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TECHNICAL MEMORANDUM

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Subject: Safety Grate Recommendations for Circular Pipes

INTRODUCTION

MHFD has documented several pipe and culvert related fatalities across the United States based primarily on media reports (see Appendix 1). Of the injuries and deaths documented, most incidents have been related to smaller circular pipes ranging from a 12-inch to 54-inch diameter. In these instances, most victims were either playing in water or attempting to cross ponded water. The victims were primarily children (aged 6 to 17) and first responders. In many of these cases, the pipe opening was unprotected, and victims inadvertently entered or were pulled into the storm drain. In fewer cases, the storm drain opening was protected by a grate; however, the victims were unable to remove themselves from the grate. The total number of occurrences is unknown as there is no official agency that tracks how many Americans get pulled into storm drains or culverts during flood events. ProPublica identified 35 cases since 2015 using news accounts and court records. They reported that 21 of these people died and nearly half of those lost were children (ProPublica 2021).

MHFD partnered with Colorado State University's Hydraulics Laboratory (CSU), AECOM, and Larimer County Dive Rescue Team (LCDRT) to conduct flume tests and computational fluid dynamics (CFD) modeling to assess various culvert grate configurations and determine conditions that limited a person's ability to self-rescue. The details of these field tests and hydraulic modeling efforts are detailed in two publications (CSU 2024 and AECOM 2024). This memorandum is based on the findings in these publications, observations during the study, and MHFD's review of injuries and deaths related to pipe entrances. The memorandum serves to summarize this research and provide recommendations for when a safety grate should be installed on a pipe opening and what type of grate is needed. Recommendations will be included in future criteria for the Bridges and Culverts chapter of MHFD's Urban Storm Drainage Criteria Manual (USDCM).

KEY FINDINGS OF THE STUDY

As described in CSU's report, the primary findings are:

- The CFD model prepared by AECOM corresponded to field data collected in the flume.
- When a force on a human subject exceeds 110 lbf in the flow direction, the subject may find it difficult to free themself from a safety grate.
- A safety grate with a 1:1 (horizontal:vertical) slope and 12-inch offset from the face of the pipe orifice was suitable (did not exceed the design threshold of 110 lbf) in all conditions tested in the flume.
- Horizontal bars placed behind the sloped portion of the grate did not increase a person's ability to self-rescue and may restrict mobility during rescue.

LIMITATIONS OF THE STUDY

While a safety grate with a 1:1 (H:V) slope and 12-inch offset from the face of the pipe orifice (referred to as an "MHFD grate") was suitable in all conditions tested in the flume, flume testing was limited to approximately 200 cfs. CFD modeling primarily focused on openings from 12 to 60 inches in diameter and flows from 25 to 200 cfs. The relationship between discharge and force exerted on a body for each pipe size is shown in Figure 6-2 of AECOM's report. However, a single CFD run at 310 CFS was consistent with the relatively linear relationship between discharge and force. Governing force equations are linear in nature and thus models for this study are in line with these equations. This figure and all other figures referenced in this memorandum are provided in Appendix 2. Therefore, the safety grate configuration recommendations in this memorandum are relevant for flows up to approximately 300 cfs.

The finding that a force of 110 lbf is the approximate point where a person may start to have difficulty removing themself from a safety grate is independent of configuration and therefore not limited to a specific discharge. During the study, divers found they could navigate freely on the grate at this force. When force increased to 142 lbf with additional flow, one diver stated "It's hard – it's not easy for me" but divers experiencing this condition did not require assistance in removing themselves from the flume. Selecting a threshold force of 110 lbs is somewhat conservative for a healthy adult could approach 142 lbs. However, it is appropriate to select a conservative value as several of the cases in Appendix 1, identify children as the victims.

While a 1:1 slope proved to be adequate from a standpoint of safety, the research did not include evaluation of maintenance operations. A milder slope may help push debris to a higher elevation on the grate. A milder slope would also result in a larger grate area which would help maintain adequate capacity when partially clogged with debris.

This study did not include rectangular openings (box culverts). The MHFD grate may be suitable for rectangular configurations; however, additional modeling is needed to understand limitations for box culvert configurations using the MHFD grate.

This study did not include multiple pipe opening configurations. However, it is reasonable and potentially conservative to divide the flow by the number of openings and consider these openings the same as singular openings when their invert elevations are the same.

VARIABLES FOR DETERMINING RELATIONSHIPS AND CRITERIA

Because the force on a body is not known without CFD modeling, which is not typical in culvert design, the research team explored different variables that could be used in lieu of force. This would allow MHFD to develop criteria engineers can meet without detailed models. However, a CFD model could still be used for any configuration including box culverts to ensure the threshold force on a safety grate does not exceed 110 lbf.

The team explored using velocity at the face of the pipe opening (flow/area). See Figures 6-6 through 6-9 in AECOM's report for graphical representations. Velocity did not prove effective in developing criteria for safety grate design. The team also explored the ratio of headwater depth to culvert diameter (HW/D). Typical sizing of circular pipe culverts is based on this ratio which is typically limited to 1.5, beyond which additional measures are required to protect the culvert inlet. (USDCM 2016). While HW/D is not as straightforward as a known force in understanding when and how to provide pipe protection, the combination of HW/D and design discharge can be used as a surrogate for some safety grate configurations.

