration of Flared Entrance Grate for 12-In Culverts

5.2 Object Laying Against the Grate

Three-dimensional views of the body dummy used in the CFD model are shown in Figure 5-10 for both the adult size body and child size body. The adult size body has a height of 6-ft, representing the height of an average adult male, while the child size body has a height of 50-in, or 4 ft 2 in, representing the height of an average 10-year-old child of. In the CFD model, the body dummy would either be placed vertically against a vertical grate or placed directly on the inclined grate surface for a sloping grate, as illustrated in Figure 5-11 for the 48-in storm drain flared inlet grate scenario. The adult body dummy was used for storm drain inlet size of 30-in or greater, and the child body dummy was used for storm drain inlet sizes of 18-in and 12-in.

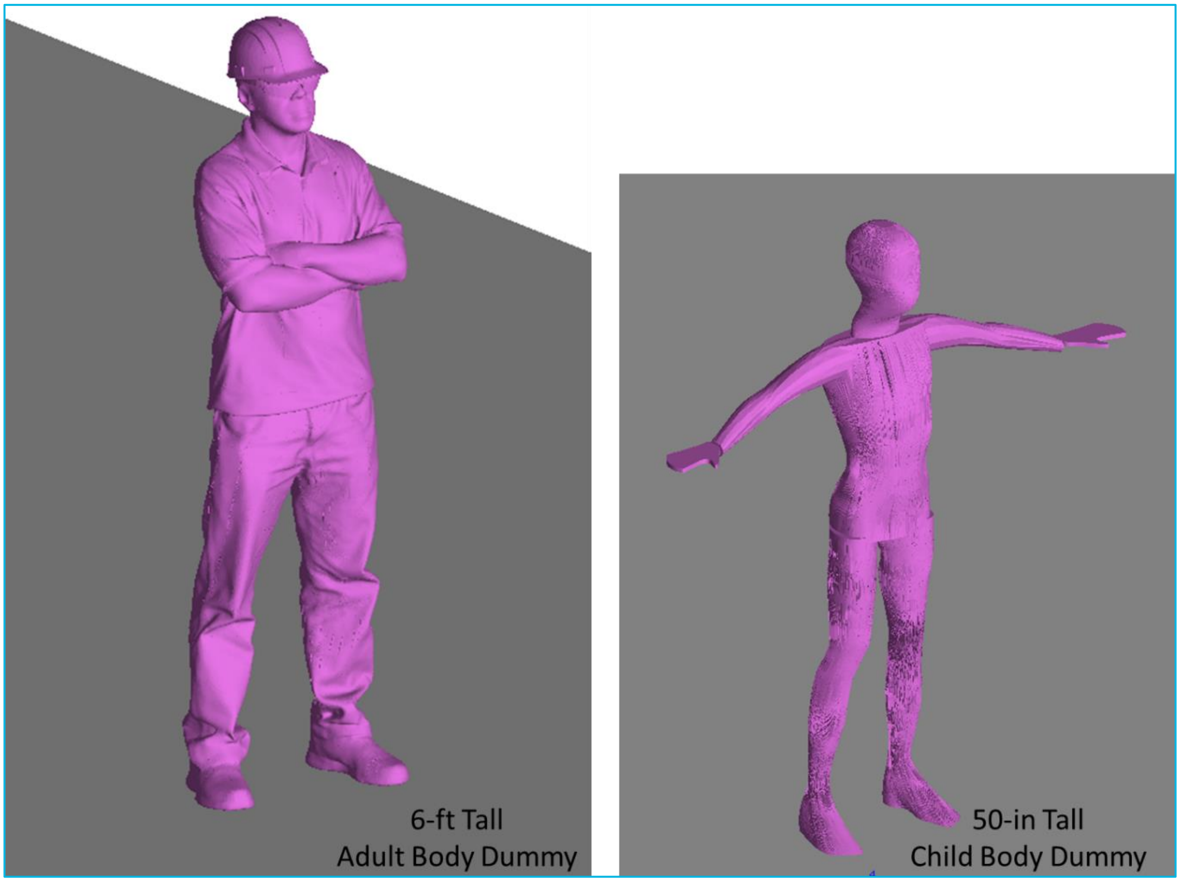

Figure 5-10. 3D View of Body Dummies used in CFD Modeling

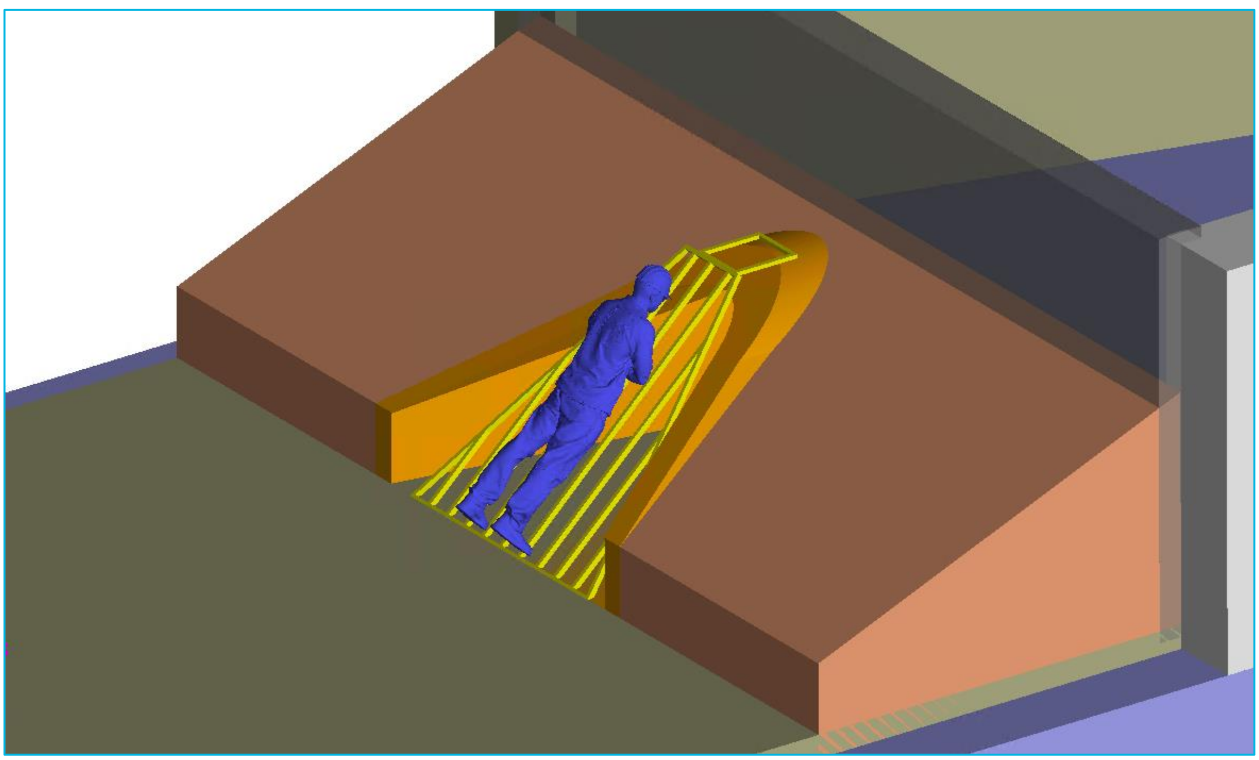

Figure 5-11. 3D View of Body Dummy Position for 48-In Flared Entrance Grate

5.3 Results of MHFD Grates

Forces acting on the body dummy, in terms of pressure and shear, were calculated automatically in the CFD models. All forces are reported by the model in the three-major coordinate directions. For this analysis, the results in the x-direction (flow direction) and y-direction are used to assess the forces that could be detrimental to the falling body dummy on the grate. The Z-component (vertical) force was not considered in this analysis mainly because the vertical component represents a buoyant force that is highly variable based on the objects that could fall against the grate. Buoyancy works in the positive (up) z-direction and would help lift an object off the grate. Ignoring the z-component results in a conservative estimate of forces acting on an object against the grate.

Results of the horizontal components of the total forces acting on the body dummy are summarized in Table 5-1 to Table 5-5 below.

Table 5-1. Simulated Horizontal Forces on Body Dummy on MHFD Grate of 60-in Storm Drain Inlet

60-in Storm drain inlet		**Simulated Forces (lbf)**								
U/S Flow Depth	**(ft)**	**4**			**5.2**			**6.5**		
Flow Rate	**(cfs)**	**87**			**144**			**193**		
		Upper Body	**Lower Body**	**Total**	**Upper Body**	**Lower Body**	**Total**	**Upper Body**	**Lower Body**	**Total**
Pressure-X	(lbf)	1.2	20.9	22.1	0.6	38.7	39.3	-1.6	59.5	57.9
Shear Force-X	(lbf)	0.2	0.4	0.6	0.6	0.6	1.2	0.7	0.6	1.3
Total Force-X		1.4	21.2	22.6	1.2	39.2	40.4	-0.9	60.1	59.2
Pressure-Y	(lbf)	0.5	1.8	2.3	4.8	2.9	7.7	1.8	3.5	5.3
Shear Force-Y	(lbf)	-0.1	0	-0.1	-0.1	0	-0.1	-0.1	0	-0.1
Total Force-Y	(lbf)	0.4	1.8	2.2	4.7	2.9	7.6	1.7	3.5	5.2

Table 5-2. Simulated Horizontal Forces on Body Dummy on MHFD Grate of 48-in Storm Drain Inlet

48-in Storm drain inlet		**Simulated Forces (lbf)**											
U/S Flow Depth	**(ft)**	**4.4**			**5.1**			**6.4**			**7.7**		
Flow Rate	**(cfs)**	**90**			**115**			**150**			**175**		
		Upper Body	**Lower Body**	**Total**	**Upper Body**	**Lower Body**	**Total**	**Upper Body**	**Lower Body**	**Total**	**Upper Body**	**Lower Body**	**Total**
Pressure-X	(lbf)	-1.1	35.8	34.7	-6.5	47.5	41.1	-16.9	68.7	51.8	-21.4	85.9	64.5
Shear Force-X	(lbf)	0.3	0.4	0.7	0.5	0.5	1.0	0.5	0.5	1.0	0.5	0.5	1.0
Total Force-X		-0.8	36.2	35.4	-5.9	48.0	42.1	-16.3	69.2	52.9	-20.9	86.5	65.6
Pressure-Y	(lbf)	-1.2	2.2	1	-0.6	2.5	1.9	-1.4	2.8	1.4	-2	3.1	1.1
Shear Force-Y	(lbf)	0	0	0	0.0	0.0	0.0	0	0	0.0	0	0	0.0
Total Force-Y	(lbf)	-1.2	2.2	1	-0.6	2.5	1.9	-1.4	2.8	1.4	-2	3.1	1.1

Table 5-3. Simulated Horizontal Forces on Body Dummy on MHFD Grate of 30-in Storm Drain Inlet

30-in Storm drain inlet		Simulated Forces (lbf)											
U/S Flow Depth	(ft)	3			4			5.5			5.5*		
Flow Rate	(cfs)	27.1			40.5			54.9			54.9		
		Upper Body	Lower Body	Total	Upper Body	Lower Body	Total	Upper Body	Lower Body	Total	Upper Body	Lower Body	Total
Pressure-X	(lbf)	0.1	10	10.1	5.4	21.2	26.6	9.6	40.1	49.7	-9.5	27	17.5
Shear Force-X	(lbf)	0	0.2	0.2	0.2	0.3	0.5	0.3	0.4	0.7	0.2	0.2	0.4
Total Force-X		0.1	10.2	10.3	5.6	21.5	27.1	9.8	40.4	50.2	-9.4	27.1	17.7
Pressure-Y	(lbf)	0.6	1.1	1.7	2.2	1.5	3.7	1.1	1.4	2.5	-0.1	0.9	0.8
Shear Force-Y	(lbf)	0	0	0	0	0	0	0	0	0	0	0	0
Total Force-Y	(lbf)	0.6	1.1	1.7	2.2	1.5	3.7	1.1	1.4	2.5	-0.1	0.9	0.8

*) This run has the back of the grate 1 ft away from the storm drain inlet entrance.

Table 5-4. Simulated Horizontal Forces on Body Dummy on MHFD Grate of 18-in Storm Drain Inlet

18-in Storm drain inlet		Simulated Forces (lbf)								
U/S Flow Depth	(ft)	3			4			5		
Flow Rate	(cfs)	13.3			17.3			20.5		
		Upper Body	Lower Body	Total	Upper Body	Lower Body	Total	Upper Body	Lower Body	Total
Pressure-X	(lbf)	0	3.3	3.3	0	5.4	5.4	0	7.7	7.7
Shear Force-X	(lbf)	0	0.1	0.1	0	0.1	0.1	0	0.1	0.1
Total Force-X		0	3.4	3.4	0	5.5	5.5	0	7.8	7.8
Pressure-Y	(lbf)	0	-0.1	-0.1	0	-0.1	-0.1	0	-0.1	-0.1
Shear Force-Y	(lbf)	0	0	0	0	0	0	0	0	0
Total Force-Y	(lbf)	0	-0.1	-0.1	0	-0.1	-0.1	0	-0.1	-0.1

Table 5-5. Simulated Horizontal Forces on Body Dummy on MHFD Grate of 12-in Storm Drain Inlet

12-in Storm drain inlet		**Simulated Forces (lbf)**								
U/S Flow Depth	**(ft)**	**3**			**4**			**5**		
Flow Rate	**(cfs)**	**6.8**			**8.4**			**10**		
		Upper Body	**Lower Body**	**Total**	**Upper Body**	**Lower Body**	**Total**	**Upper Body**	**Lower Body**	**Total**
Pressure-X	(lbf)	0	1	1	0	1.6	1.6	0	2.2	2.2
Shear Force-X	(lbf)	0	0	0	0	0	0	0	0	0
Total Force-X		0	1	1.0	0	1.6	1.6	0	2.2	2.2
Pressure-Y	(lbf)	0	0	0	0	0	0	0	0	0
Shear Force-Y	(lbf)	0	0	0	0	0	0	0	0	0
Total Force-Y	(lbf)	0	0	0	0	0	0	0	0	0

The CFD modeling indicates that the main force acting on the body dummy is the x-component in the flow direction while the y-component is negligible. Figure 5-12 below illustrates the x-component total force versus the flow discharges as simulated in the CFD models. Overall, the total force in the x-direction is significantly below the threshold of 110 lbf that could lead to an unsafe condition. The 110 lbf was the estimated force when an adult diver started having difficulty moving off the grate. The 110 lbf force was estimated from a physical model study that was conducted in parallel by CSU.

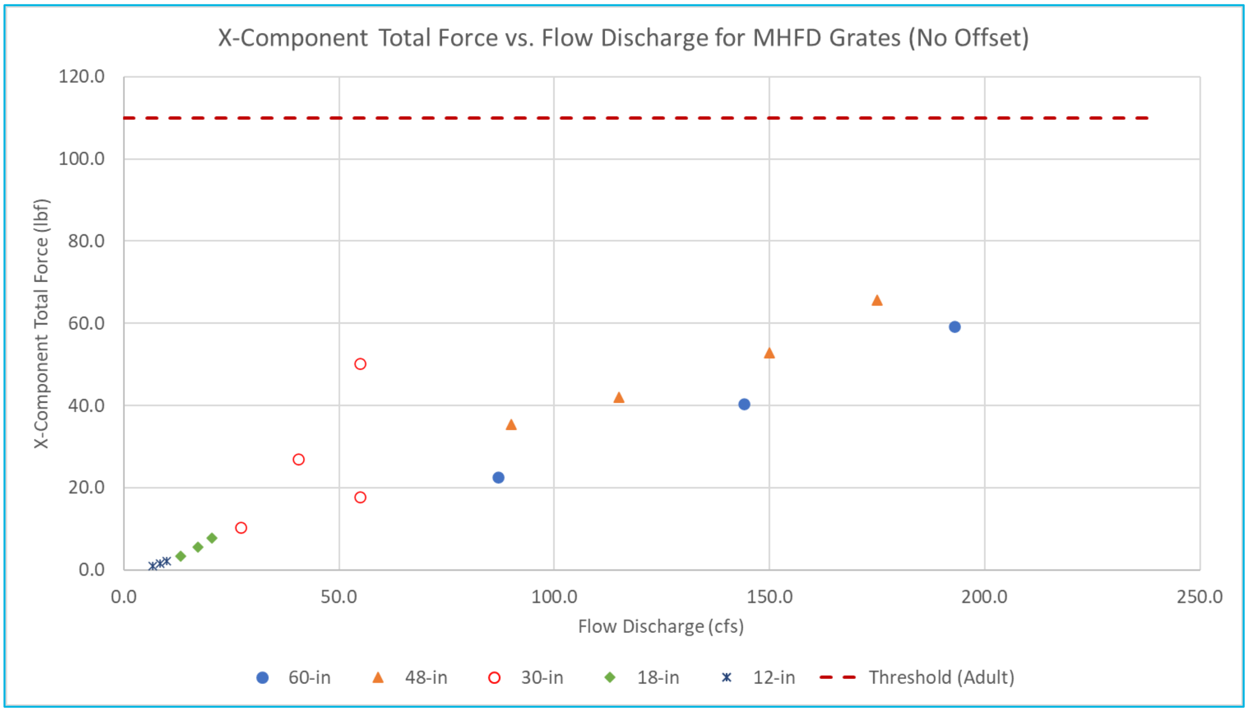

Figure 5-12. Relationship between Total Force and Flow Discharge for MHFD Grates

5.4 Results of Vertical Grates

Vertical grates were modeled at two distances upstream from the storm drain inlet, 18-in and 0-in. The results for the grate placed 0-in from the storm drain inlet are presented in Table 5-6 to Table 5-10 below. The results for the grate placed 18-in from the storm drain inlet are presented in Table 5-11 to Table 5-13.

For the vertical grate, CFD modeling was also conducted for three flow conditions without the body dummy being placed on the grate for the 48-in culvert. The results were used to compared to measured flow velocity from a physical model conducted at Colorado State University. The comparison is presented in Appendix A, which shows good agreement between the CFD and the physical models.

Table 5-6. CFD Simulation Results with Vertical Grate for 60-in Storm Drain Inlet (Grate 0-in Upstream)

60-in Storm drain inlet		**Simulated Forces (lbf)**								
U/S Flow Depth	**(ft)**	**4.5**			**5.6**			**6.9**		
Flow Rate	**(cfs)**	**86**			**129**			**166**		
		Upper Body	**Lower Body**	**Total**	**Upper Body**	**Lower Body**	**Total**	**Upper Body**	**Lower Body**	**Total**
Pressure-X	(lbf)	30.4	214.7	245.1	176	419	595	225.4	465	690.4
Shear Force-X	(lbf)	0.5	2.9	3.4	2	4.7	6.7	3.6	6.7	10.3
Total Force-X		30.8	217.6	248.4	178	423.7	601.7	229	471.7	700.7
Pressure-Y	(lbf)	5.2	31.1	36.3	11.3	17	28.3	17.7	79.7	97.4
Shear Force-Y	(lbf)	0	-0.3	-0.3	0	-0.1	-0.1	-0.3	-0.5	-0.8
Total Force-Y	(lbf)	5.2	30.8	36	11.3	17	28.3	17.5	79.2	96.7

Table 5-7. CFD Simulation Results with Vertical Grate for 48-in Storm Drain Inlet (Grate 0-in Upstream)

48-in Storm drain inlet		**Simulated Forces (lbf)**								
U/S Flow Depth	**(ft)**	**2.2**			**3.1**			**4.1**		
Flow Rate	**(cfs)**	**35**			**60**			**75**		
		Upper Body	**Lower Body**	**Total**	**Upper Body**	**Lower Body**	**Total**	**Upper Body**	**Lower Body**	**Total**
Pressure-X	(lbf)			0			0.0	72.3	339.3	411.6
Shear Force-X	(lbf)			0			0.0	0.8	3.9	4.7
Total Force-X		0	94.5	94.5	18.8	232.2	251.0	73.0	342.8	415.8
Pressure-Y	(lbf)			0			0.0	1.2	56.6	57.8
Shear Force-Y	(lbf)			0			0.0	0.0	-0.5	-0.4
Total Force-Y	(lbf)			0			0.0	1.2	56.1	57.3

Table 5-8. CFD Simulation Results with Vertical Grate for 30-in Storm Drain Inlet (Grate 0-in Upstream)

30-in Storm drain inlet		Simulated Forces (lbf)								
U/S Flow Depth	(ft)	3.4			4.5			5.4		
Flow Rate	(cfs)	30			40			50		
		Upper Body	Lower Body	Total	Upper Body	Lower Body	Total	Upper Body	Lower Body	Total
Pressure-X	(lbf)		244	244		445	445		647.4	647.4
Shear Force-X	(lbf)			0			0			0
Total Force-X			244	244.0		445	445		647.4	647.4
Pressure-Y	(lbf)			0			0			0
Shear Force-Y	(lbf)			0			0			0
Total Force-Y	(lbf)			0			0			0

Table 5-9. CFD Simulation Results with Vertical Grate for 18-in Storm Drain Inlet (Grate 0-in Upstream)

18-in Storm drain inlet		Simulated Forces (lbf)								
U/S Flow Depth	(ft)	3			4			5		
Flow Rate	(cfs)	13.9			17.6			20.9		
		Upper Body	Lower Body	Total	Upper Body	Lower Body	Total	Upper Body	Lower Body	Total
Pressure-X	(lbf)	0	32.7	32.7	0	54.4	54.4	0	75.4	75.4
Shear Force-X	(lbf)	0	0.3	0.3	0	0.5	0.5	0	0.7	0.7
Total Force-X		0	33	33.0	0	54.9	54.9	0	76.2	76.2
Pressure-Y	(lbf)	0	0	0	0	-0.6	-0.6	0	-0.9	-0.9
Shear Force-Y	(lbf)	0	0	0	0	0	0	0	0	0
Total Force-Y	(lbf)	0	0	0	0	-0.5	-0.5	0	-0.9	-0.9

Table 5-10. CFD Simulation Results with Vertical Grate for 12-in Storm Drain Inlet (Grate 0-in Upstream)

12-in Storm drain inlet		**Simulated Forces (lbf)**								
U/S Flow Depth	**(ft)**	**3**			**4**			**5**		
Flow Rate	**(cfs)**	**7.2**			**8.9**			**10**		
		Upper Body	**Lower Body**	**Total**	**Upper Body**	**Lower Body**	**Total**	**Upper Body**	**Lower Body**	**Total**
Pressure-X	(lbf)	0	11.7	11.7	0	18.7	18.7	0	24.3	24.3
Shear Force-X	(lbf)	0	0.1	0.1	0	0.2	0.2	0	0.2	0.2
Total Force-X		0	11.9	11.9	0	18.8	18.8	0	24.5	24.5
Pressure-Y	(lbf)	0	0.5	0.5	0	0.8	0.8	0	1	1
Shear Force-Y	(lbf)	0	0	0	0	0	0	0	0	0
Total Force-Y	(lbf)	0	0.5	0.5	0	0.8	0.8	0	1	1