STORM DRAIN ENTRANCE CONFIGURATIONS

The physical and CFD modeling for this study evaluated different entrance configurations including:

1) A grate mounted flush to an orifice opening. The intent of this configuration was to safely produce a force on the divers similar to an opening with no grate while ensuring they do not pass through the orifice during flume testing.
2) A prefabricated flared end section (FES) with prefabricated grate, and
3) The MHFD grate with vertical bars spaced such that openings are 5 inches clear.

The AECOM report shows relationships between discharge and force for all entrance configurations. In general, as discharge increases under a given configuration, force on a body increases. Open pipes with no safety grate are most likely to exceed the threshold force, followed by prefabricated FES grates. The MHFD grate only just exceeded the threshold force in the CFD model at 310 cfs with an upstream flow depth of 11.5 feet on a 60-inch circular opening with a body standing on the floor. The total force for this condition was 113.5 lbf.

<u>Open Pipe (no Grate):</u>

Figure 6-3 in AECOM's report shows that for both 12-inch and 18-inch pipes, discharges below 20 cfs produce a force on a body that is below the threshold force of 110 lbf for the grate mounted flush to the orifice configuration. While CFD modeling did not extend beyond 21 cfs for the 18-inch configuration, the relationship suggests that the threshold force could be exceeded at approximately 25 cfs.

For this same configuration and a 30-inch opening, a discharge of 30 cfs produced a force of 244 lbf on a body, more than double the threshold force. The force on a 48-inch opening with a grate mounted flush to the orifice was just below the threshold force at a discharge of 35 cfs and exceeded the threshold force at 60 cfs. However, it would be uncommon to specify a 48-inch pipe for a design flow below 60 cfs.

For the reasons above, MHFD recommends that, when specifying circular pipe, a safety grate should be installed on the opening when the design flow is greater than 20 cfs. However, some of the deaths investigated as part of this study involved small pipes designed with head water depths greater than typical design values. Small pipes are sometimes used to restrict flows leaving detention basins. This configuration is especially dangerous when the opening is not protected and has caused multiple deaths. In these cases, the suction force on a person could pull someone into the pipe opening even when the design discharge is less than 20 cfs. For this reason, MHFD recommends limiting open grates to design discharges less than 20 cfs and where HW/D is less than or equal to 1.5.

Prefabricated FES Openings with Prefabricated Grates:

For the larger pipes in this study (48-inch and 60-inch diameter), the threshold force was typically exceeded for this entrance configuration once the discharge was more than 100cfs. This is shown in Figure 6-5 of AECOM's report. This figure also shows that the same is not true for smaller pipes studied (12 to 30-inch diameter). For pipe sizes between 12 to 30 inches in diameter, the HW/D becomes an important variable for consideration. Figure 6-10 in AECOM's report shows the relationship between HW/D and force. Based on the relationships shown, these pipe sizes can cause threshold force exceedances as HW/D increases beyond a value of 2. This means that for typical FES designs, a prefabricated grate will be sufficient. However, for FES inlet configurations with a design flow of 100 cfs or more, a custom grate will be needed to avoid exceeding the threshold force at the face of the grate.

MHFD Grate (1:1 slope, 12-inch offset from the face of the pipe opening, and vertical bars 5 inches clear):

Where open pipe and FES prefabricated grates are subject to the threshold force, this study found that the MHFD grate configuration was suitable under all other flow conditions. For this reason, MHFD recommends using this configuration for circular pipe entrances with design discharges between 100 and 300 CFS or where HW/D exceeds a value of 2 for pipe culverts 30-inches in diameter and less.

SUMMARY OF RECOMMENDED CRITERIA

The safety grate recommendations included in this technical memorandum are summarized below in Table 1.

Table 1

CONDITION	OPEN PIPE (NO GRATE)	FES WITH PREFABRICATED GRATE	MHFD GRATE
Design Discharge < 20 cfs and Design H/W≤1.5	suitable	suitable	suitable
Design Discharge < 100 cfs and H/W≤1.5	not suitable	suitable	suitable
H/W>1.5 or 100 cfs < Design Discharge < 300 cfs	not suitable	not suitable	suitable

The term “MHFD Grate” in this memorandum as well as the AECOM and CSU reports describes a grate that is offset 12 inches from the face of the pipe opening, has a 1:1 slope, and bar spacing five inches on center. The 12-inch offset serves to increase the distance between the orifice and a person, which reduces the force exerted on a person and can provide a step to aid in self-rescue (or a place for a first responder to stand while assisting a person attempting to remove themselves from the grate). LCDRT divers found the 5-inch on center spacing to be appropriate to limit foot entrapment and provide for some maneuverability while on the grate.

REFERENCES

AECOM (2024) *Storm Drain Safety Grates: Computational Fluid Dynamics Modeling Report*. Available at www.mhfd.org.Colorado State University (2024) *Physical Model Flume Tests of Storm Drain Safety Grates*. Available at www.mhfd.org

Propublica (2021) *Storm Drains Keep Swallowing People During Floods.* Retrieved April 26, 2024 at https://www.propublica.org/article/storm-drains-keep-swallowing-people-during-floods.

Mile High Flood District (MHFD) 2016. Urban Storm Drainage Criteria Manual, Culverts and Bridges (Chapter 11). MHFD: Denver, CO. Accessible at www.mhfd.org

APPENDIX 1 – Pipe and Culvert Related Fatalities

Date	Location	Pipe Diameter	Culvert Length	Fatalities	Age	Survivors	Description
5/5/1996	Kentucky	30-inch	>100 feet	1	9	1, injured	Tried to cross ponded water.
8/4/1998	Illinois	12-inch	0.5 miles	1	6	0	Playing in ponded water.
9/9/1999	Delaware	unreported	1500 feet	2	11, 12	1 (age 8)	Tried to cross ponded water.
8/17/2000	Colorado	48-inch	900 feet	1	37	0	Firefighter attempted rescue in ponded water. Ten to 12 feet of headwater at inlet.
9/23/2000	Ohio	14-inch	N/A	2	13	0	Boys playing in basin. It filled quickly to 15 feet of head on a 14-inch unprotected culvert.
8/29/2005	Kentucky	N/A	N/A	1	10		Playing near a drainage ditch.
9/20/2009	Illinois	unreported	unreported	1	56	0	Attempting to clear debris from the inlet of a detention discharge pipe.
2/19/2011	California	Approx. 15 ft wide Canal	2600 feet	2	16,17	0	Attempted to raft a small tributary and unintentionally entered a walled section followed by a long box culvert.
8/14/2013	Colorado	Under Motor vehicle bridge	N/A	1	17		Sought shelter during rain.
5/31/2013	Oklahoma	unreported	1200 feet	5	3 to 21	6	Sought shelter during a tornado warning.
6/20/2014	Nebraska	96-inch	1100 feet	1	29	0	Drove car into ditch and was swept into the culvert after escaping his partially submerged car.
6/30/2014	Iowa	54-inch	> 1 mile	1	17	1	Attempted to retrieve a flying disc.
5/19/2015	Louisiana	Small round pipe	unreported	1	15	0	Drowned after being swept into an unprotected irrigation drainage pipe on his property.
5/23/2015	Oklahoma	30-inch	600	1	44	1	Firefighter attempted to cross ponded water, swept into storm drain.
5/24/2015	Texas	24-inch	800 feet	1	14	0	Unobserved entry.
11/25/2016	Arkansas	unreported	25 feet	0	8 mo	1	infant ejected from car crash found in storm drain 25 feet away
9/9/2018	Kentucky	unreported	unreported	1	9	1 (12 yo)	Fell into drain while playing with friend swept by flood water.
9/11/2018	Louisville, Kentucky	Small round pipe	Approx. 360 ft	1	15	0	Reported to be playing near a drainage ditch in his backyard when he fell and was swept away through an underground drain into a neighbors yard. Died from injuries 2 weeks after event.
7/4/2019	Indiana	16 in	30 ft	0	5	1	Fell down a narrow storm drain.
1/1/2020	New Jersey	unreported	4000 ft	0	24	1	Swept into drain during flood. Flood water moving at 40mph, crushed her car
8/4/2020	Pennsylvania	Approx. 3 ft diameter, small round pipe	Approx. 20 ft	0	6, 16	2	6 yo was playing in the water and got sucked into a drain pipe. 16 yo dove in to save him. Both were transported through the pipe. Hurricane Isaias.
8/4/2020	Delaware	unreported	unreported	0	unreported	3	Bystanders trying to help people stuck in car on flooded road sucked into vortex and through a culvert. Hurricane Isaias.
7/10/2021	Missouri	Large box culvert	unreported	1	12	0	Girl sucked into drainage system after exiting flooded car
9/1/2021	Maplewood, New Jersey	36 in to 3 ft	unreported	1	31	0	Man sucked into drain while crossing a flooded road (Hurricane Ida) on foot with his girlfiend after parking his car in the high flood waters. He was unable to be saved when rescuers couldn't reach him and ended up saving the chick-fil-a employee at the same time when they spotted him.