Table 5-11. CFD Simulation Results with Vertical Grate for 60-in Storm Drain Inlet (Grate 18-in Upstream)

60-in Storm drain inlet		**Simulated Forces (lbf)**								
U/S Flow Depth	**(ft)**	**4**			**5.2**			**6.7**		
Flow Rate	**(cfs)**	**150**			**175**			**200**		
		Upper Body	**Lower Body**	**Total**	**Upper Body**	**Lower Body**	**Total**	**Upper Body**	**Lower Body**	**Total**
Pressure-X	(lbf)	56.7	91.6	148.3	110.8	160.3	271.1	65.5	111.9	177.4
Shear Force-X	(lbf)	1	1.7	2.7	1.2	2.1	3.3	1.2	2.3	3.5
Total Force-X		57.7	93.3	151.0	112	162.4	274.4	66.7	114.1	180.8
Pressure-Y	(lbf)	2	17.5	19.5	9.6	42.5	52.1	9.9	10.4	20.3
Shear Force-Y	(lbf)	0	0	0	0	-0.1	-0.1	-0.1	0	-0.1
Total Force-Y	(lbf)	2	17.5	19.5	9.6	42.4	52	9.8	10.4	20.2

Table 5-12. CFD Simulation Results with Vertical Grate for 48-in Storm Drain Inlet (Grate 18-in Upstream)

48-in Storm drain inlet		Simulated Forces (lbf)								
U/S Flow Depth	(ft)	4.1			4.5			5.4		
Flow Rate	(cfs)	75			90			115		
		Upper Body	Lower Body	Total	Upper Body	Lower Body	Total	Upper Body	Lower Body	Total
Pressure-X	(lbf)	10.2	96	106.2	32.6	108.0	140.6	87.6	127.2	214.8
Shear Force-X	(lbf)	0.1	1.1	1.2	0.4	1.3	1.7	0.7	1.5	2.2
Total Force-X		10.4	97.1	107.5	32.9	109.3	142.2	88.3	128.7	217.0
Pressure-Y	(lbf)	1.2	4.6	5.8	0.5	-4.2	-3.7	-3.2	4.6	1.4
Shear Force-Y	(lbf)	0	-0.1	-0.1	0.0	0.0	0.0	0.03	-0.1	-0.1
Total Force-Y	(lbf)	1.1	4.5	5.6	0.5	-4.2	-3.7	-3.2	4.5	1.3

Table 5-13. CFD Simulation Results with Vertical Grate for 30-in Storm Drain Inlet (Grate 18-in Upstream)

30-in Storm drain inlet		Simulated Forces (lbf)								
U/S Flow Depth	(ft)	4			4.8			6.2		
Flow Rate	(cfs)	39.4			50			60		
		Upper Body	Lower Body	Total	Upper Body	Lower Body	Total	Upper Body	Lower Body	Total
Pressure-X	(lbf)	4.0	47.6	51.6			0			0
Shear Force-X	(lbf)	0.0	0.5	0.5			0			0
Total Force-X		4.1	48.1	52.1		78.4	78.4		173.4	173.4
Pressure-Y	(lbf)	0.6	4.9	5.5			0			0
Shear Force-Y	(lbf)	0.0	0.0	0.0			0			0
Total Force-Y	(lbf)	0.6	4.9	5.5			0			0

The predicted total forces in the dominant x-direction, for the grates placed 0-in upstream from the storm drain inlet are shown in Figure 5-13 below. The results indicate that the x-component of the total force would exceed the 110 lbf threshold for safe operation above 20 cfs for all three storm drain inlet sizes simulated. For the smaller storm drain inlet sizes of 18-in and 12-in with the simulated child sized body, the forces are lower than 100 lbf but will exceed the 110 lbf adult threshold to be considered safe when the flow is greater than 30 cfs. The threshold for child sized body has yet identified by MHFD.

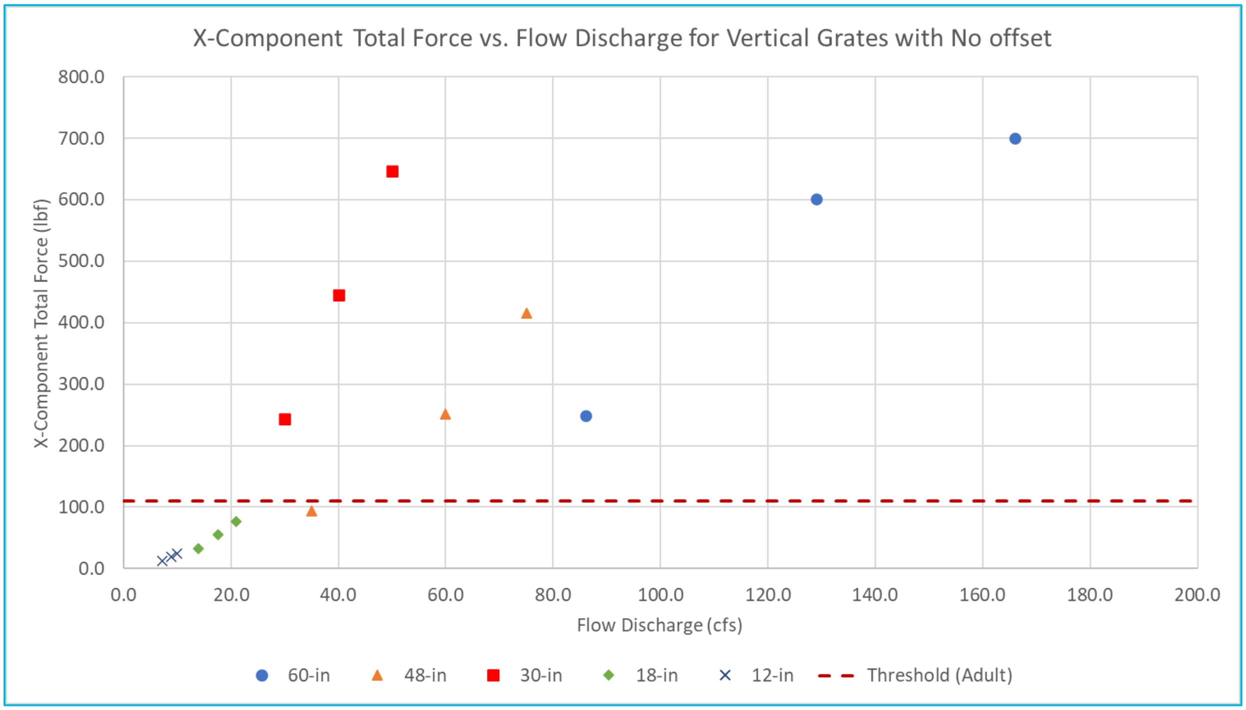

Figure 5-13. Relationship between the X-Component of the Total Force and Flow Discharge for Vertical Grates placed 0-in upstream from the Storm Drain Inlet

The predicted x-component of the total force, for the vertical grate placed 18-in away from the storm drain inlet are less than with the grate placed 0-in away from the storm drain inlet. The predicted x-component of the total force for a grate placed 18-in away from the storm drain inlet is depicted on Figure 5-14 below. The results indicate that the x-component of the total force would be above the threshold of 110 lbf for all three storm drain inlet sizes when the flow is greater than 70 cfs. CFD modeling was not conducted for the smaller storm drain inlet sizes of 18-in and 12-in with the simulated child size body since this condition would not be implemented in the field.

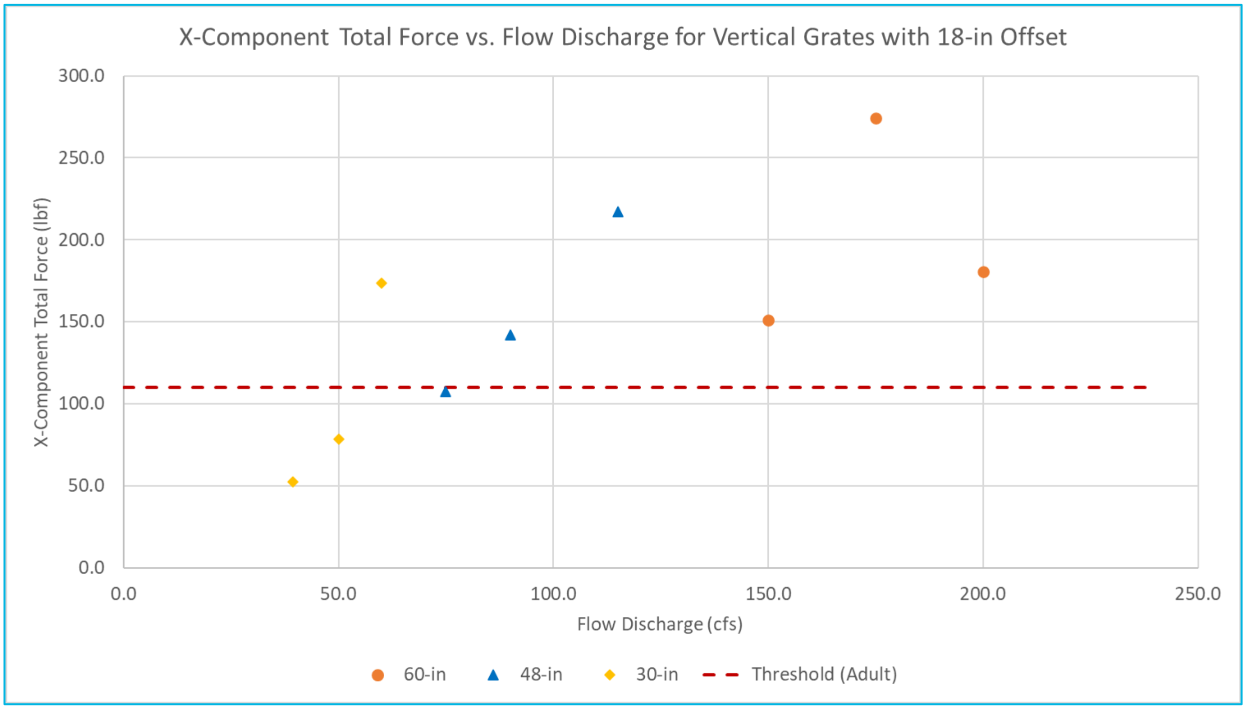

Figure 5-14. Relationship between Total Force and Flow Discharge for Vertical Grates placed 18-in upstream from the Storm Drain Inlet

5.5 Results of Flared Entrance Storm Drain Inlets and Grates

The results for the flared storm drain inlet and grates of various sizes at different flow rates are presented in Table 5-14 to Table 5-18 below.

Table 5-14. CFD Simulation Results with Flared Storm Drain Inlet Grate for 60-in Storm Drain Inlet

60-in Storm drain inlet		Simulated Forces (lbf)								
U/S Flow Depth	(ft)	4.0			5.2			6.7		
Flow Rate	(cfs)	105			155			204		
HW/D*	(ft)	0.80			1.04			1.34		
		Upper Body	Lower Body	Total	Upper Body	Lower Body	Total	Upper Body	Lower Body	Total
Pressure-X	(lbf)	34	73.9	107.9	80	103.7	183.7	106.1	121.9	228
Shear Force-X	(lbf)	0.6	1.6	2.2	1.5	2	3.5	2	2.3	4.3
Total Force-X		34.5	75.5	110.0	81.5	105.7	187.2	108.1	124.2	232.3
Pressure-Y	(lbf)	7.6	18.2	25.8	3.8	21.3	25.1	9	19.5	28.5
Shear Force-Y	(lbf)	0	-0.1	-0.1	0	-0.1	-0.1	0	-0.1	-0.1
Total Force-Y	(lbf)	7.6	18.1	25.7	3.8	21.2	25	9	19.4	28.4

*) See Section 6.1 for definitions of HW, and D.

Table 5-15. CFD Simulation Results with Flared Storm Drain Inlet Grate for 48-in Storm Drain Inlet

48-in Storm drain inlet		Simulated Forces (lbf)								
U/S Flow Depth	(ft)	3.6			5			6.2		
Flow Rate	(cfs)	75			115			138		
HW/D	(ft)	0.90			1.25			1.55		
		Upper Body	Lower Body	Total	Upper Body	Lower Body	Total	Upper Body	Lower Body	Total
Pressure-X	(lbf)	21.2	47.2	68.4	32.9	71.5	104.4	56.1	95.2	151.3
Shear Force-X	(lbf)	0.4	0.9	1.3	0.8	1.1	1.9	1.1	1.3	2.4
Total Force-X		21.6	48.2	69.8	33.7	72.6	106.3	57.2	96.6	153.7
Pressure-Y	(lbf)	4.3	9.6	13.9	5.4	12.1	17.5	10.2	12.2	22.5
Shear Force-Y	(lbf)	0	0	0	-0.1	0.0	-0.1	0.0	0.0	0.0
Total Force-Y	(lbf)	4.3	9.6	13.9	5.4	12.1	17.5	10.2	12.2	22.4

Table 5-16. CFD Simulation Results with Flared Storm Drain Inlet Grate for 30-in Storm Drain Inlet

30-in Storm drain inlet		**Simulated Forces (lbf)**								
U/S Flow Depth	**(ft)**	**4.3**			**6**			**6.8**		
Flow Rate	**(cfs)**	**50**			**64.6**			**74**		
HW/D	**(ft)**	**1.72**			**2.40**			**2.72**		
		Upper Body	**Lower Body**	**Total**	**Upper Body**	**Lower Body**	**Total**	**Upper Body**	**Lower Body**	**Total**
Pressure-X	(lbf)	-4.2	94.3	90.1	-3.8	108.1	104.3	16.7	143.3	160
Shear Force-X	(lbf)	0	1	1	0.2	1	1.2	0.2	1.1	1.3
Total Force-X		-4.2	95.3	91.1	-3.6	109	105.4	16.9	144.4	161.3
Pressure-Y	(lbf)	0.9	13.7	14.6	4.7	8.5	13.2	9.6	18.9	28.5
Shear Force-Y	(lbf)	-0.1	-0.1	-0.2	0	0	0	-0.1	0	-0.1
Total Force-Y	(lbf)	0.9	13.5	14.4	4.7	8.6	13.3	9.5	18.9	28.4

Table 5-17. CFD Simulation Results with Flared Storm Drain Inlet Grate for 24-in Storm Drain Inlet

30-in Storm drain inlet		**Simulated Forces (lbf)**			
U/S Flow Depth	**(ft)**	**3.0**	**5.0**	**6.0**	**8.3**
Flow Rate	**(cfs)**	**21.2**	**36.2**	**41.6**	**53.0**
HW/D	**(ft)**	**1.25**	**2.25**	**2.75**	**3.90**
		Total	**Total**	**Total**	**Total**
Pressure-X	(lbf)	27.9	89.6	118.9	198.0
Shear Force-X	(lbf)	0.4	1.0	1.2	1.9
Total Force-X		28.3	90.6	129.1	199.9
Pressure-Y	(lbf)	2.9	11.1	15.1	29.6
Shear Force-Y	(lbf)	0	0	-0.1	0
Total Force-Y	(lbf)	2.9	11.1	15.0	29.6

Table 5-18. CFD Simulation Results with Flared Storm Drain Inlet Grate for 18-in Storm Drain Inlet

18-in Storm drain inlet		**Simulated Forces (lbf)**								
U/S Flow Depth	**(ft)**	**2.0**			**3.5**			**5.0**		
Flow Rate	**(cfs)**	**10**			**17.2**			**22**		
HW/D	**(ft)**	**1.33**			**2.33**			**3.33**		
		Upper Body	**Lower Body**	**Total**	**Upper Body**	**Lower Body**	**Total**	**Upper Body**	**Lower Body**	**Total**
Pressure-X	(lbf)	0	3.4	3.4	0	9.8	9.8	0	16.1	16.1
Shear Force-X	(lbf)	0	0.1	0.1	0	0.2	0.2	0	0.3	0.3
Total Force-X		0	3.5	3.5	0	10	10	0	16.4	16.4
Pressure-Y	(lbf)	0	0.3	0.3	0	0.9	0.9	0	1.5	1.5
Shear Force-Y	(lbf)	0	0	0	0	0	0	0	0	0
Total Force-Y	(lbf)	0	0.3	0.3	0	0.9	0.9	0	1.5	1.5

Table 5-19. CFD Simulation Results with Flared Storm Drain Inlet Grate for 12-in Storm Drain Inlet

12-in Storm drain inlet		**Simulated Forces (lbf)**								
U/S Flow Depth	**(ft)**	**2.0**			**3.0**			**4.0**		
Flow Rate	**(cfs)**	**6.8**			**8.4**			**10**		
HW/D	**(ft)**	**2.00**			**3.00**			**4.00**		
		Upper Body	**Lower Body**	**Total**	**Upper Body**	**Lower Body**	**Total**	**Upper Body**	**Lower Body**	**Total**
Pressure-X	(lbf)	0	1.5	1.5	0	2.5	2.5	0	3.4	3.4
Shear Force-X	(lbf)	0	0	0	0	0	0	0	0	0
Total Force-X		0	1.5	1.5	0	2.5	2.5	0	3.4	3.4
Pressure-Y	(lbf)	0	0.2	0.2	0	0.3	0.3	0	0.4	0.4
Shear Force-Y	(lbf)	0	0	0	0	0	0	0	0	0
Total Force-Y	(lbf)	0	0.2	0.2	0	0.3	0.3	0	0.4	0.4

Figure 5-15 illustrates the relationship between the x-component of the total force on the body dummy and the flow rates simulated for the flared Storm Drain Inlet grates. The results indicate the x-component of the total force is above the 110 lbf threshold when the flow rate exceeds about 75 cfs for the 48-in and 60-in storm drain inlet sizes, when the flow exceeds about 65 cfs for the 30-in storm drain sizes, and when the flow exceeds about 40 cfs for the 24-inch storm drain size.

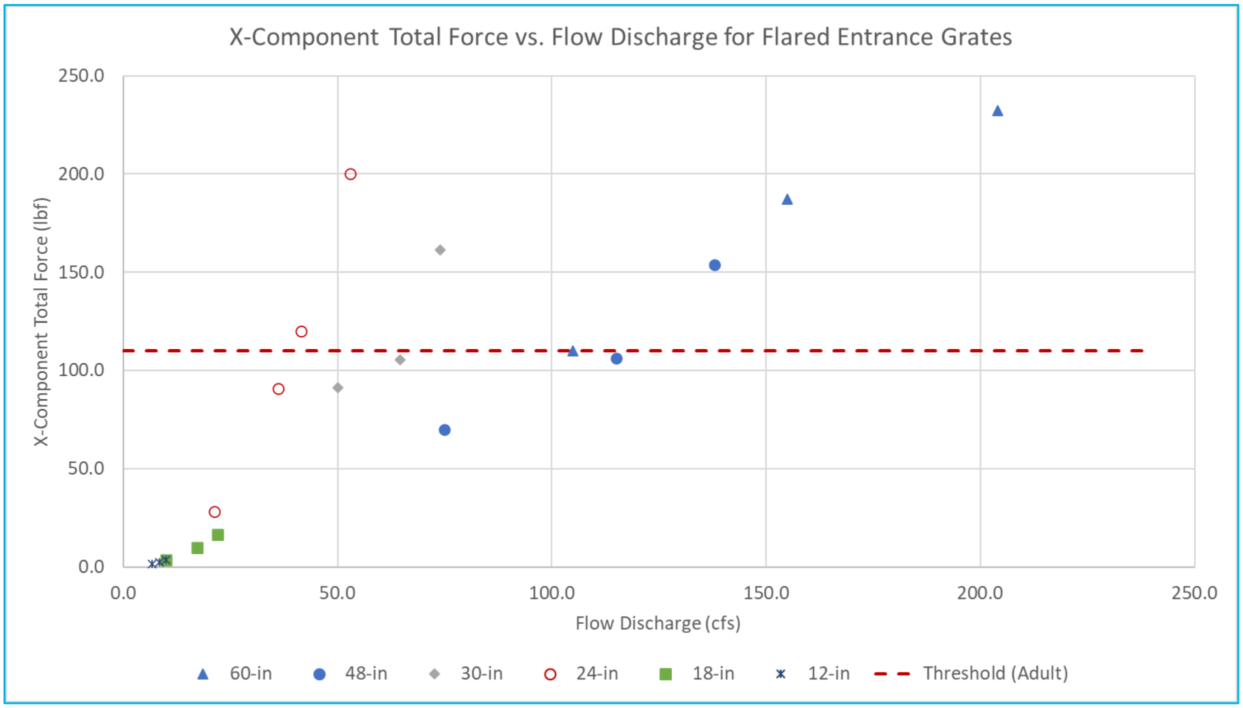

Figure 5-15. Relationship between Total Force and Flow Discharge for Flared Grates

6. Summary and Conclusions

The CFD modeling was conducted to simulate the hydraulics upstream of a storm drainage inlet of 30-in and 48-in in diameter to provide hydraulic properties under a range of inflows to help design the shape and placement of the MHFD grate in front of the inlets. The CFD modeling results show low velocities at the MHFD grate at the originally proposed 2:1 slope. The slope was subsequently modified to 1:1 to reduce the grate footprint, and the results show marginal increases in approach velocity to the grate. Accordingly, the 1:1 slope grate was selected as the preferred grate slope for the MHFD grate.

With the MHFD grate modified to the 1:1 slope, additional modeling was conducted to evaluate the dynamic forces on a body dummy that lays on top of the grate. The results of the modeling with the body dummy were then used to evaluate when the dynamic forces would exceed 110 lbf (adult) causing safety concerns in field conditions during stream flow. The threshold for child-sized body has yet identified by MHFD.

For a comparison, modeling was conducted to estimate forces on the body dummies for two other types of grates, a vertical grate that is flush against the culvert inlet or at a short distance upstream of the inlet, and a flared entrance with grate. All grates were simulated with inlet sizes from 12-in to 60-in in diameter.

Based on the CFD modeling results, dynamic forces on the body dummy were established. The results helped to establish design guidelines for the geometry of grates for storm drain inlets. The improved geometry of the MHFD grate helps reduce dynamic forces as compared to a vertical grate or a grate placed on a storm drain flared inlet improving safety for an object falling against the grate.

Figure 6-1 provides a summary of the simulated total force in the flow direction in relation to the flow discharges for all scenarios modeled. Similar relationships for individual types of grates are given in Figure 6-2, Figure 6-3, Figure 6-4, and Figure 6-5. Detailed Results for individual types of grates are presented in Section 5.