Date	Location	Pipe Diameter	Culvert Length	Fatalities	Age	Survivors	Description
9/2/2021	Maplewood, New Jersey	36in	unreported	0	18	1	Chick-fil-a employee headed home after work while he was waist deep in water searching for the sidewalk when he was pulled into a ravine through a narrow swere pipe. Was found in a tree while police were searching for 31 yo man above.
9/1/2021	Maplewood, New Jersey	3ft wide tunnel under ground	unreported	1	55	0	Trying to clear/unblock the storm drain of debris between his and his elderly neighboors house. Was sucked into the storm drain and died (From Hurricane Ida in New Jersey in 2021).
9/1/2021	New Jersey	Circular	unreported	2	18 and 21	0	2 College students swept into drain after their car had oveturned and they were trying ot get out (Hurricane Ida)
9/5/2021	Queens, NY	unreported	30 feet	0	47	1	Unknown situtaion. Man fell down a storm drain and was rescued by firefighters. Sustained a leg injury.
8/9/2022	Tennessee	Aprox. 3 ft, circular	unreported	1	37	2, child and father	Drowned trying to save child that had fallen into a drainage culvert
8/30/2022	Arkansas	Sinlge boxed Culvert and Arched Pipe culvert	unreported	1	11	2	11 year old swept away after playing near a retention, 47 year old women tried to rescue him
11/8/2022	Oregon	Approx. 2x3 grated drop road drain	unreported	1	65	0	Found in drain below his mailbox
1/27/2023	Maui, Hawaii	4 feet	800 yards	1	24	0	Firefighter responding to storm in Kihei, along Maalaea Bay on the western side of the island. He was swept into a strom drain and carried out to sea. He died over a week later from his injuries - family is sueing.
3/31/2023	Arlington, Texas	short parking lot drain	0	0	unreported	1	Elementary aged girl chased an apron into a storm drain and got stuck
7/25/2023	Toronto, Canada	Large Drainage system - 20 feet wide drain at exit into pond	300m to 984.25ft	1	18	1	Two boys adventuring in storm drain system in Toronto Park. Water levels rised too quickly and one of them ulitmately died after being swept away, the other boy climbed to safety.
11/5/2023	Texas	Large Roadside drain - Still under construction	15 - 20 feet	0	Unreported	1	Man fell into storm drain that was covered with plywood
12/27/2023	Australia	36 in	unreported	3	9 and 2 young females	1	A nine year old was swept into a flooded storm drain (Brisbane, Australia) and then 3 women were exploring the popular storm drain and were swept as floodwaters began to surge through the town. One women survied the other two died
1/7/2024	Spain	Unkown Size - Large box storm drain	5 meters	0	unreported	1	Man involved in motor accident climbed out of the car window and fell into a storm drain
3/2/2024	Florida	3x3 ft flat parking lot drain (google earth)	unreported	1	28	0	Drowned after falling into drain after removing grate to reach for his keys
4/1/2024	Daylesford, Australia	Approx. 3 ft	0 ft	0	58	1	Woman slipped down an embankment and into a drain. Was able to self rescue.
4/2/2024	Oklahoma	42 in	104 feet	1	46	0	Homeless woman and her boyfriend were sleeping in the entrance of the drain and was awoken by flood waters.
5/8/2024	Tennessee	<24" circular (approx.)	500 yrds	0	10	1, injured	Playing in water where a storm drian, then was swept into the storm drain and came out after going under the streets. On life support due to injuries.

APPENDIX 2 – Referenced Figures from AECOM (2024) Report

Note: All data in this appendix are AECOM's CFD models.

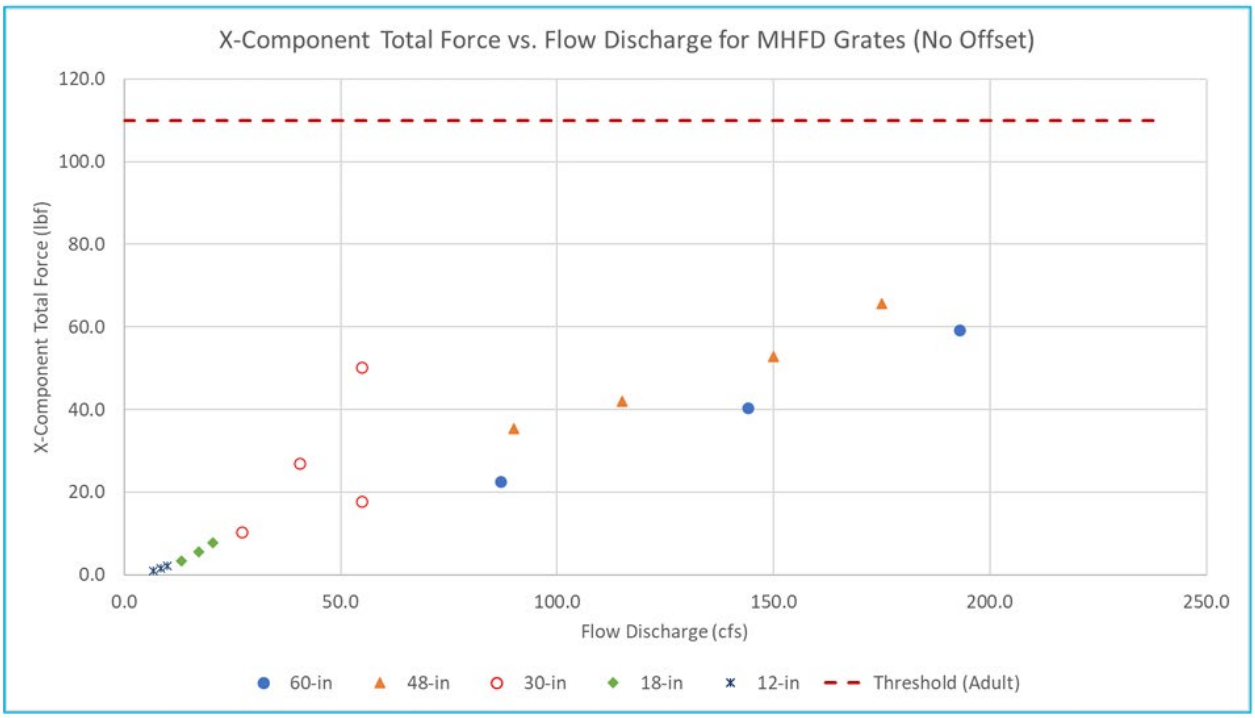

Figure 6-2. Relationship between Total Force and Flow Discharge for MHFD Grates (No Grate Offset)

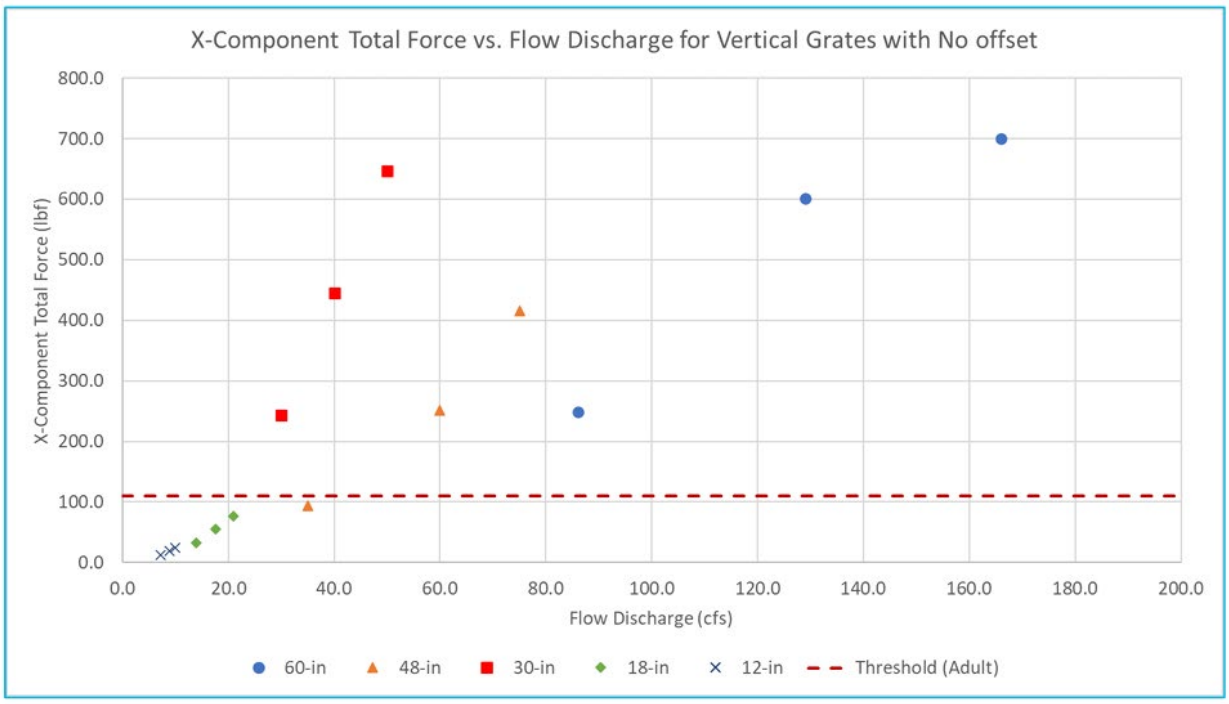

Figure 6-3. Relationship between Total Force and Flow Discharge for Vertical Grates (No Grate Offset)

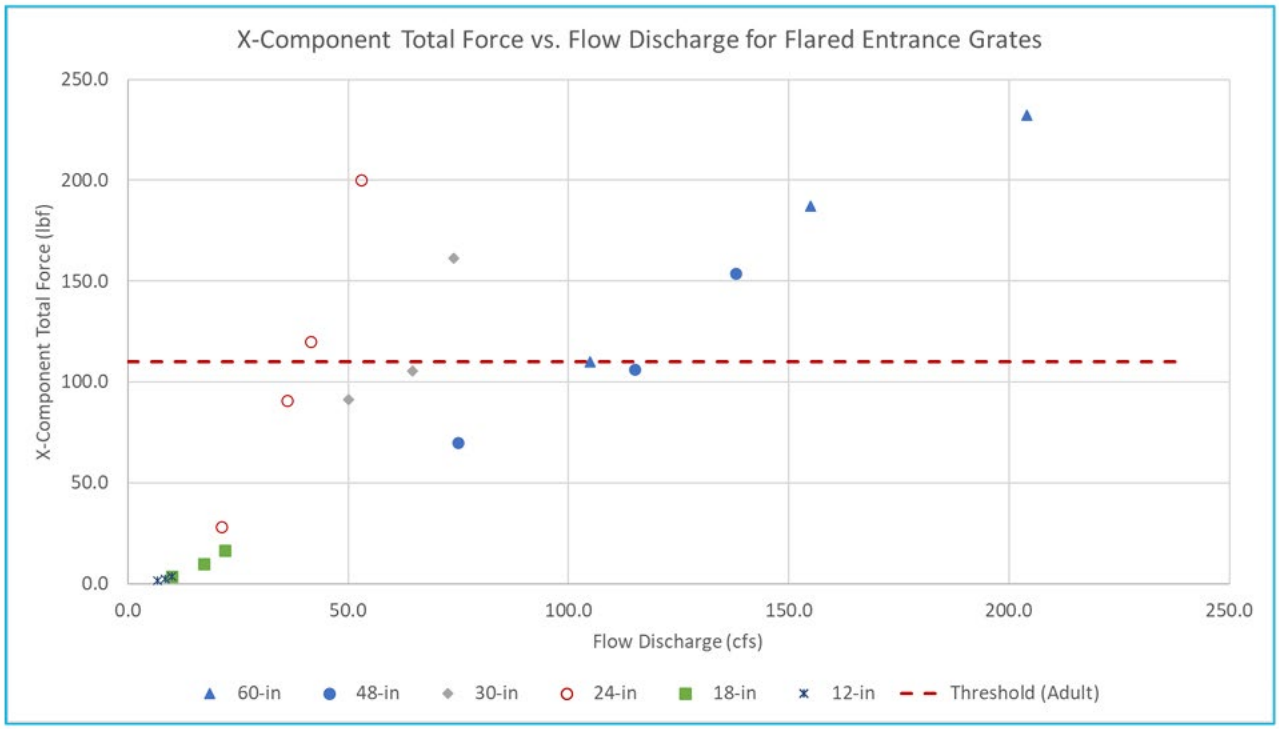

Figure 6-5. Relationship between Total Force and Flow Discharge for Flared Entrance Grates