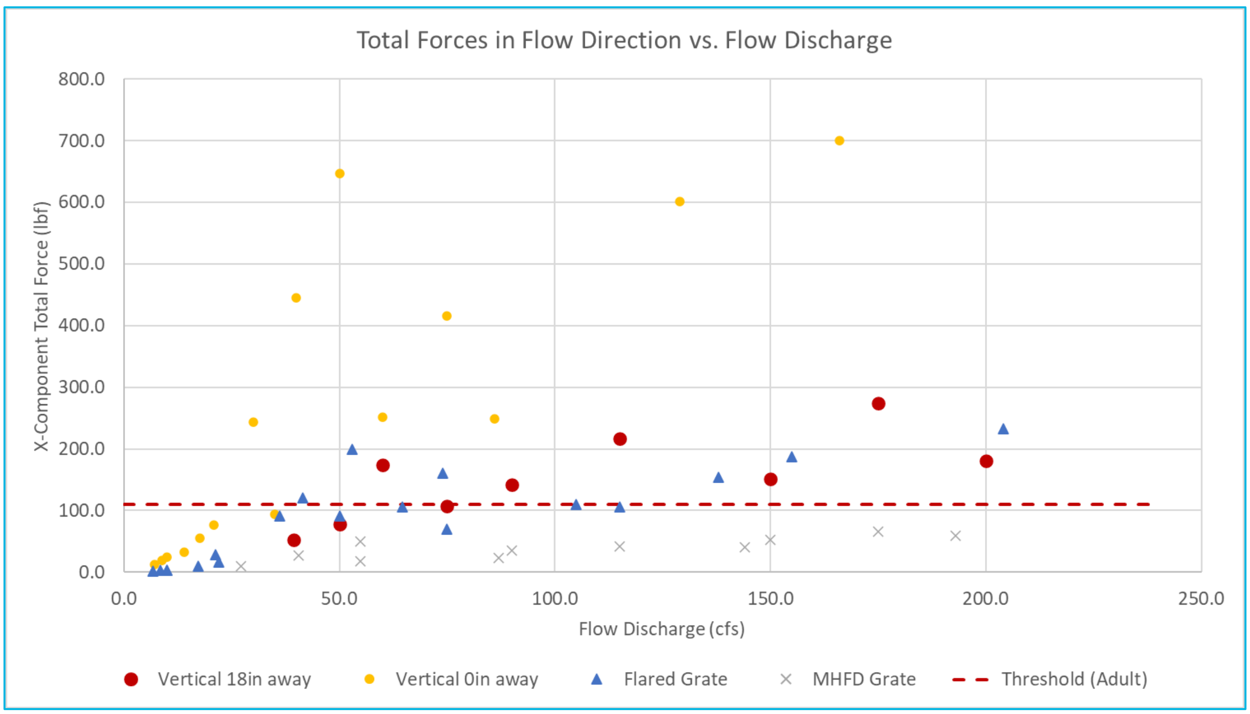

Figure 6-1. Relationship between Total Force and Flow Discharge for All Grates

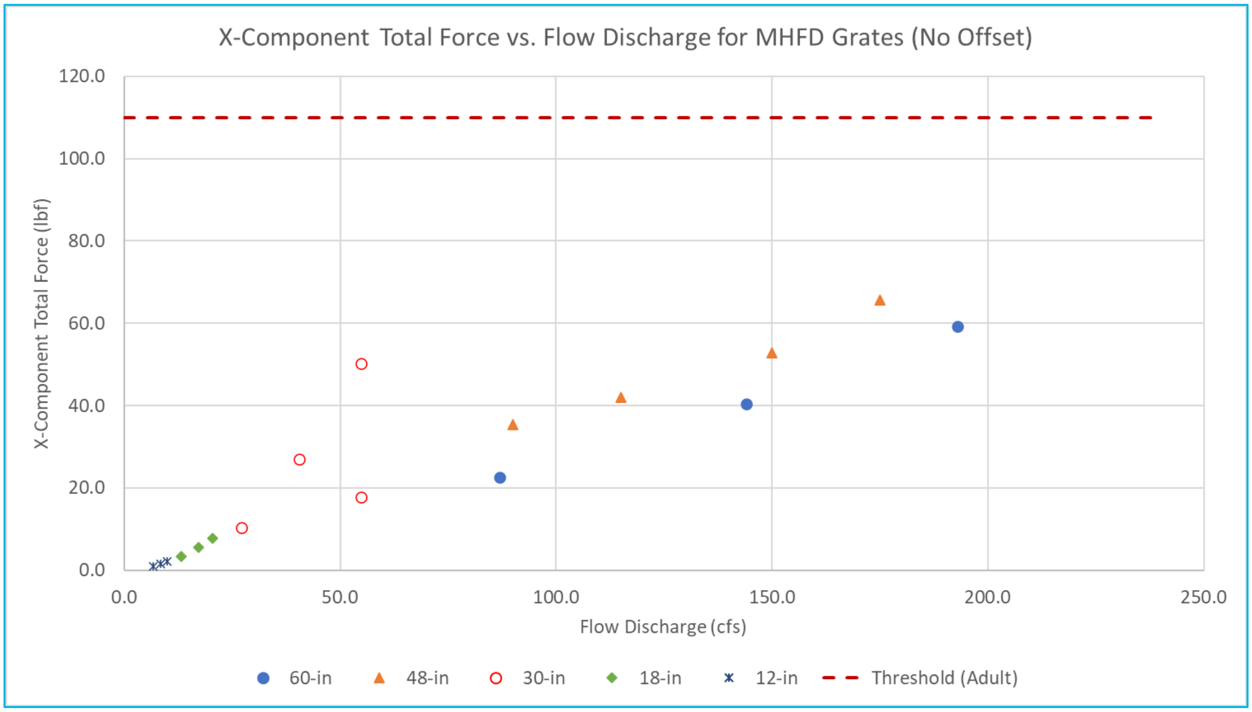

Figure 6-2. Relationship between Total Force and Flow Discharge for MHFD Grates (No Grate Offset)

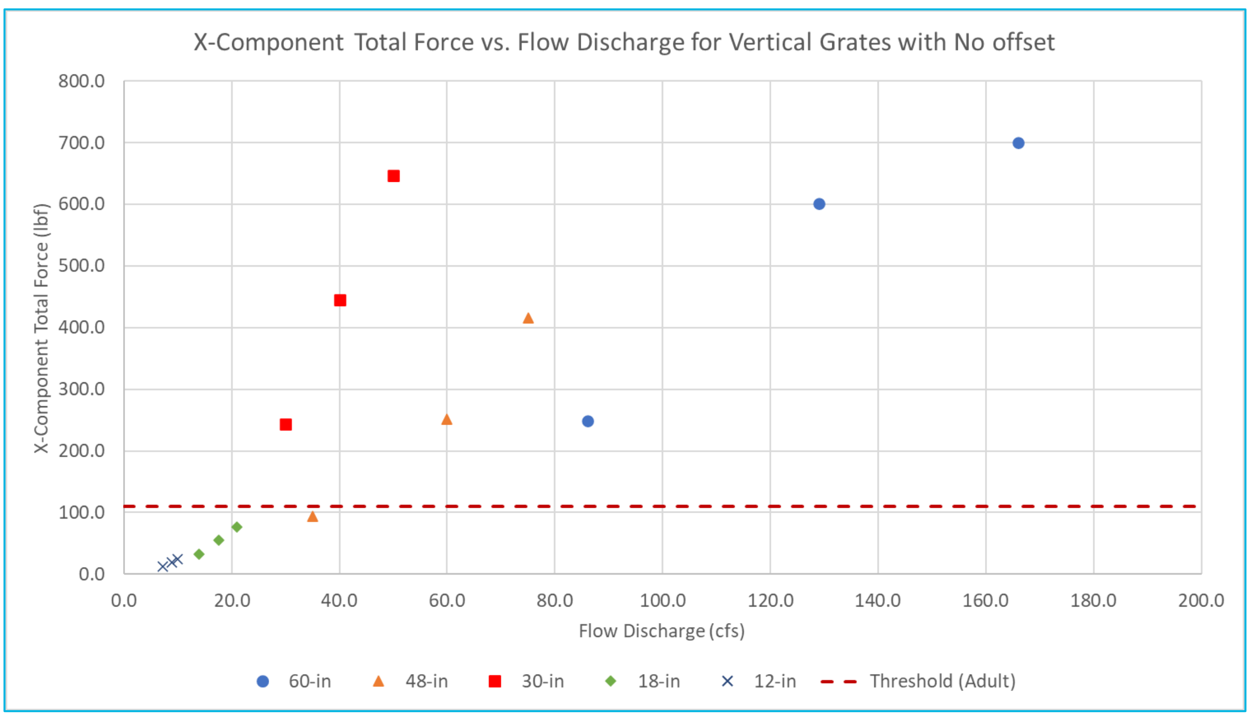

Figure 6-3. Relationship between Total Force and Flow Discharge for Vertical Grates (No Grate Offset)

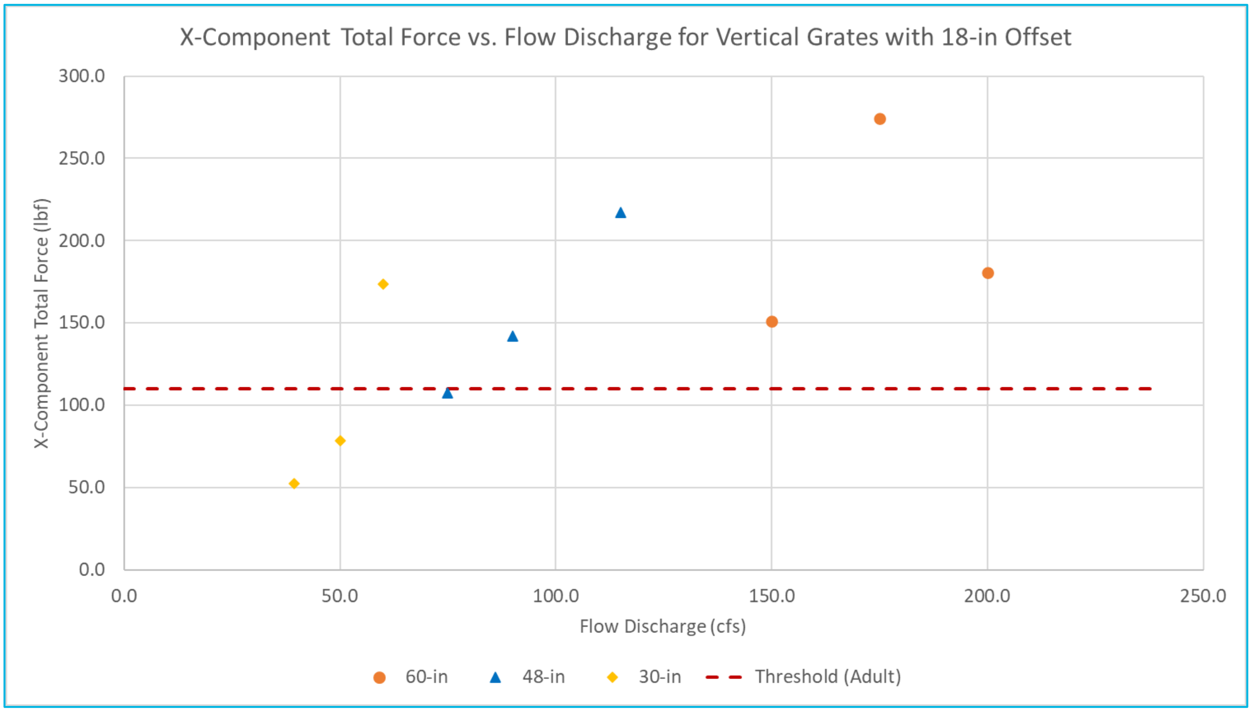

Figure 6-4. Relationship between Total Force and Flow Discharge for Vertical Grates (18-in Grate Offset)

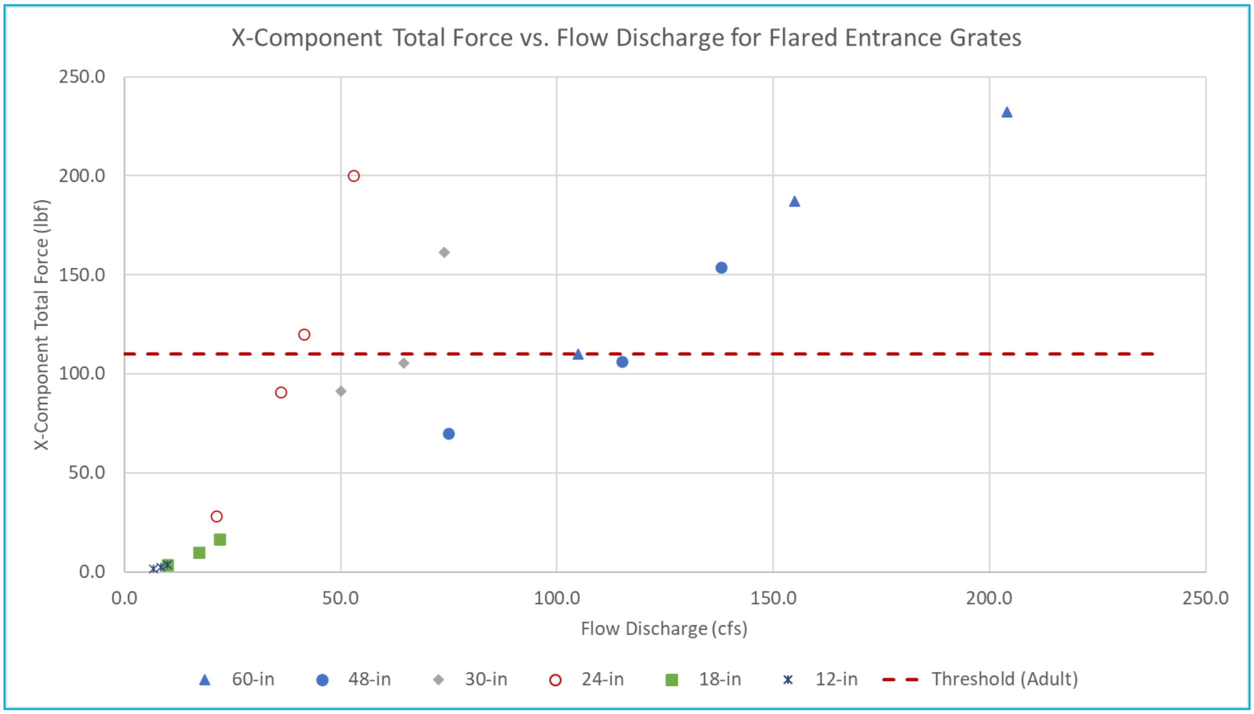

Figure 6-5. Relationship between Total Force and Flow Discharge for Flared Entrance Grates

Based on interpretation of the CFD modeling results presented in Section 5, two relationships were developed for force on the body dummy for different grate configurations and culvert sizes:

1) Relationship between the force on the body dummy and the velocity through the culvert,

2) Relationship between the force on the body dummy and factor (HW/D) for the flared entrance grates, where HW is the headwater depth above the invert of the culvert, and D is the diameter of the culvert.

The first relationship is presented in Figure 6-6 for the flared entrance grates, Figure 6-7 for the MHFD grates, and Figure 6-8 and Figure 6-9 for the vertical grates. The second relationship is presented in Figure 6-10.

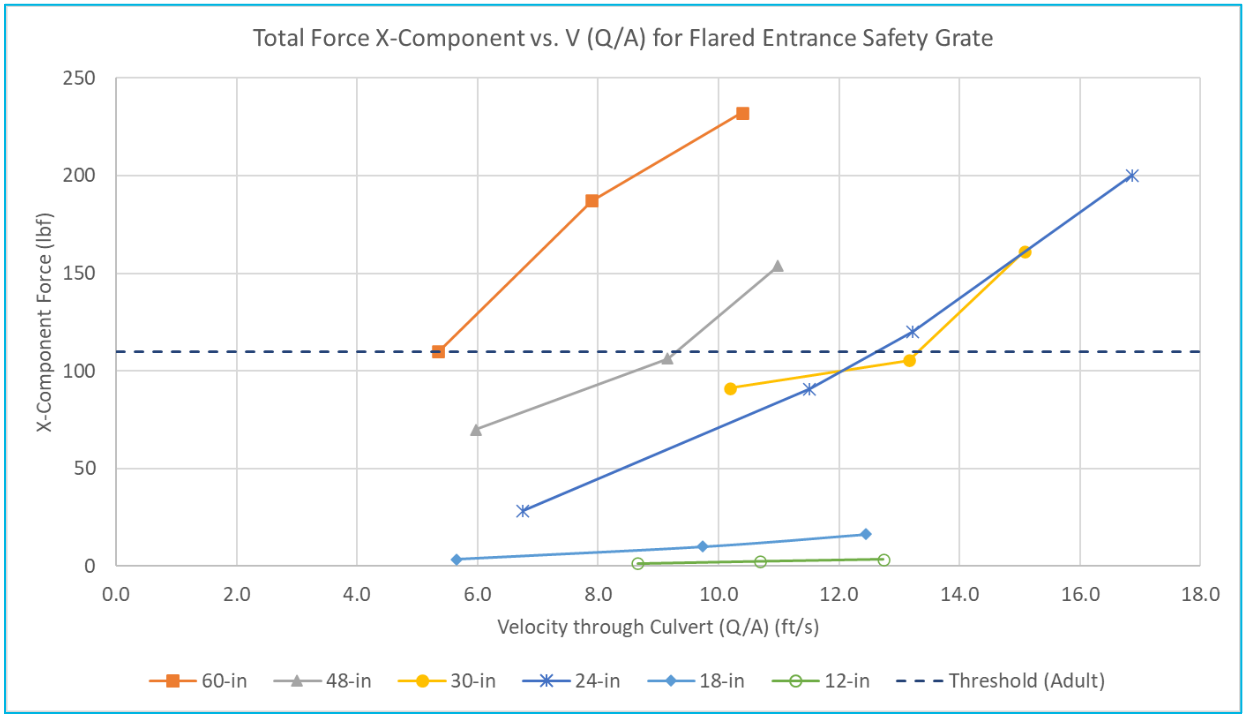

Figure 6-6. Relationship between Total Force and Velocity for Flared Entrance Grates

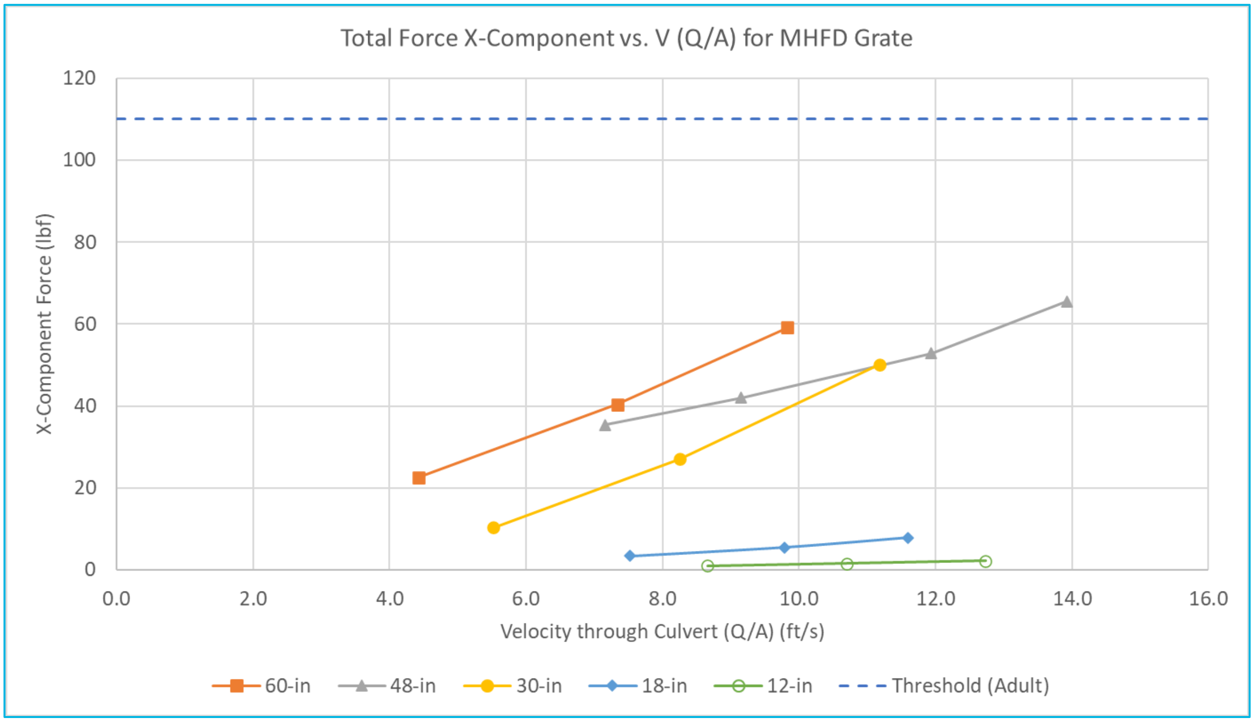

Figure 6-7. Relationship between Total Force and Velocity for the MHFD Grates

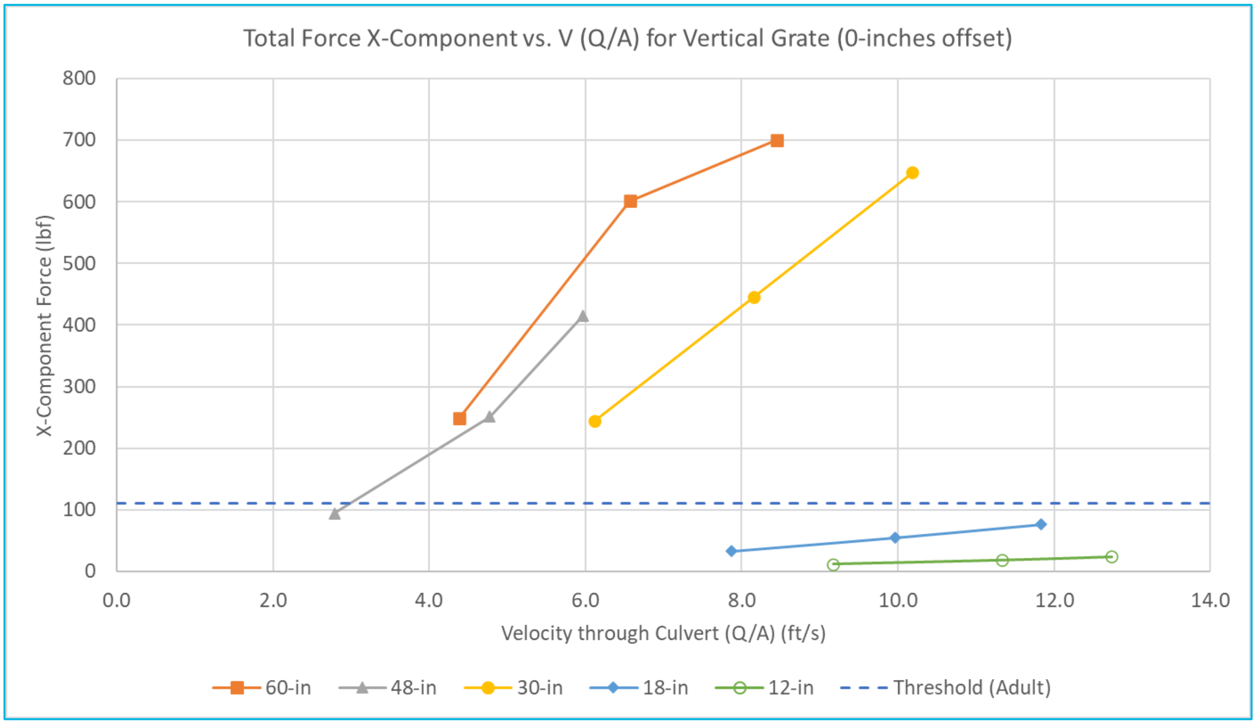

Figure 6-8. Relationship between Total Force and Velocity for Vertical Grates with 0-in Offset