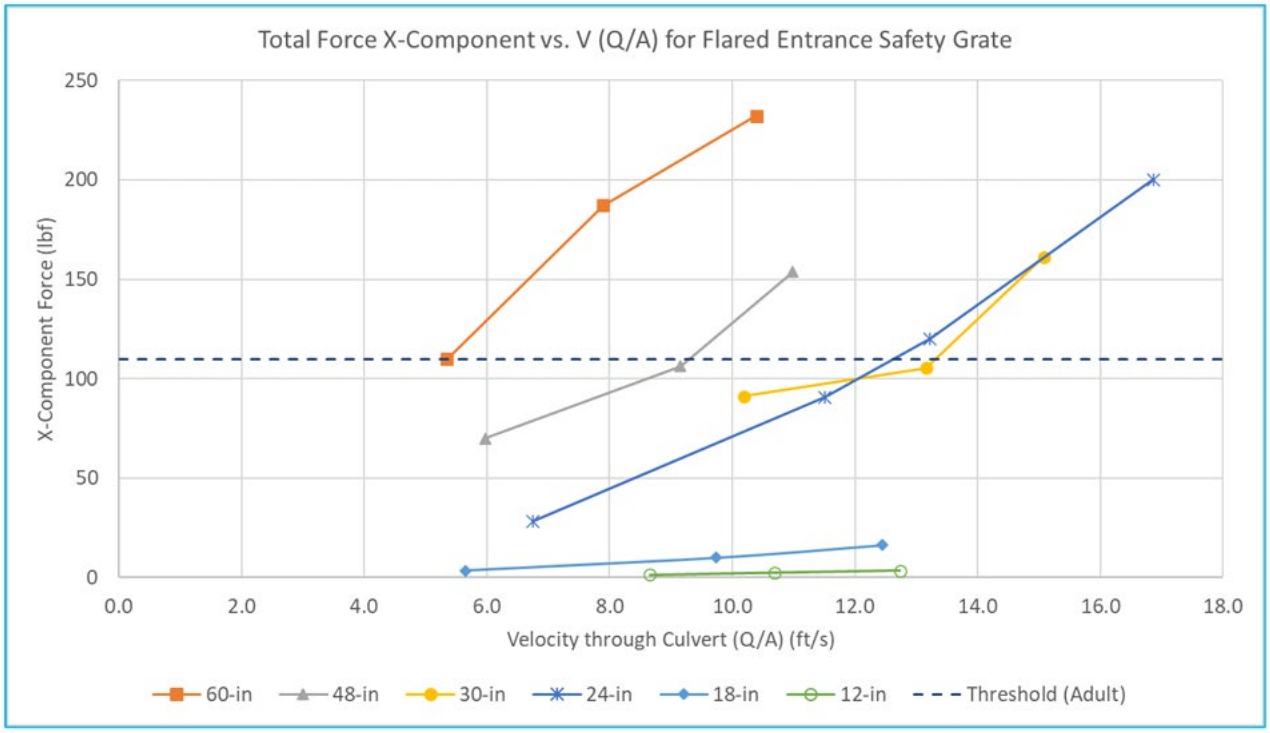

Figure 6-6. Relationship between Total Force and Velocity for Flared Entrance Grates