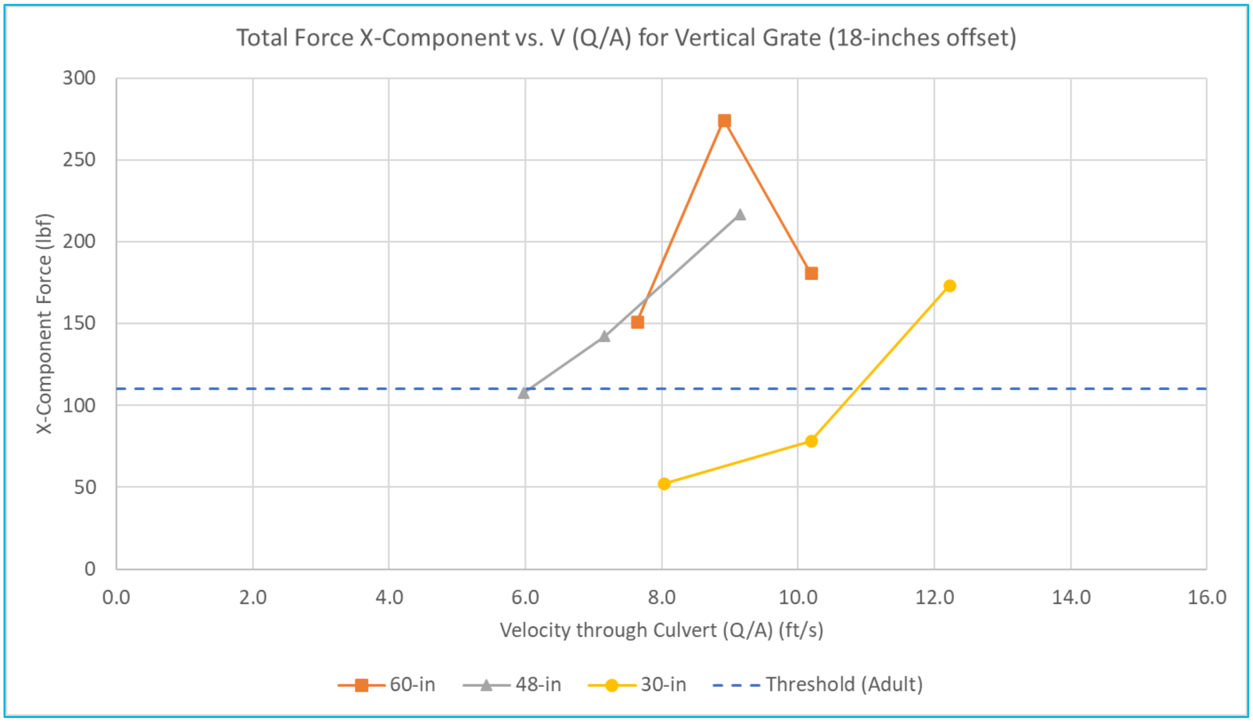

Figure 6-9. Relationship between Total Force and Velocity for Vertical Grates with 18-in Offset

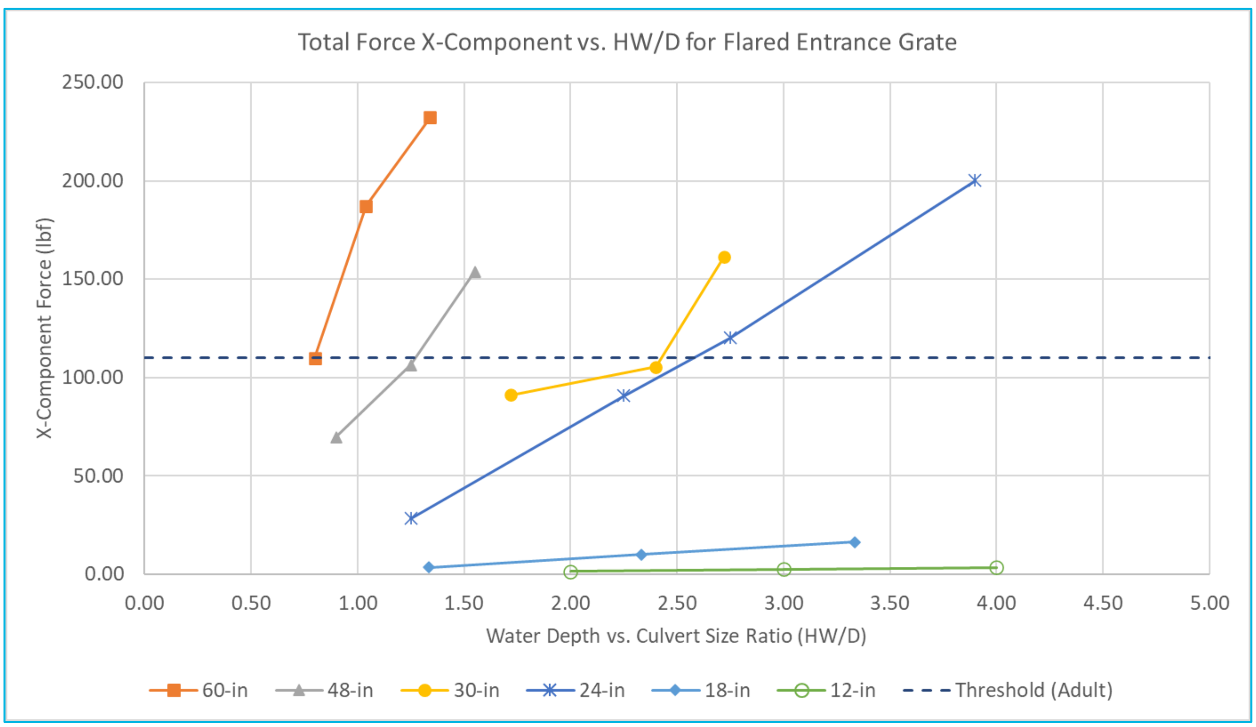

Figure 6-10. Relationship between Total Force and HW/D for Flared Entrance Grates

It should be mentioned that the CFD simulation results for the body dummy simulations herein were strictly for the shapes and positions of the body dummy as defined in Section 5.2. Due to the complicated flow conditions around a human body, the forces may change quickly if the position of the body moves from left to right as well as being positioned at a different location or orientation to the grates. The results from this analysis might not be applicable under such conditions.

7. Statement of Limitations

Professional judgment in this report is based partly on evaluation of technical information and partly on our experience with similar projects. The AECOM Team represents services performed within the limits prescribed by Mile High Flood District in a manner consistent with the level of care and skill ordinarily exercised by other professional consultants under similar circumstances. No other representation expressed or implied, and no warranty or guarantee is included or intended.

The scope of services performed during this analysis may not be appropriate to satisfy the needs of other users, and any use or re-use of this document or of the findings, conclusions, or recommendations presented herein is at the sole risk of said user.

This report has been prepared based on certain key assumptions made by the AECOM Team that may affect the conclusions and recommendations of this report. These assumptions were made based on the best knowledge at the time of this analysis. The conclusions and recommendations of the AECOM Team are conditioned upon these assumptions that may change in the future.

This report is based on data, site conditions, and other information that is generally applicable as of December 2023 and the conclusions and recommendations herein are therefore applicable only to that time frame.

8. References

Chow, V.T. (1959). Open Channel Hydraulics, McGraw-Hill Book Company, Inc, New York.

FLOW Science, Inc., (2013). FLOW-3D Hydraulic Training Class.

FLOW Science, Inc., (2022). FLOW-3D User Manuals.

Appendix A - Comparison Between CFD and Physical Models

This appendix provides a summary of comparison between results from the CFD models and measurements from a physical model conducted at Colorado State University for a vertical grate. The comparisons are for the vertical grate with a 48-in culvert with wingwalls upstream of the culvert entrance. The vertical grate was placed at 18-in upstream of the culvert entrance, as it's illustrated in Figure A-1 below.

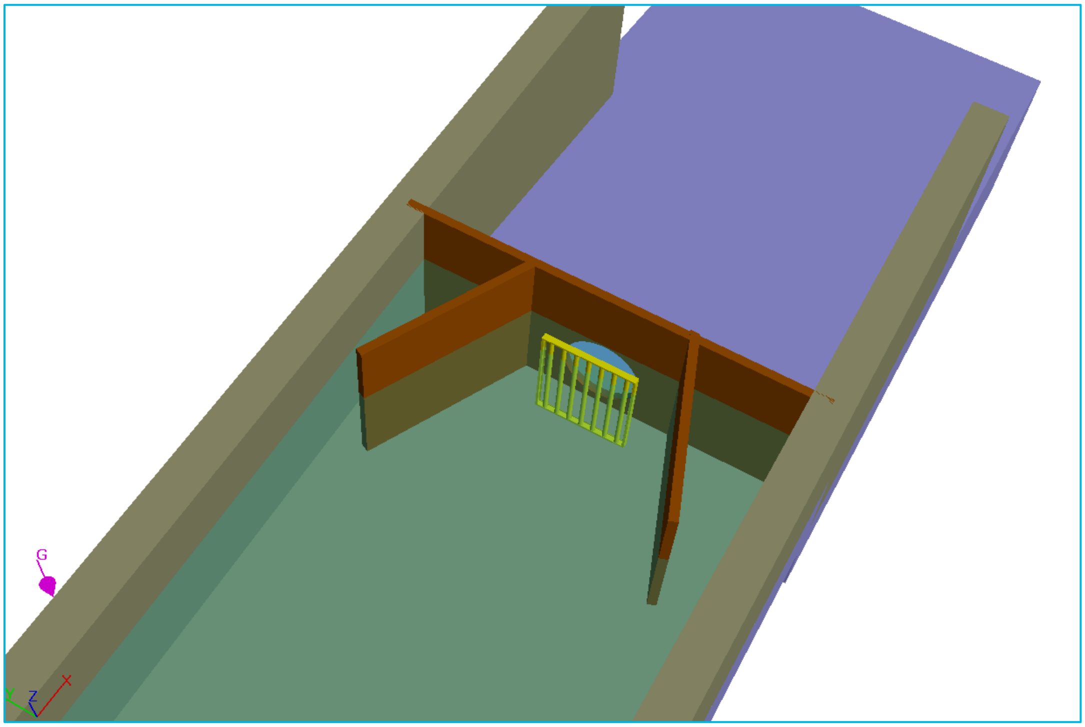

Figure A-1. Vertical Grate Setup in Physical Modelling Study for Comparison with CFD Modeling Results

The comparisons were made at about 6-inches upstream of the grate along the centerline as well as on the left side of the culvert, as illustrated in Figure A-2.

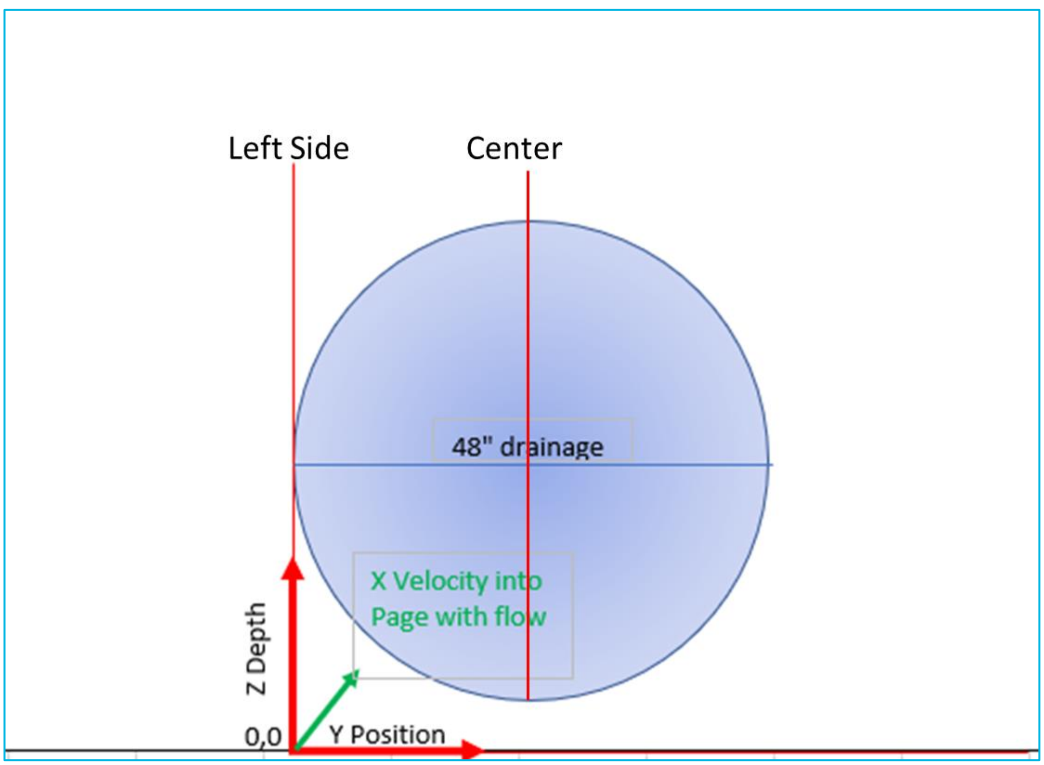

Figure A-2. Locations Selected for Velocity Comparisons between CFD and Physical Model

The comparison between the CFD and physical model for the 75 cfs scenarios are shown in Figure A-3 and A-4.

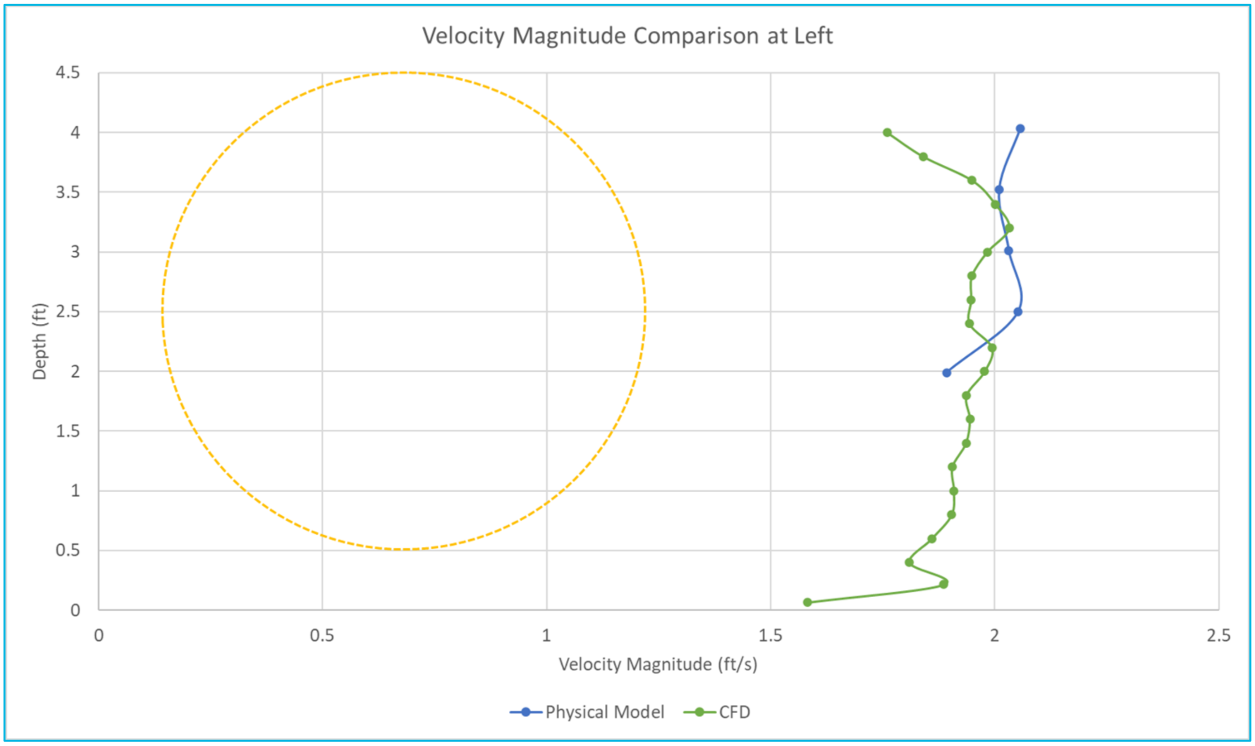

Figure A-3. Comparison of Velocity Magnitude at Left Side of Grate (75 cfs)

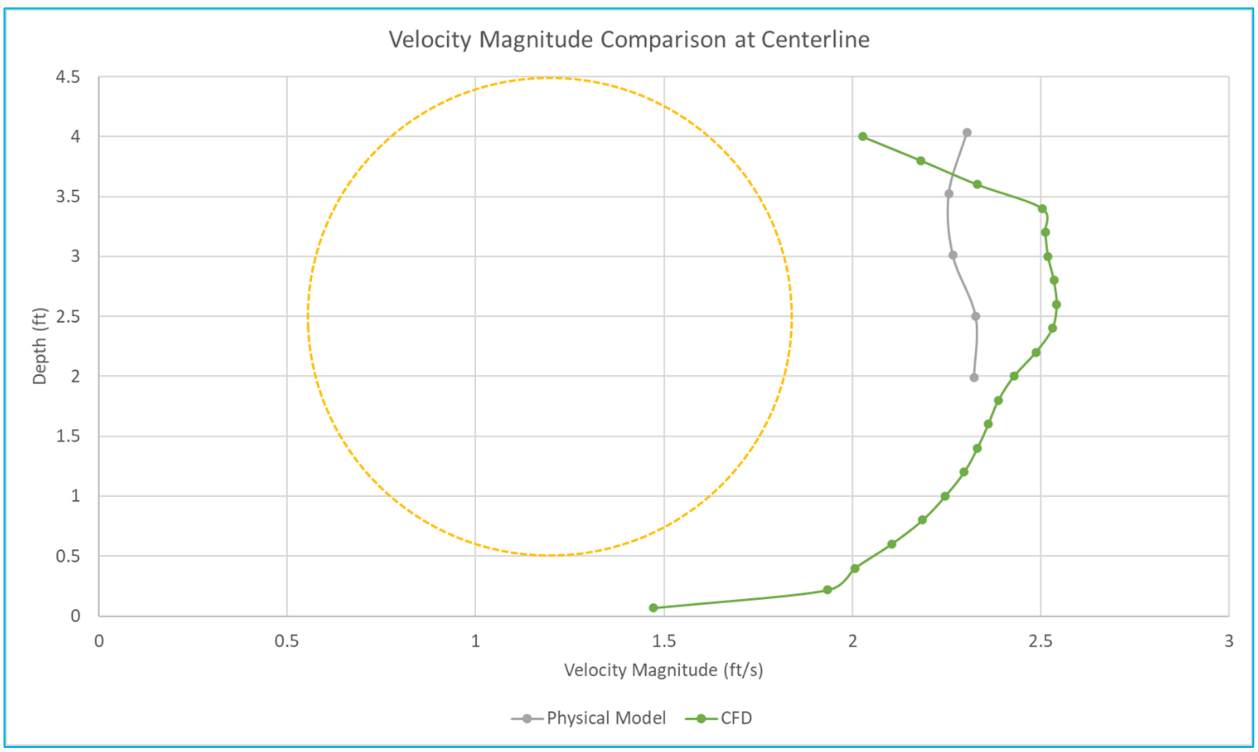

Figure A-4. Comparison of Velocity Magnitude at Center of the Grate (75 cfs)

The comparison between the CFD and physical model for the 90 cfs scenarios are shown in Figure A-5 and A-6.