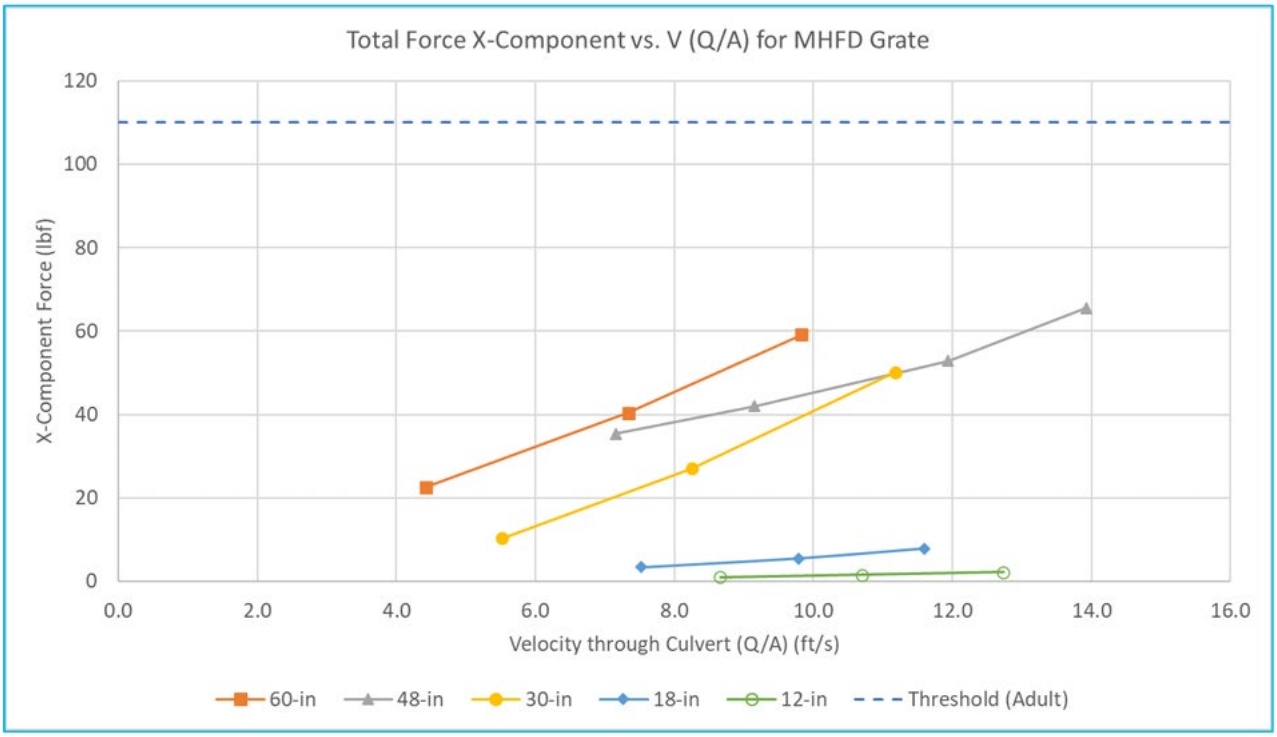

Figure 6-7. Relationship between Total Force and Velocity for the MHFD Grates

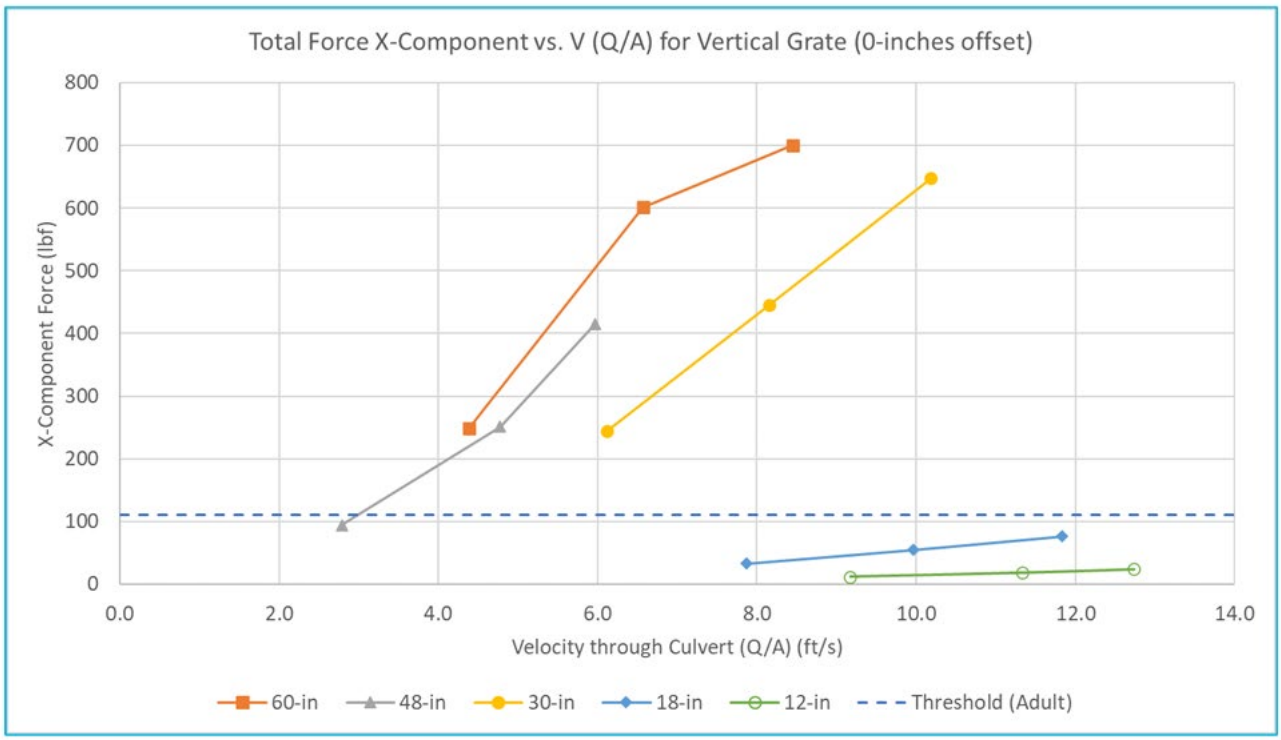

Figure 6-8. Relationship between Total Force and Velocity for Vertical Grates with 0-in Offset