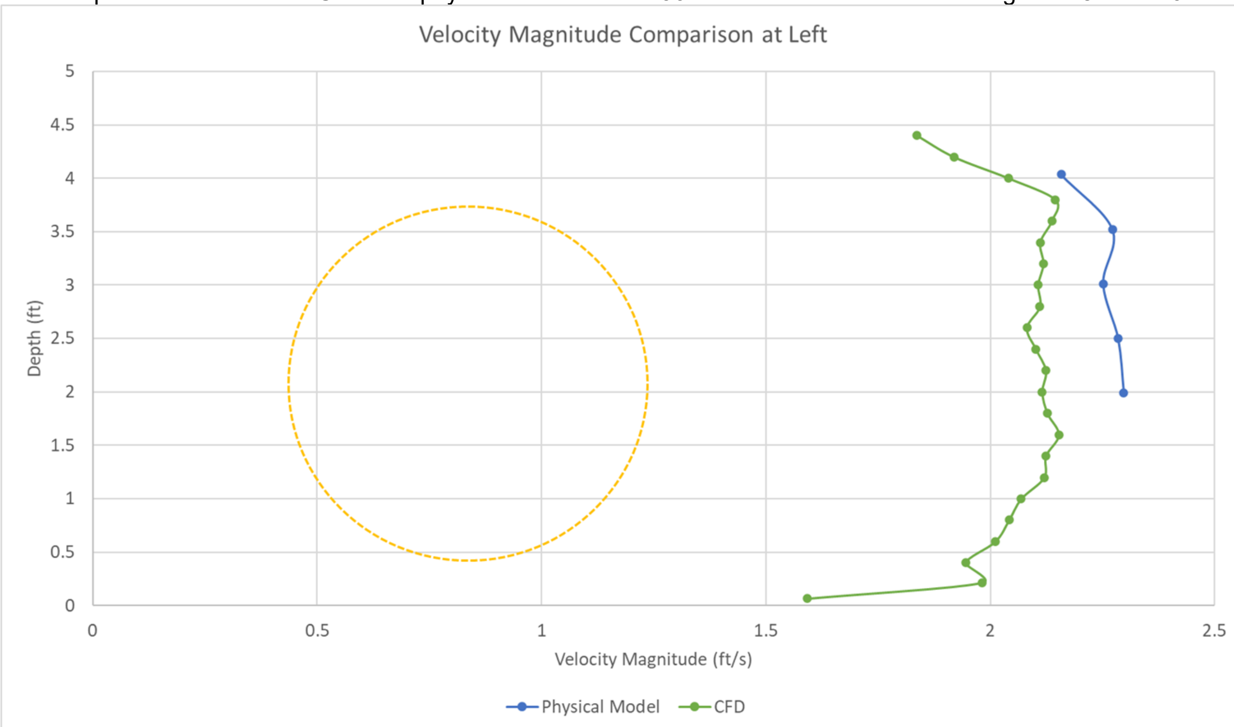

Figure A-5. Comparison of Velocity Magnitude at Left Side of Grate (90 cfs)

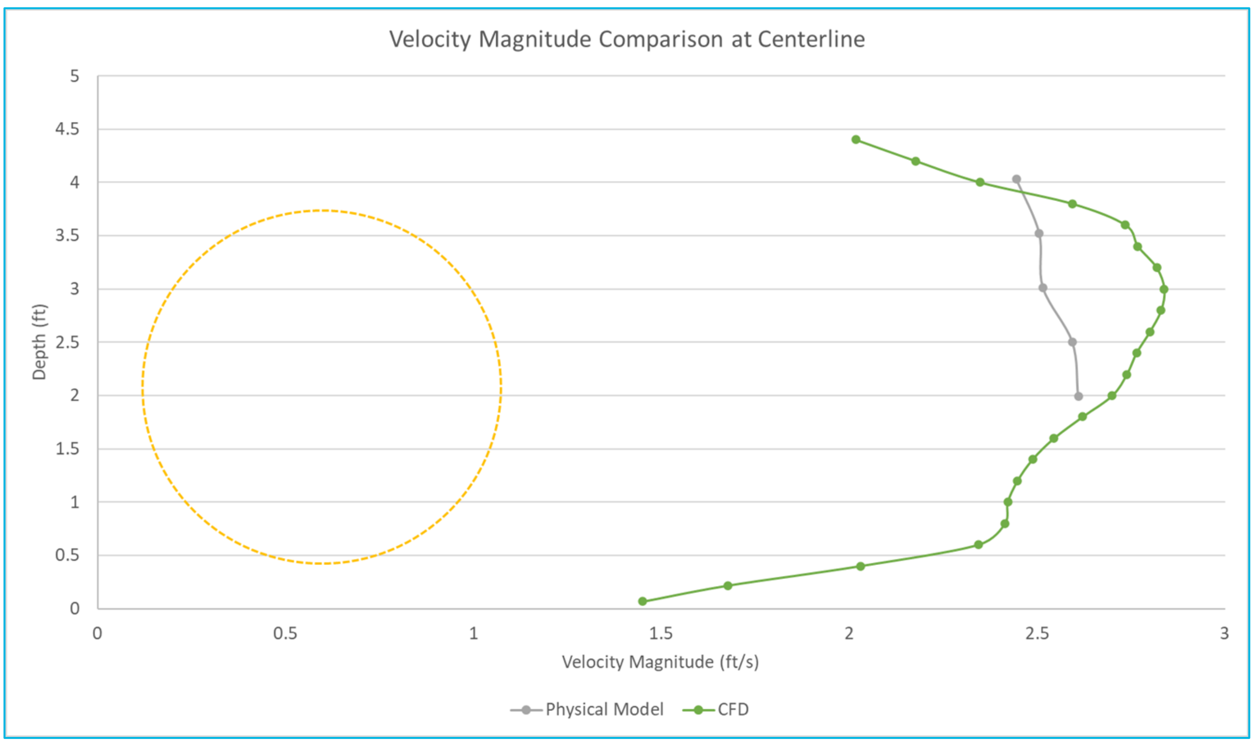

Figure A-6. Comparison of Velocity Magnitude at Center of the Grate (90 cfs)

The comparison between the CFD and physical model for the 115 cfs scenarios are shown in Figure A-7 and A-8.

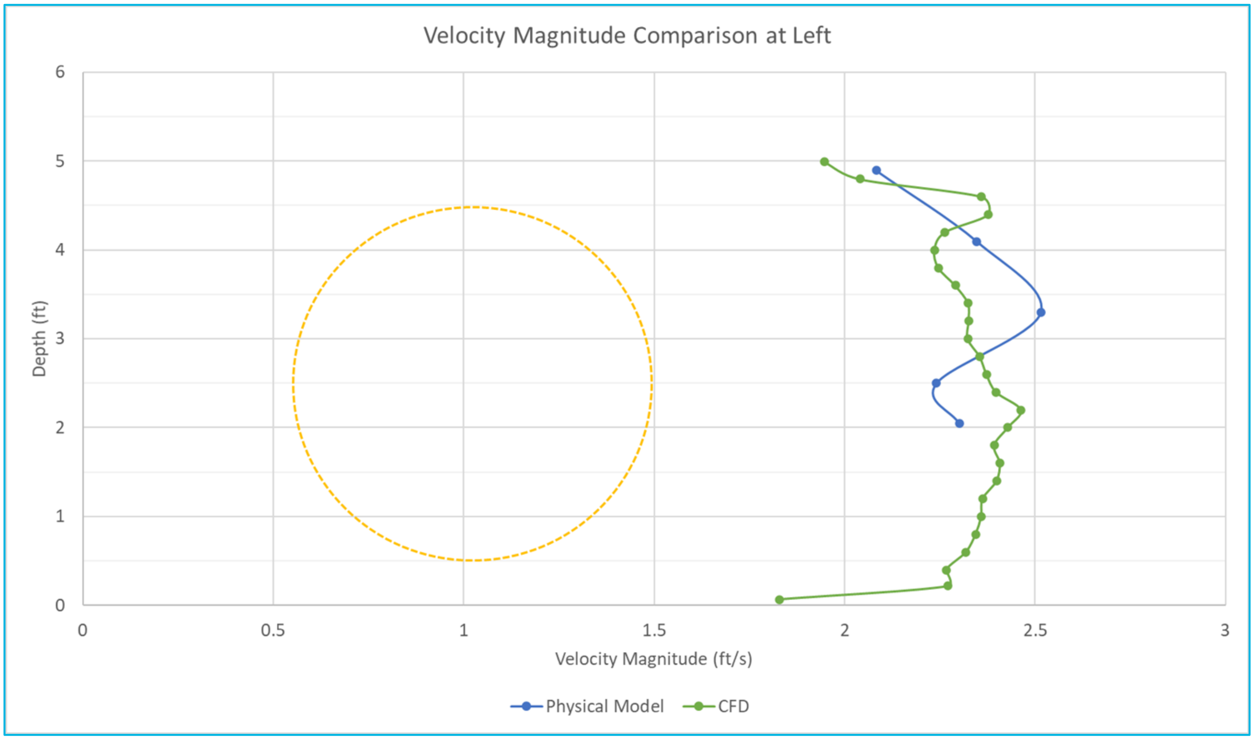

Figure A-7. Comparison of Velocity Magnitude at Left Side of Grate (115 cfs)

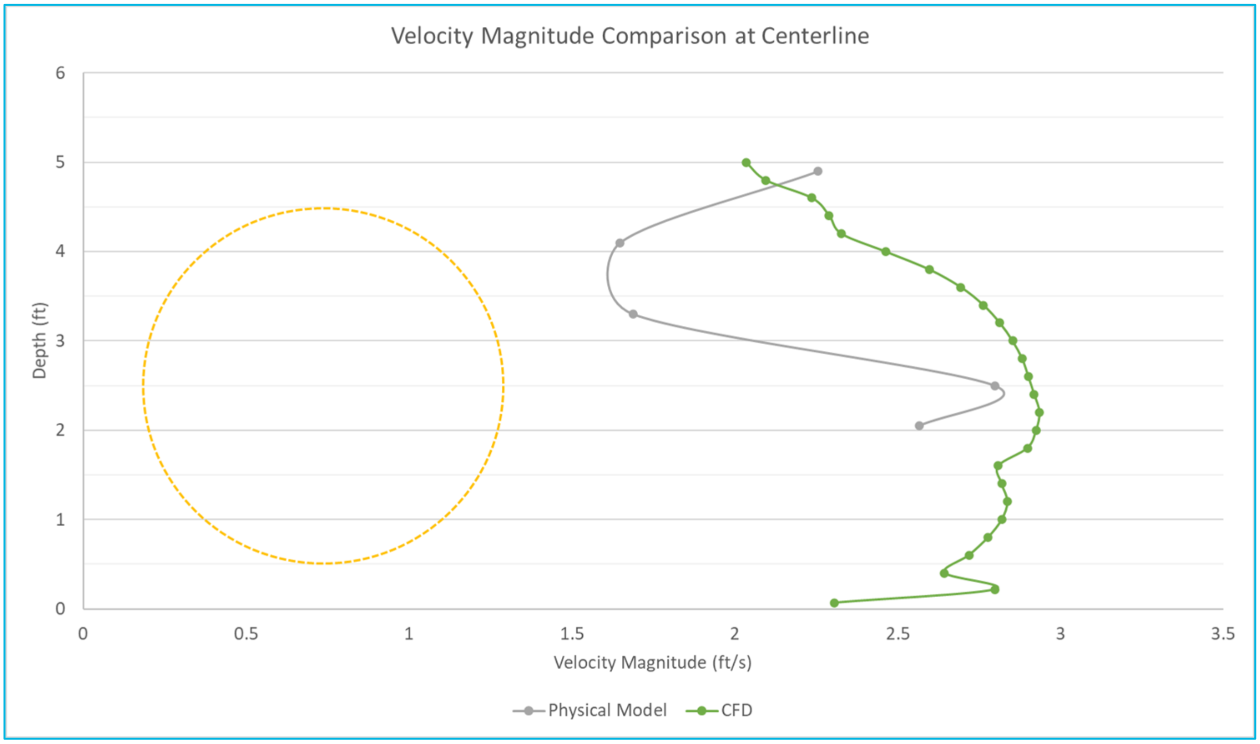

Figure A-8. Comparison of Velocity Magnitude at Center of the Grate (115 cfs)

Appendix B - Additional CFD Images

B-1. Selected Images for MHFD Grates

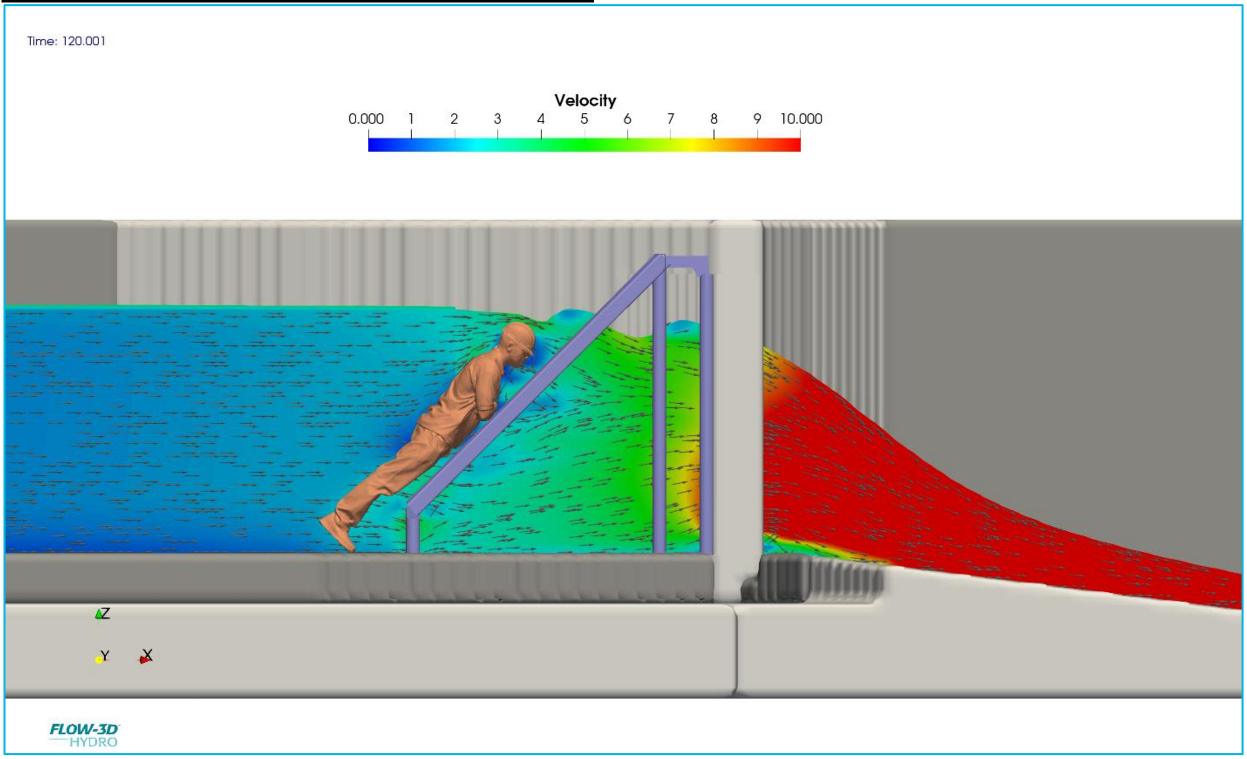

Figure B-1. Velocity Profile along Centerline for 60-in Culvert at 144cfs, Upstream Depth 5.2ft

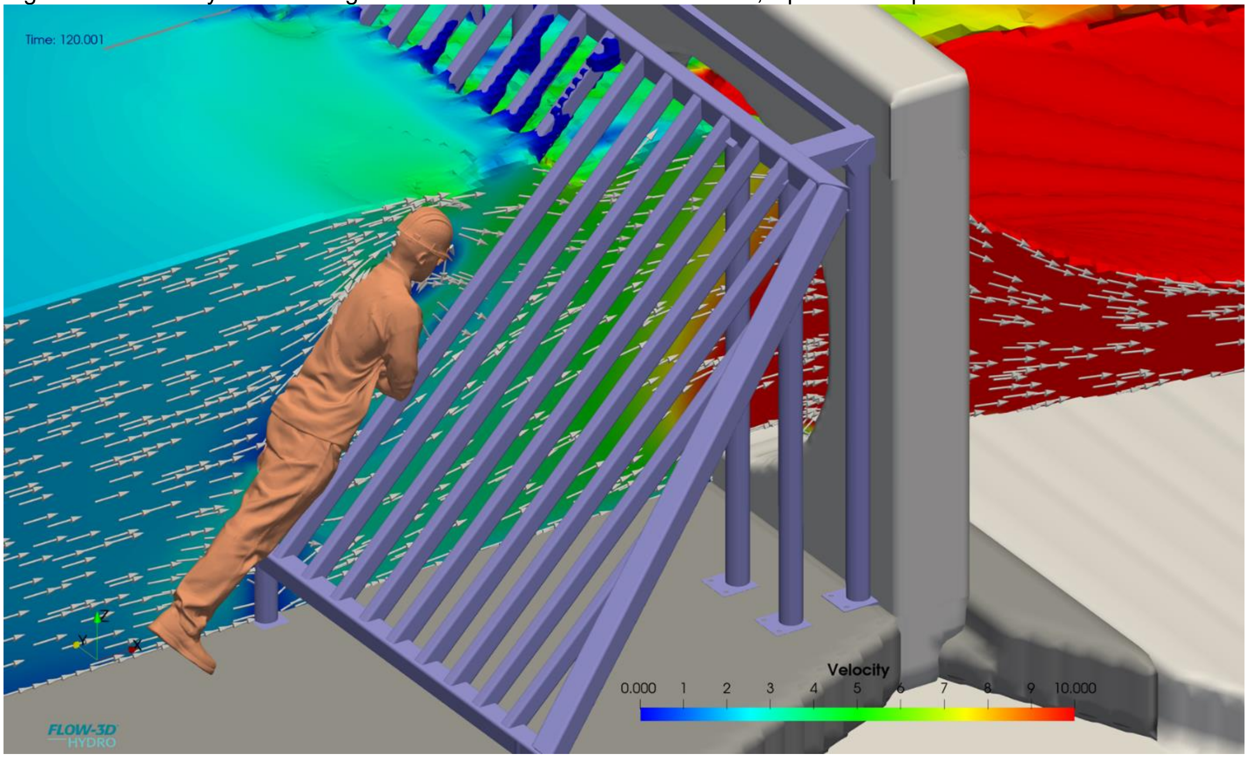

Figure B-2. 3D View of Velocity for 60-in Culvert at 144cfs, Upstream Depth 5.2ft

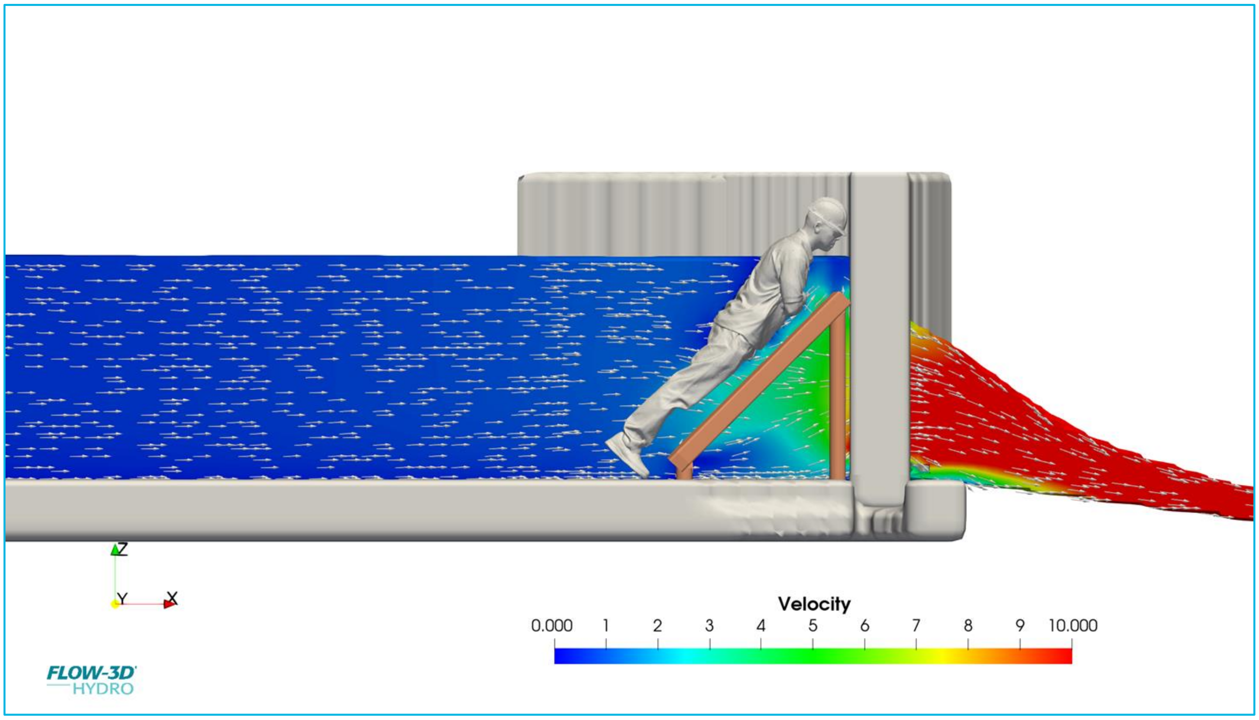

Figure B-3. Velocity Profile along Centerline for 30-in Culvert at 40.5 cfs, Upstream Depth 4.0ft

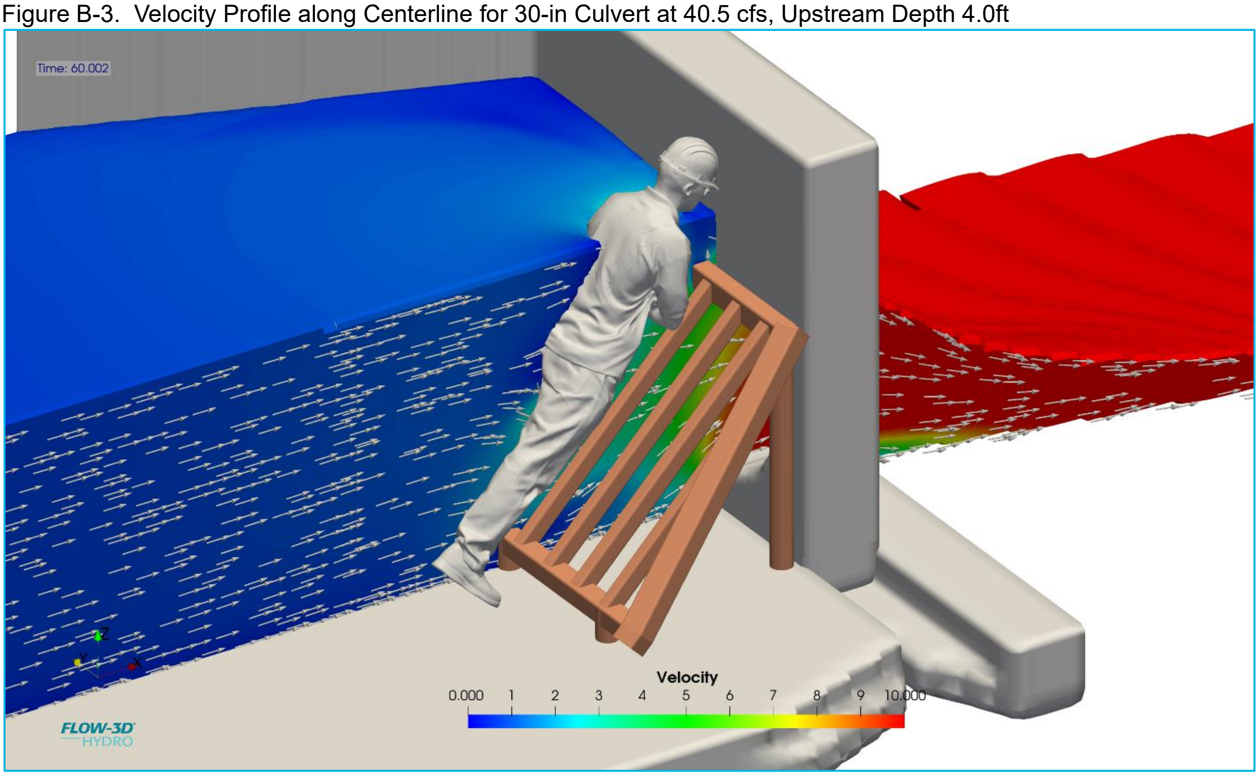

Figure B-4. 3D View of Velocity for 30-in Culvert at 40.5 cfs, Upstream Depth 4.0ft