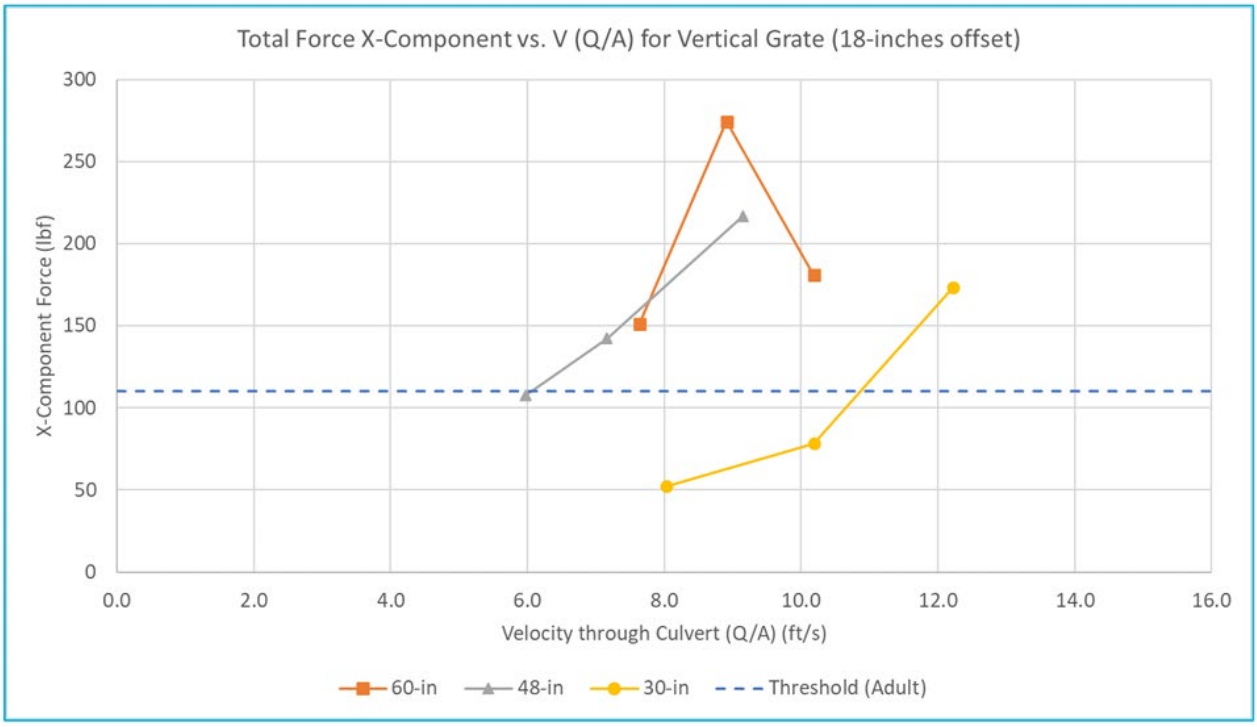

Figure 6-9. Relationship between Total Force and Velocity for Vertical Grates with 18-in Offset

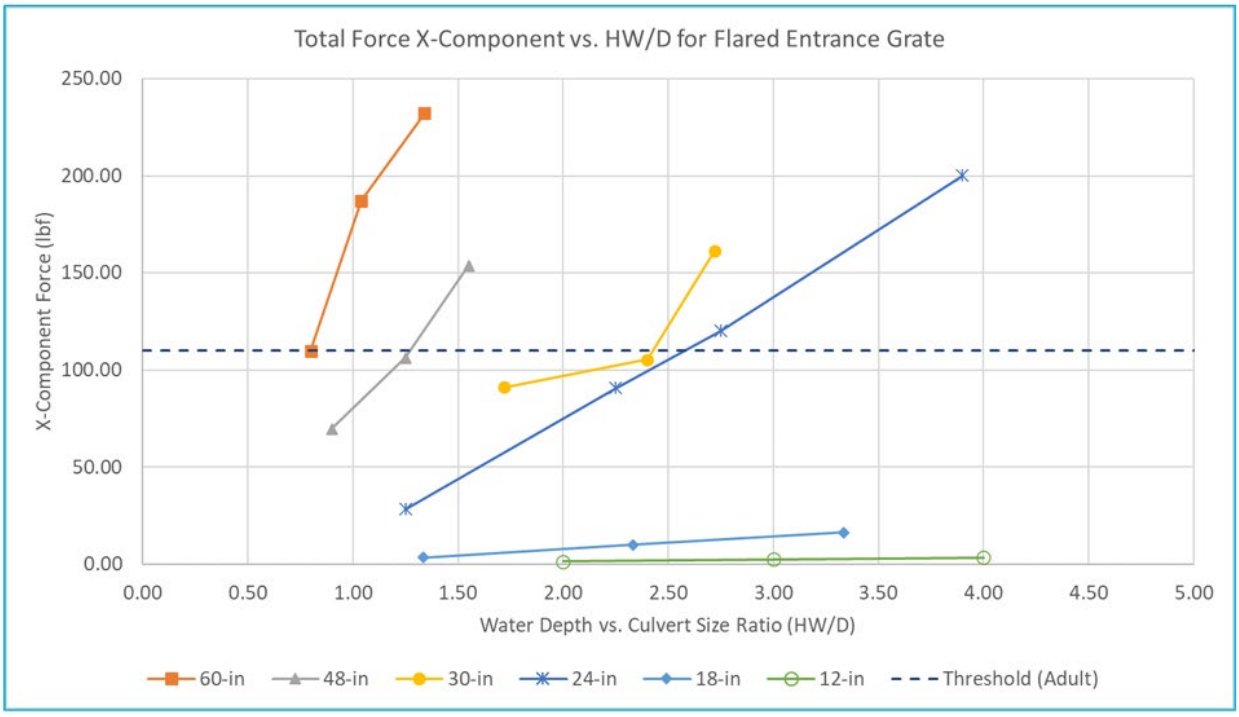

Figure 6-10. Relationship between Total Force and HW/D for Flared Entrance Grates