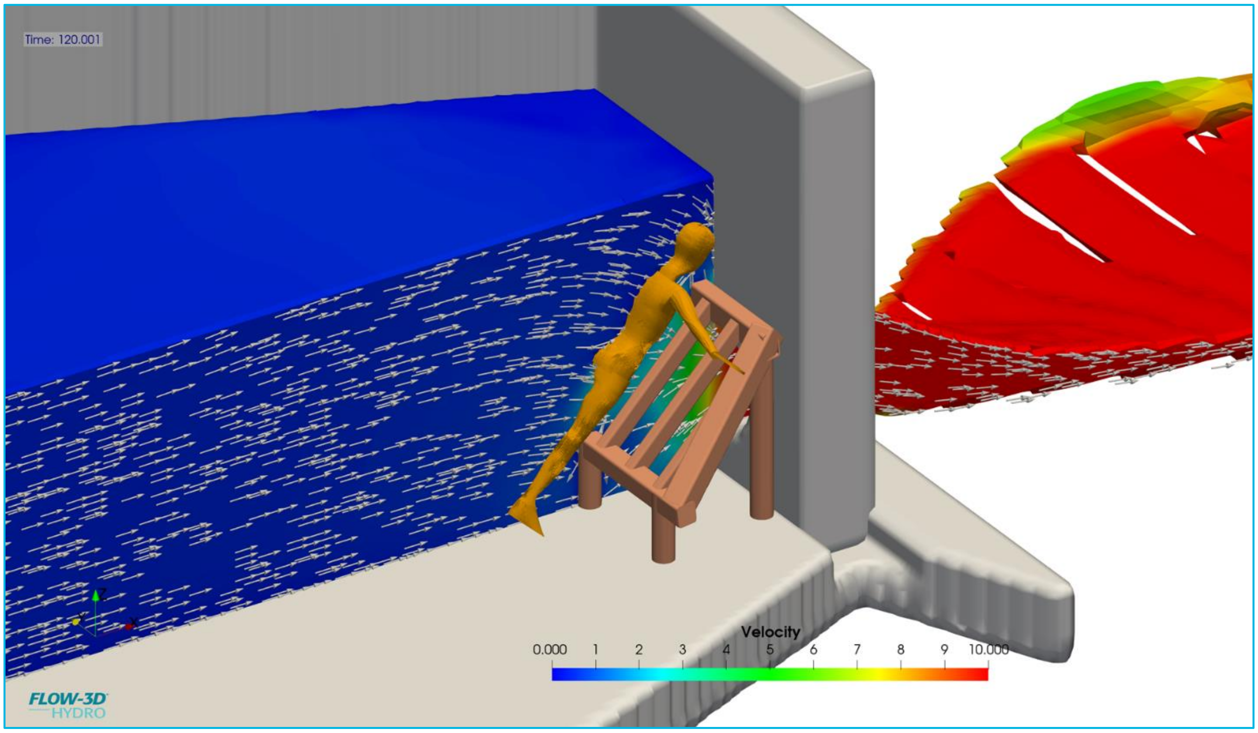

Figure B-5. 3D View of Velocity for 18-in Culvert at 17.3 cfs, Upstream Depth 4.0ft

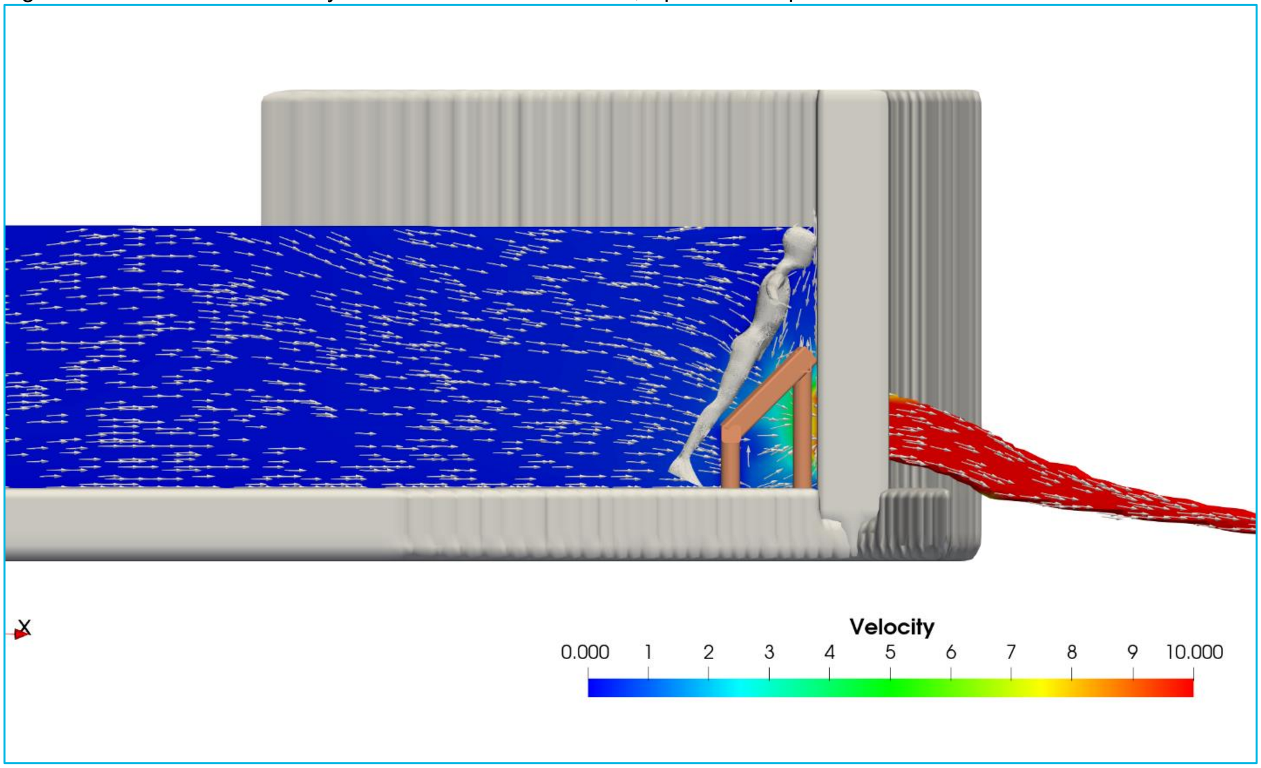

Figure B-6. Velocity Profile along Centerline for 18-in Culvert at 8.4 cfs, Upstream Depth 4.0ft

B-2. Selected Images for Vertical Grates

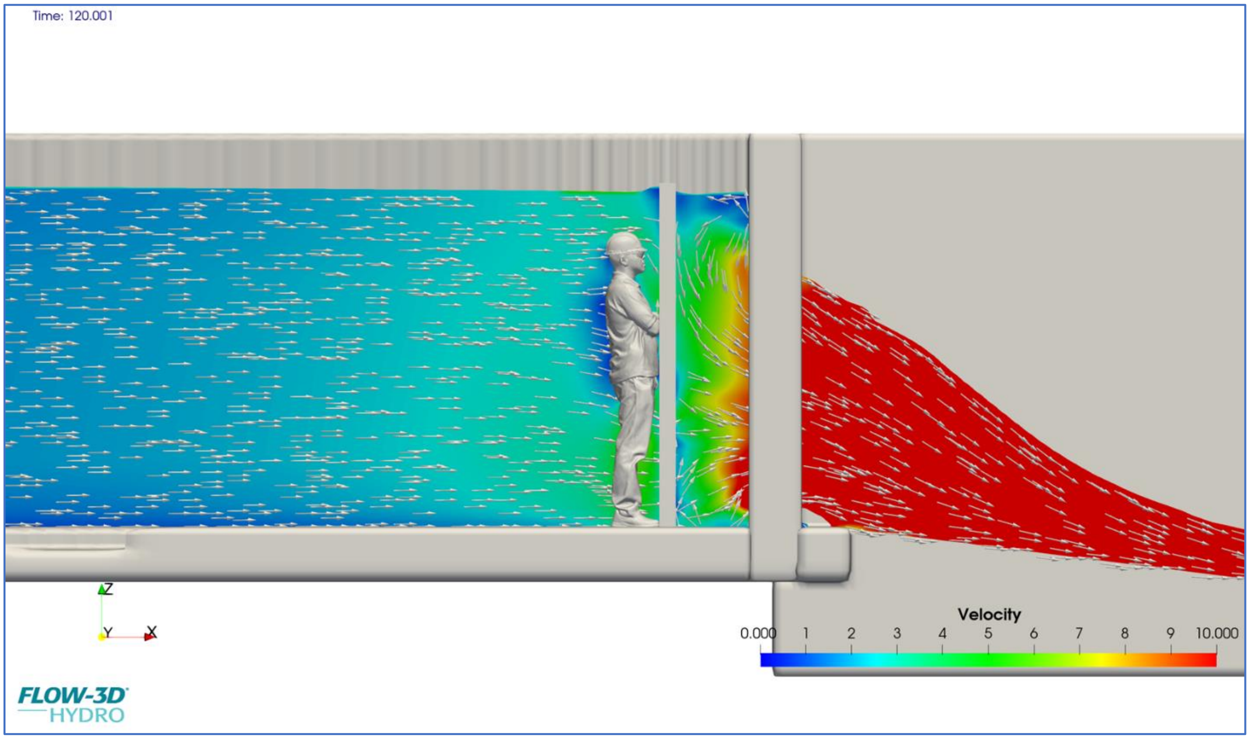

Figure B-7. Velocity Profile along Centerline for 60-in Culvert at 200cfs, Upstream Depth 6.7ft

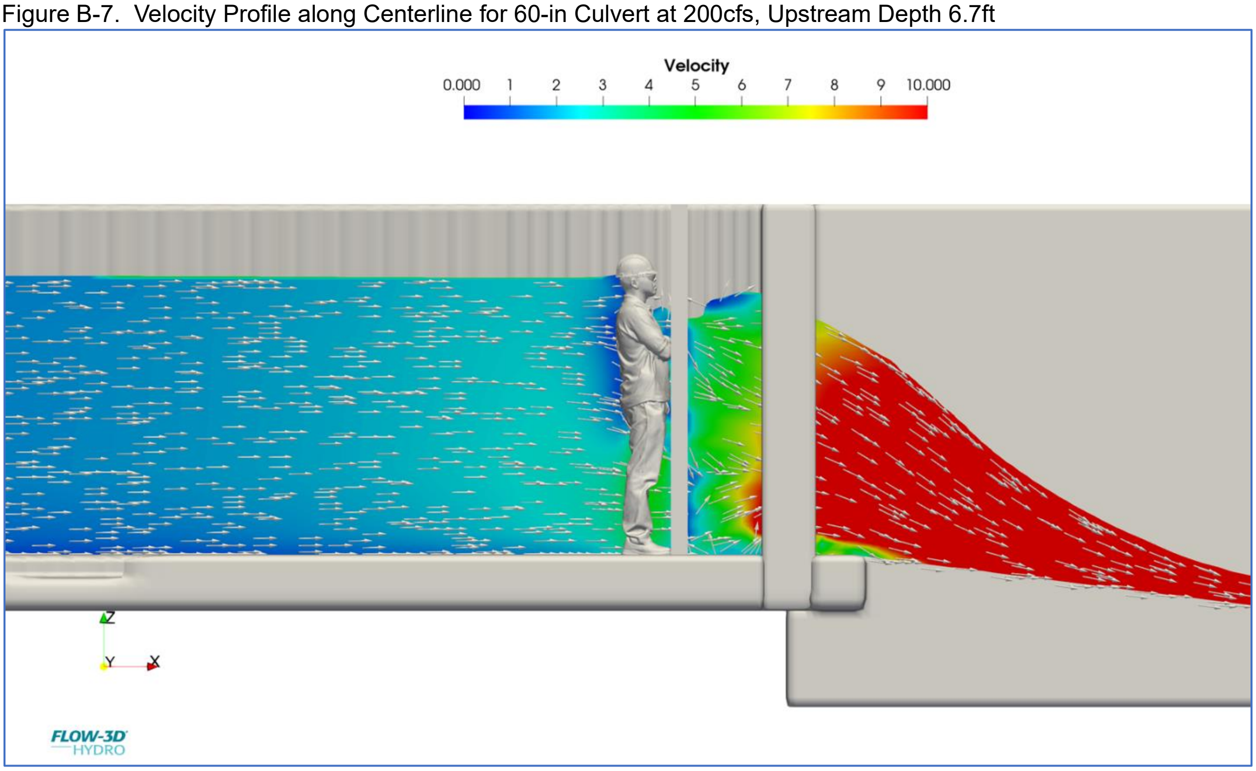

Figure B-8. Velocity Profile along Centerline for 60-in Culvert at 150cfs, Upstream Depth 5.2ft

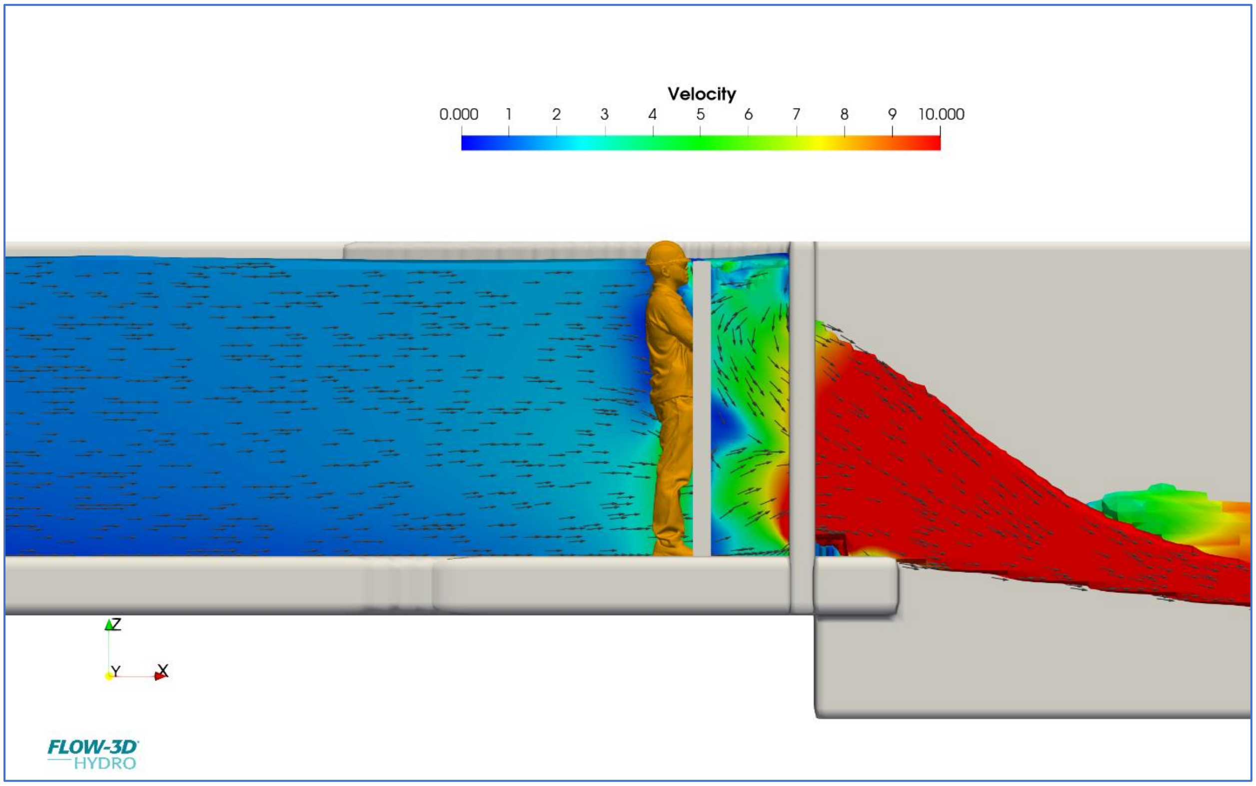

Figure B-9. Velocity Profile along Centerline for 48-in Culvert at 115cfs, Upstream Depth 5.4ft

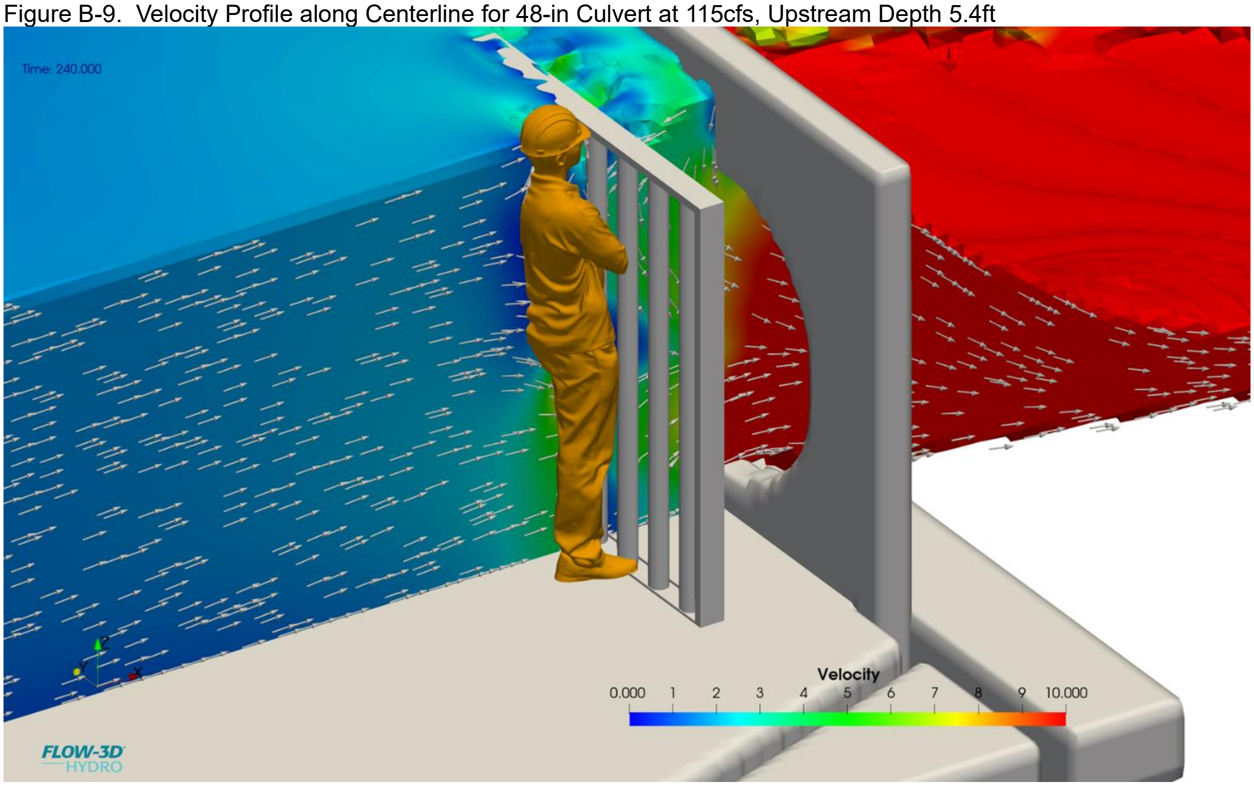

Figure B-10. 3D View of Velocity for 48-in Culvert at 115cfs, Upstream Depth 5.4ft

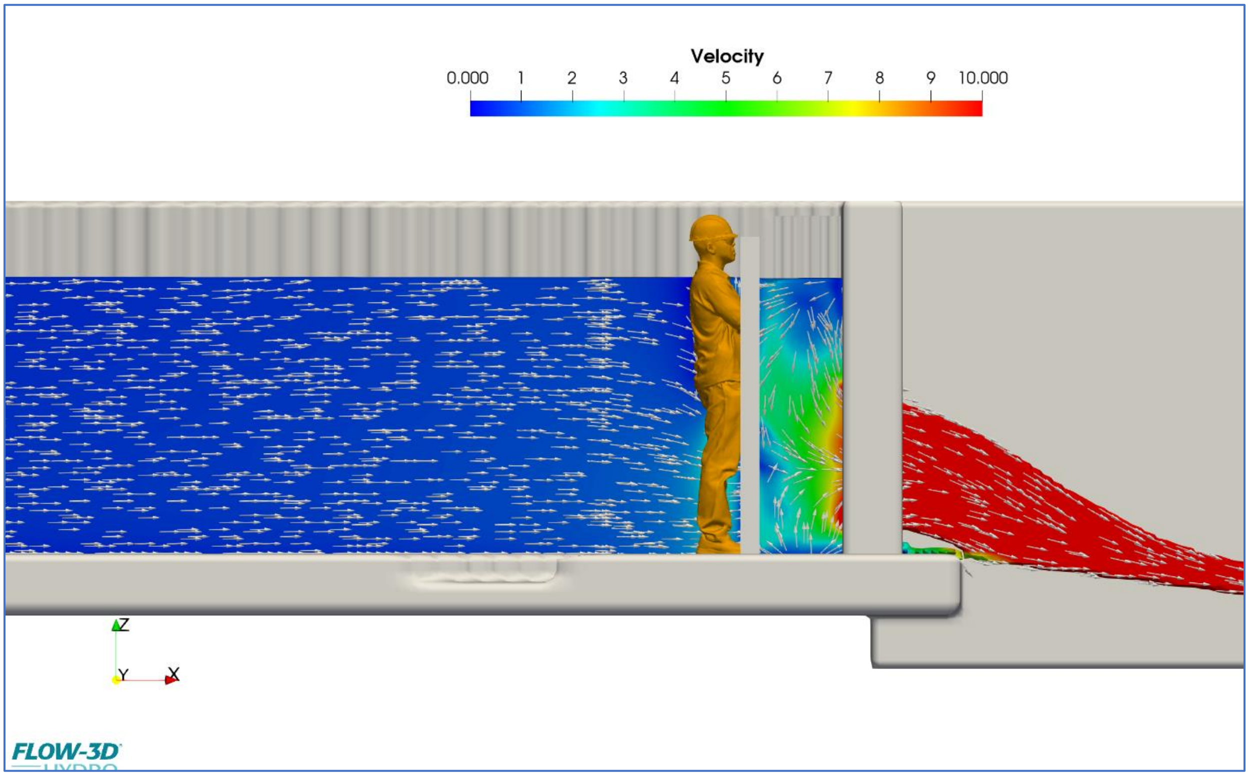

Figure B-11. Velocity Profile along Centerline for 30-in Culvert at 50cfs, Upstream Depth 4.8ft

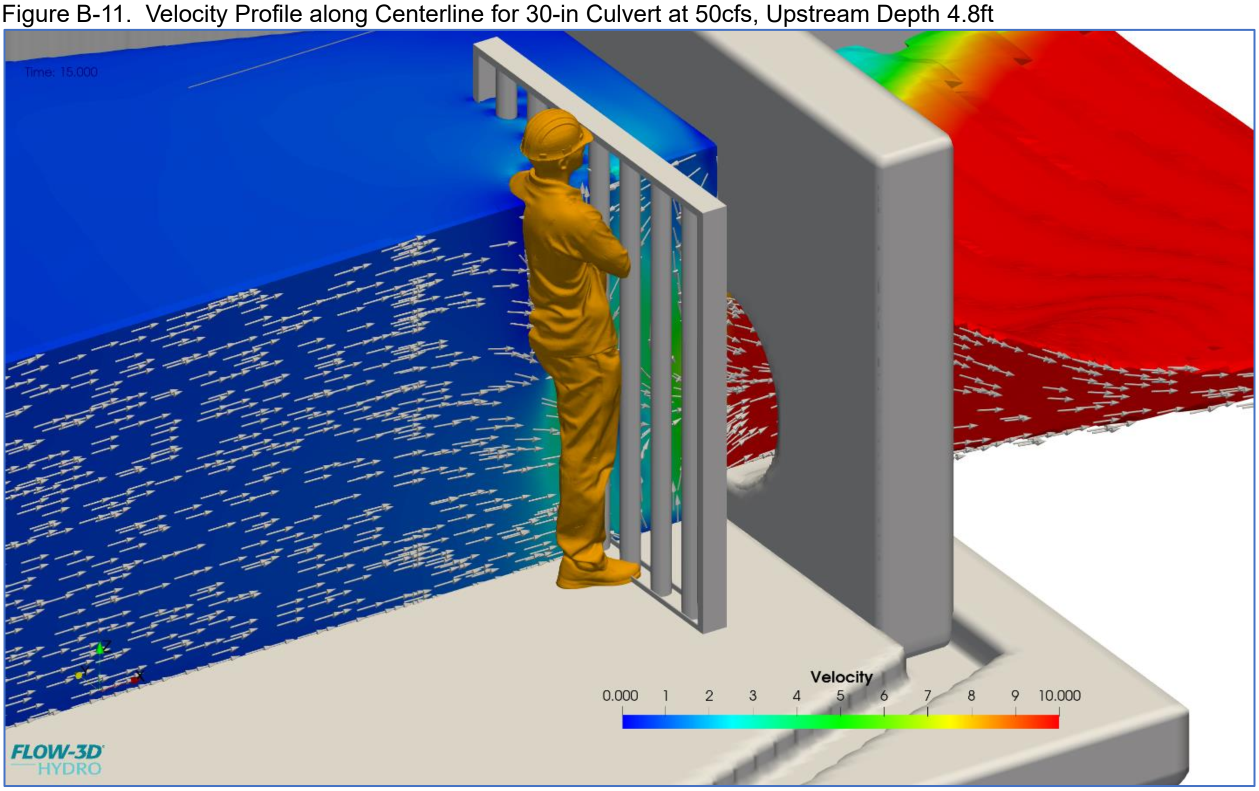

Figure B-12. 3D View of Velocity for 30-in Culvert at 50cfs, Upstream Depth 4.8ft

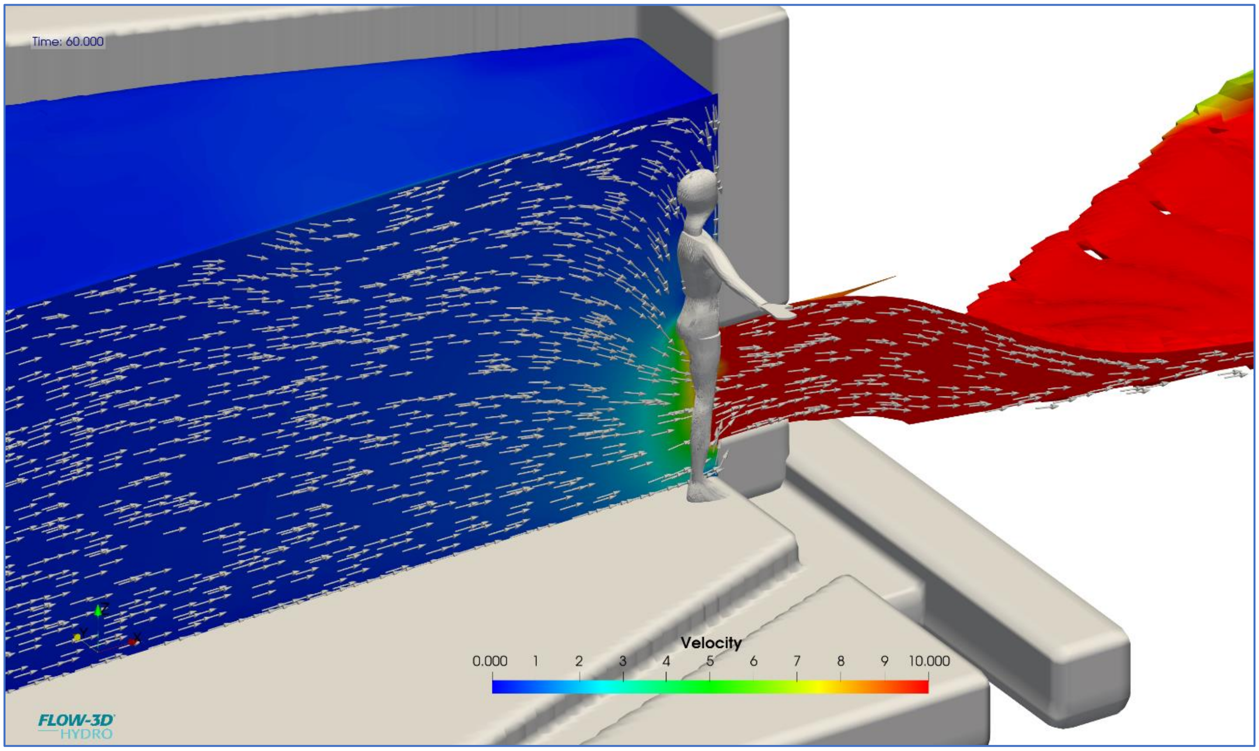

Figure B-13. 3D View of Velocity for 18-in Culvert at 21cfs, Upstream Depth 5.0ft

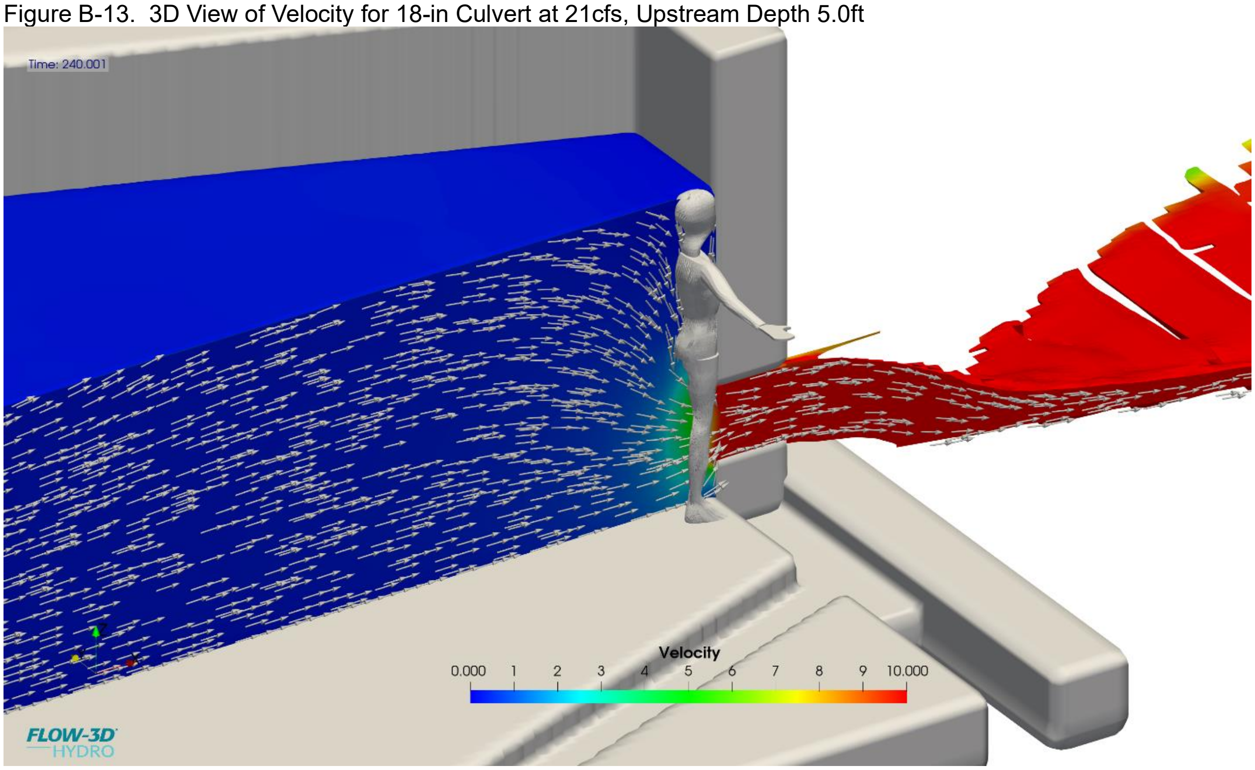

Figure B-14. 3D View of Velocity for 12-in Culvert at 10cfs, Upstream Depth 5.0ft

B-3. Selected Images for Flared Entrance Grates

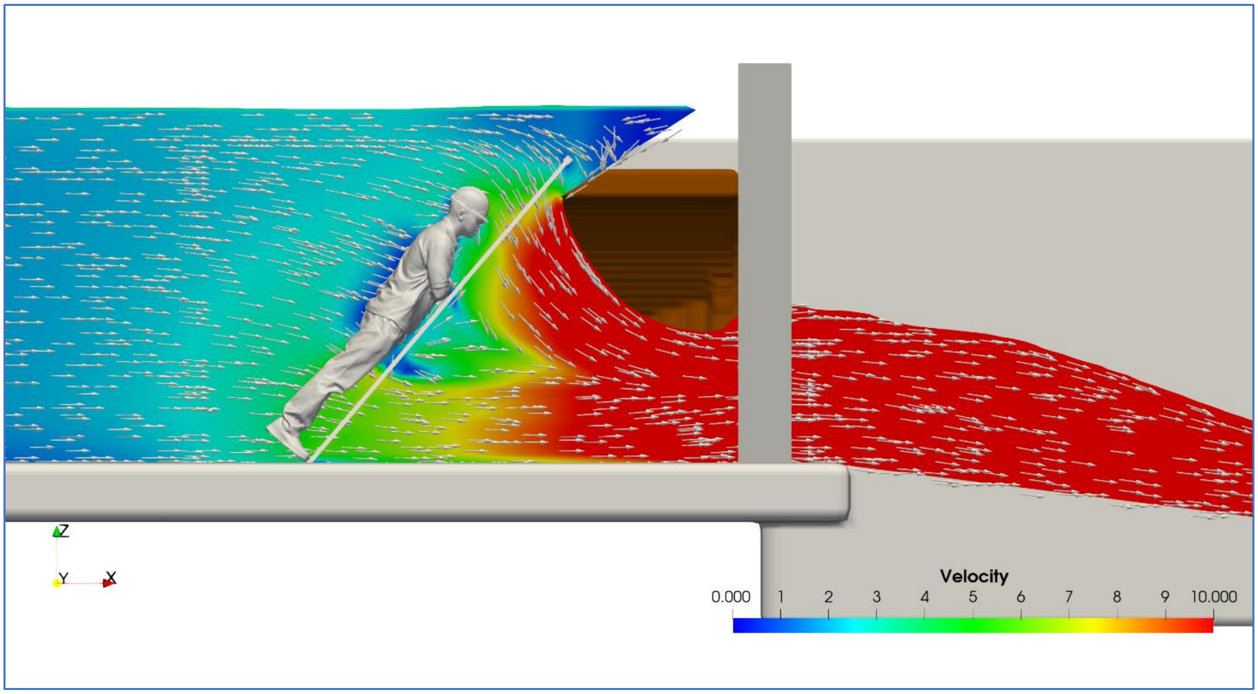

Figure B-15. Velocity Profile along Centerline for 60-in Culvert at 204cfs, Upstream Depth 6.7ft

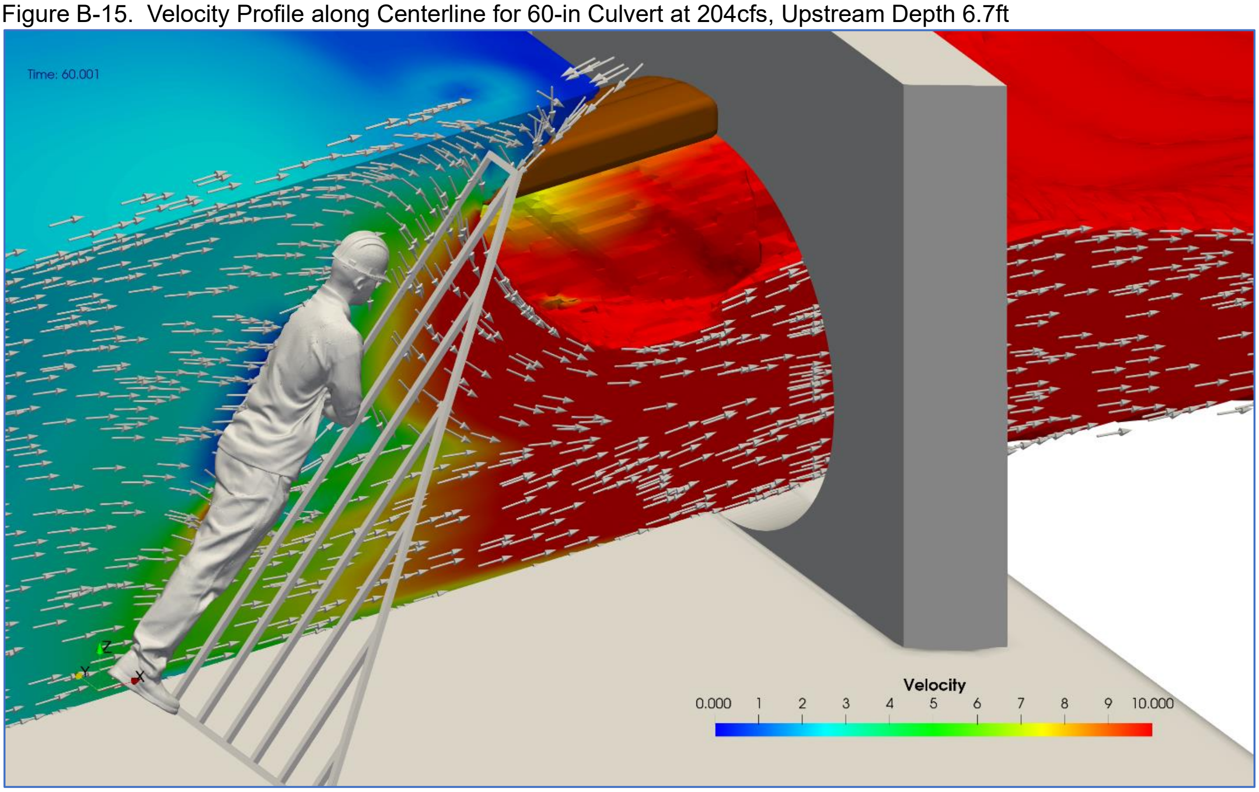

Figure B-16. 3D View of Velocity for 60-in Culvert at 204cfs, Upstream Depth 6.7ft

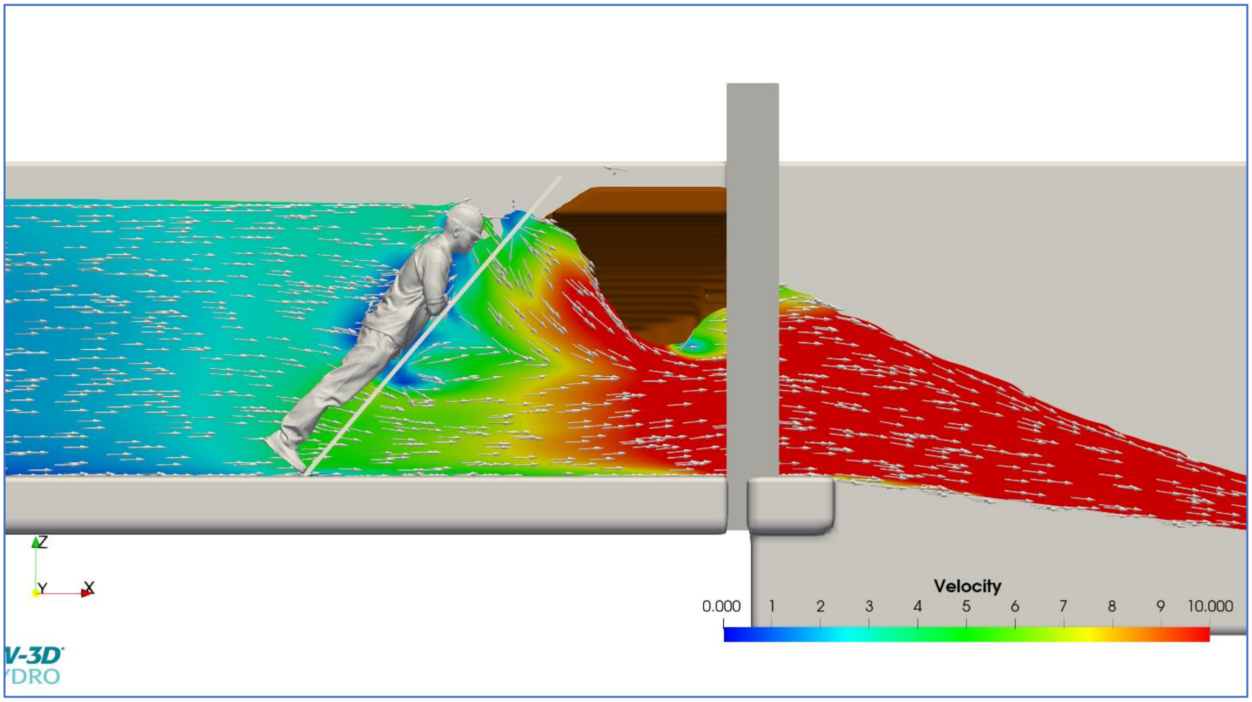

Figure B-17. Velocity Profile along Centerline for 60-in Culvert at 155cfs, Upstream Depth 5.2ft

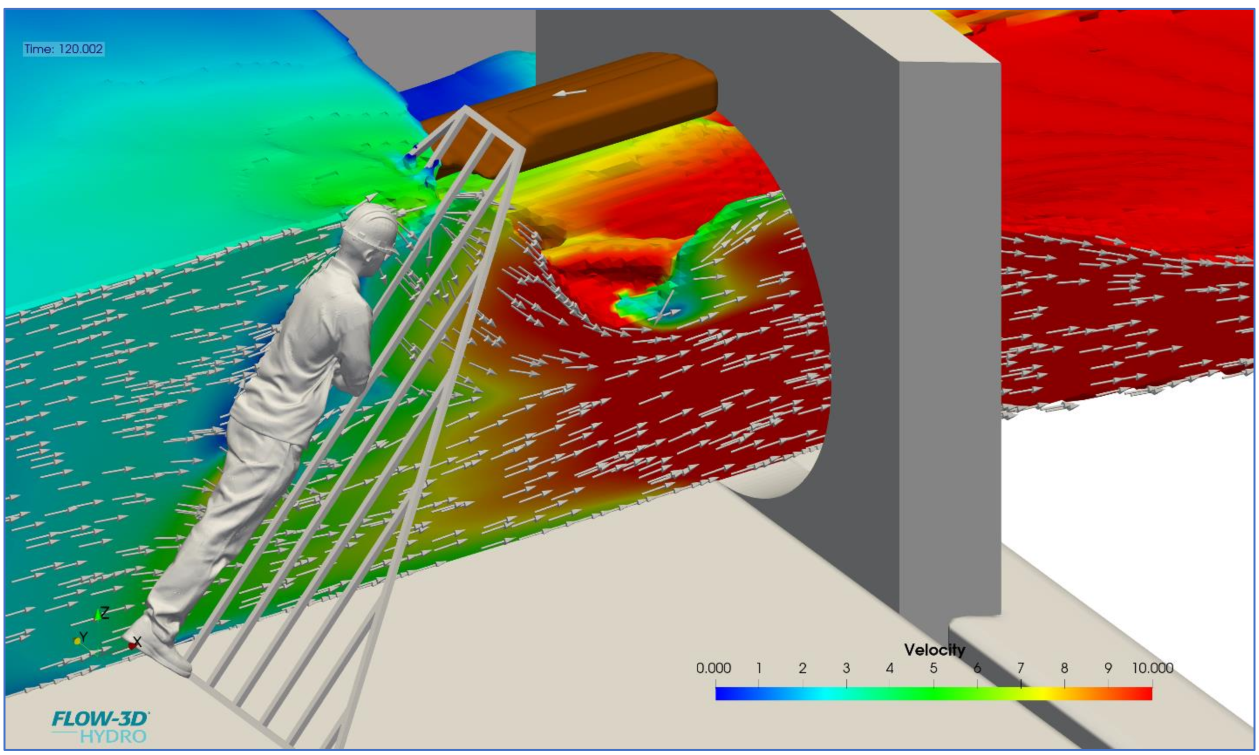

Figure B-18. 3D View of Velocity for 60-in Culvert at 155cfs, Upstream Depth 5.2ft

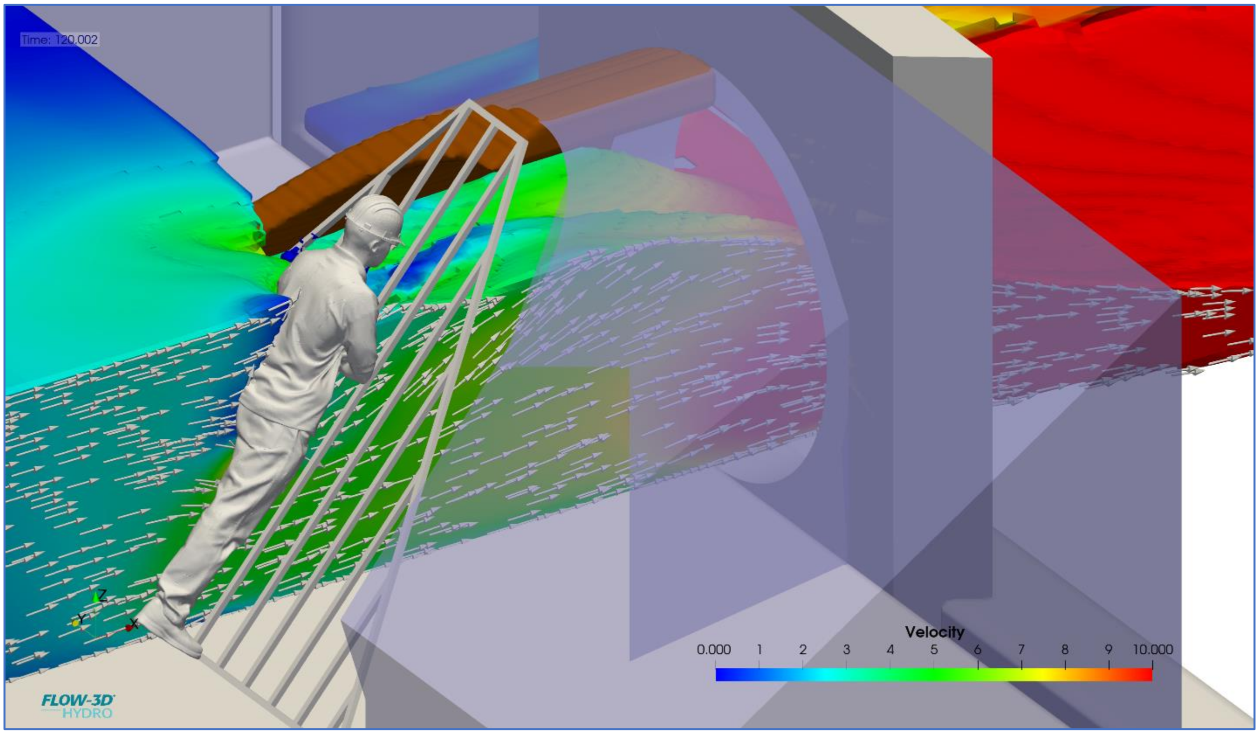

Figure B-19. 3D View of Velocity for 60-in Culvert at 105cfs, Upstream Depth 4.0ft

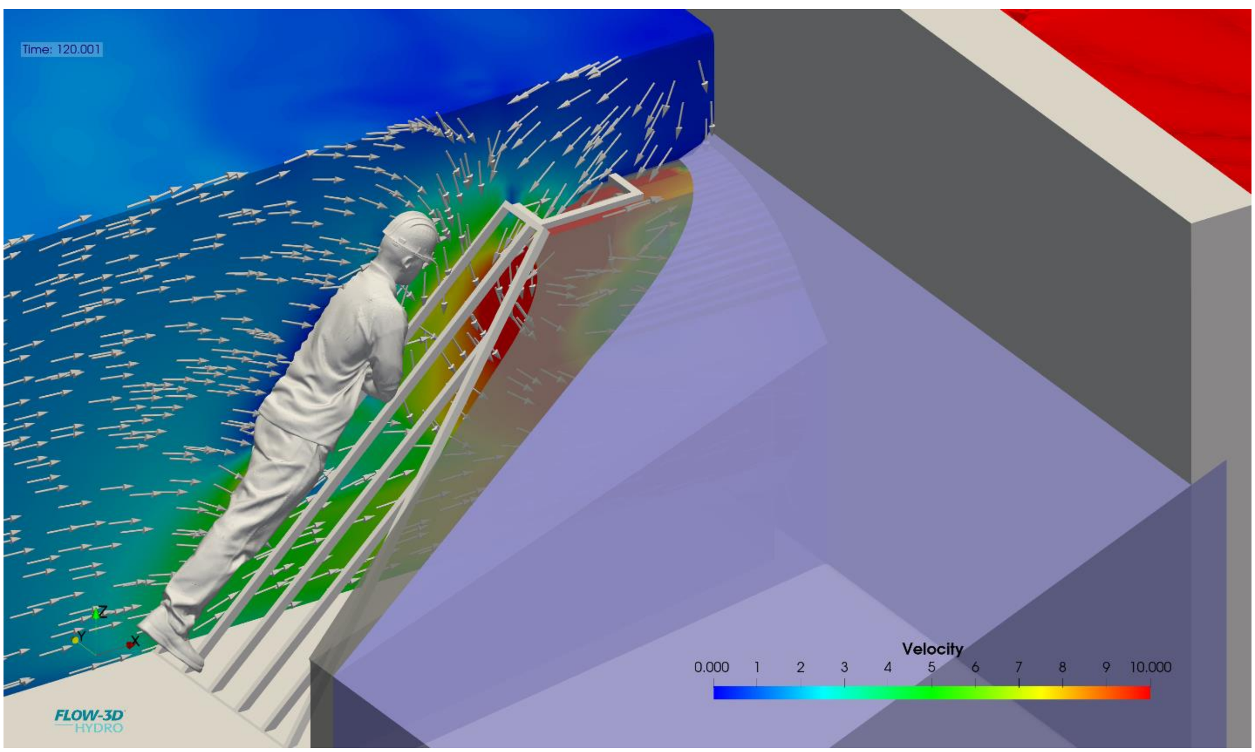

Figure B-20. 3D View of Velocity for 48-in Culvert at 115cfs, Upstream Depth 6.2ft

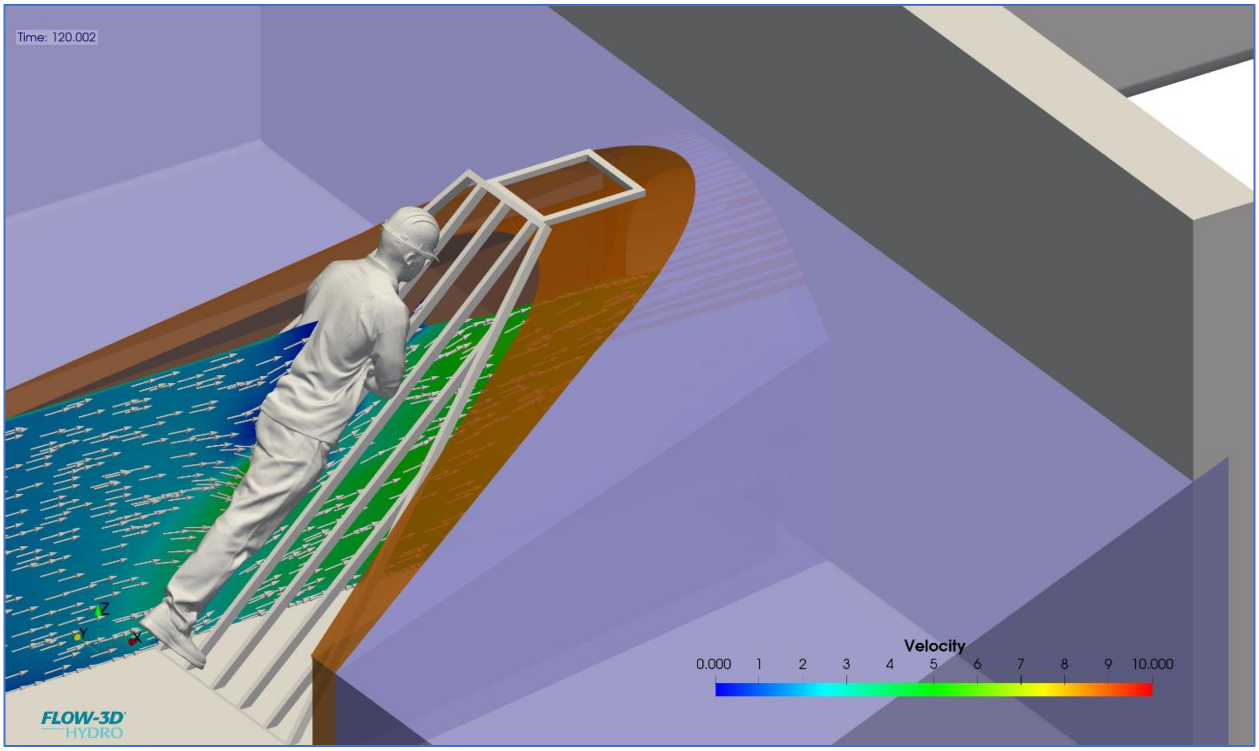

Figure B-21. 3D View of Velocity for 48-in Culvert at 75cfs, Upstream Depth 3.6ft

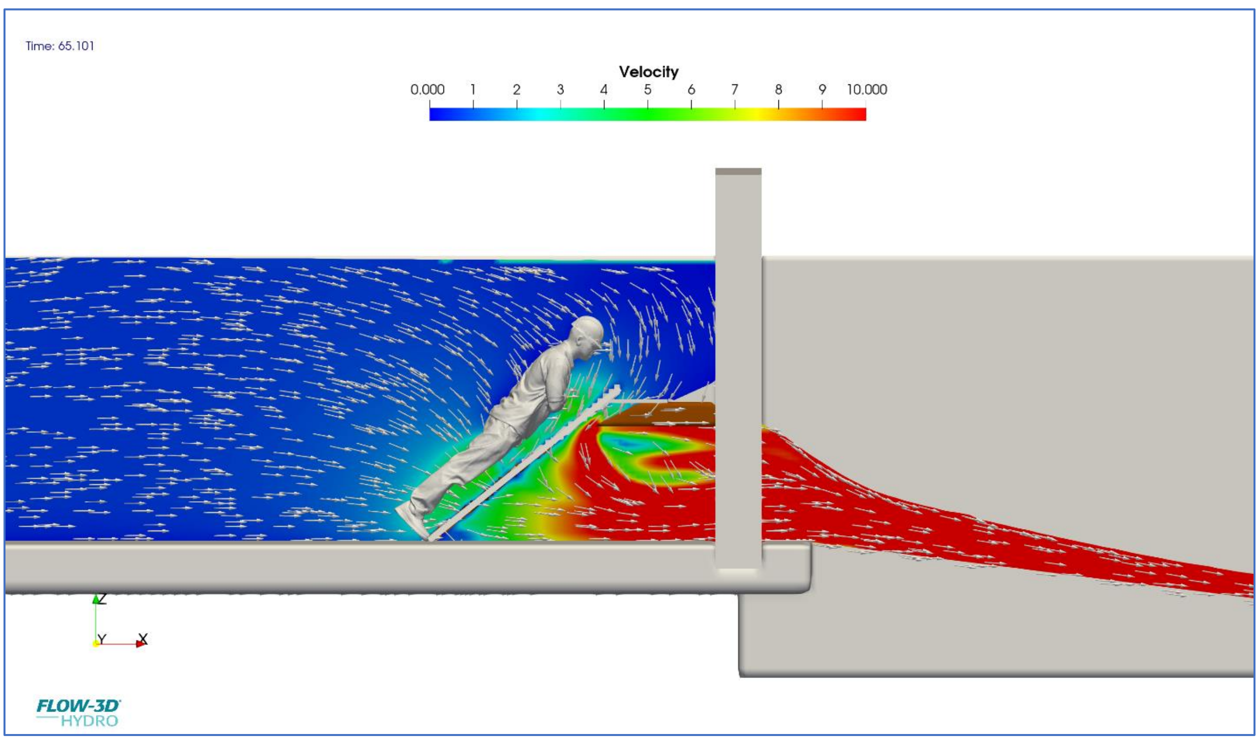

Figure B-22. Velocity Profile along Centerline for 30-in Culvert at 65cfs, Upstream Depth 6.0ft

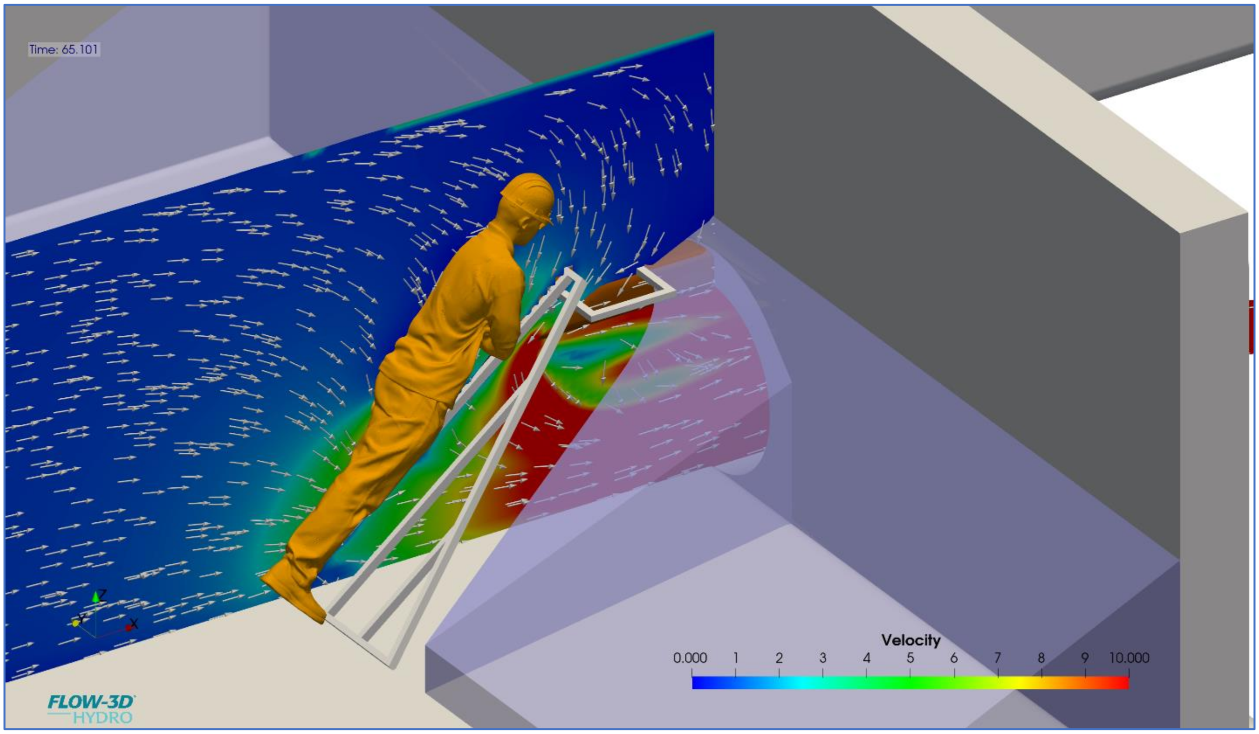

Figure B-23. 3D View of Velocity or 30-in Culvert at 65cfs, Upstream Depth 6.0ft

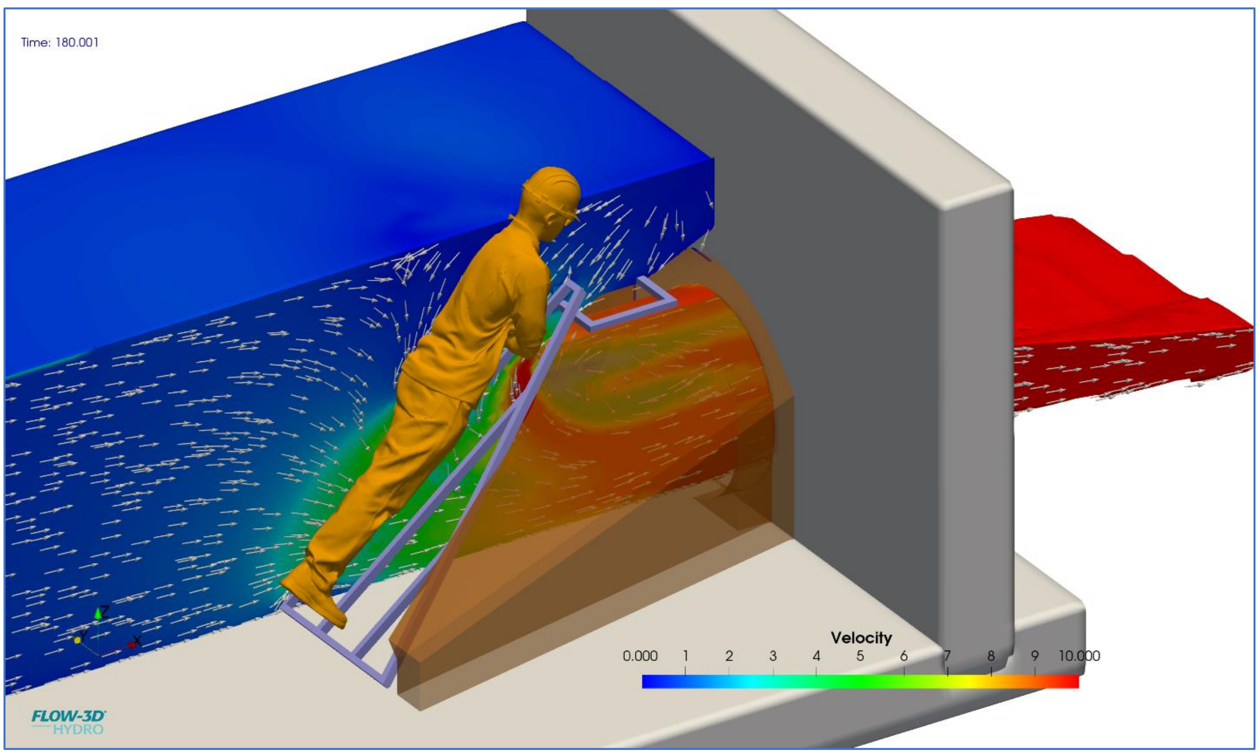

Figure B-24. 3D View of Velocity or 30-in Culvert at 50cfs, Upstream Depth 4.3ft

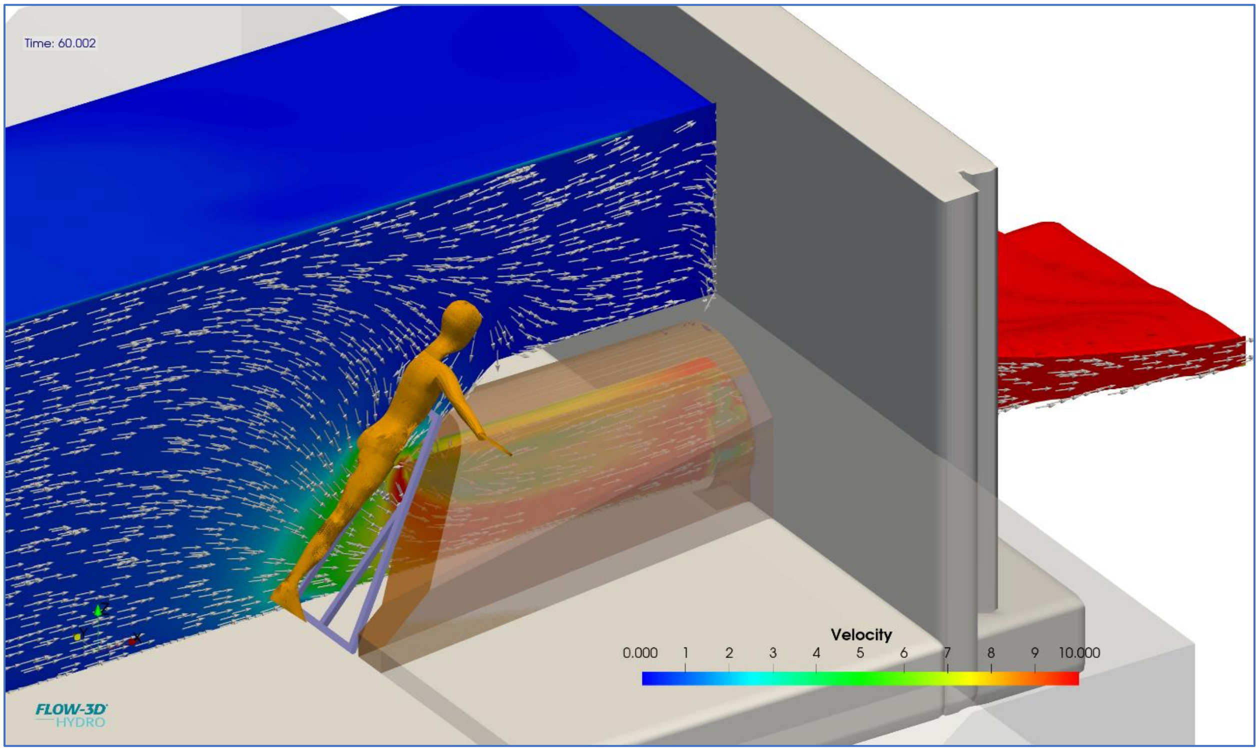

Figure B-25. 3D View of Velocity or 18-in Culvert at 22cfs, Upstream Depth 5.0ft

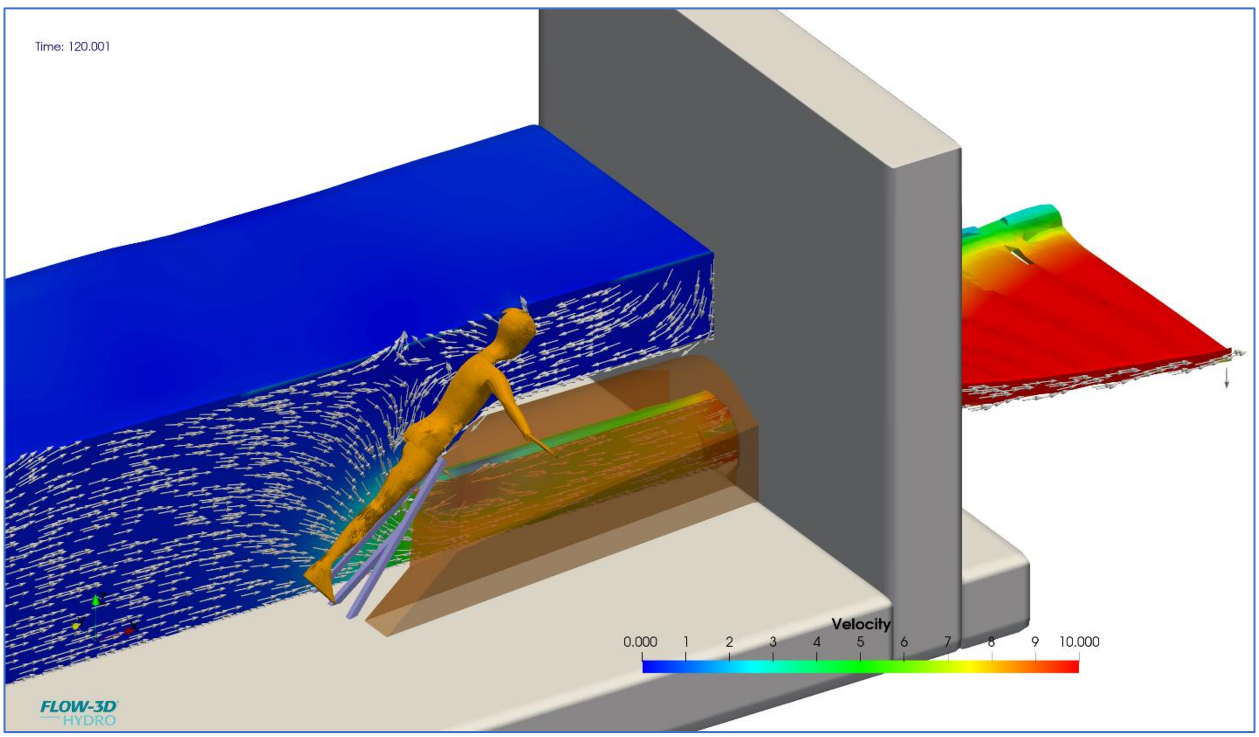

Figure B-26. 3D View of Velocity or 12-in Culvert at 8.4cfs, Upstream Depth 3.0ft