How Accurate Are Gravity Sewer Flow Meters?

The following discusses the various flow monitoring technologies for use in gravity sewers and their ability to measure accurate flow rates. Before jumping into the various theories of operation and technical aspects of each instrument, let’s dispel of a few broad-sweeping statements that will be referred to throughout this discussion:

1. *Flow monitoring equipment does not measure the flow rate.*
   
   True. Flow monitoring equipment measures the parameters used in formula to calculate a flow rate.

2. *The accuracy of each sensor determines the accuracy of a calculated flow rate.*
   
   False. In addition to sensor precision, each sensor must measure the correct parameter. Depth of flow and other geometric measurements are used to derive the wetted area. Velocity measurements must yield an average velocity of the measured cross section. To put into other words, successfully climbing a ladder to the roof fails if it is not leaning against the right wall.

3. *The continuity equation requires a depth and a velocity measurement to accurately calculate the flow rate.*
   
   False. The continuity equation requires measurements of the wetted area derived from depth, pipe geometry and silt, along with the average velocity, not a velocity. Because gravity sewer hydraulics are non-uniform, not always free-flow and highly unpredictable, variable silt levels and unstable average velocity spectra present significant challenges when deriving accurate flow rates.

4. *Some equipment does not require calibrations to accurately measure the flow rate.*
   
   False. This proclamation is among the most widely abused by manufacturers that misleadingly equate sensor precision with flow rate accuracy. Accurate sensors do not mean accurate flow rates, because they must also measure the correct parameter. For example, depth sensors measure the depth of flow, but not changes in the wetted area due to varying silt levels. Point velocity sensors measure a velocity at a location, but not the average velocity nor any underlying hydraulic influences such as backwater or induced head pressure.

   Precision differs from bias. Hydraulic Profile calibrations are used to confirm both sensor precision and bias to validate flow rate accuracy. They must be obtained routinely to confirm any changes in geometry, the average velocity and the resultant flow rate as it compares to the meter’s calculated rate.

5. *For most meters, the depth and velocity are not that different for measuring accurate flow rates.*
   
   False. What they measure, the theories of operation, performance envelopes, technology and processing algorithms all differ. As a result, each has strengths and optimal applications; all have weakness and are often misused.

To understand accuracy, we must first understand the means by which accuracy is validated. “Calibrations” are a widely generalized expression for which other terms are more appropriate:
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1. **Calibration** (sensor precision) – a comparison of measurements, one being a control standard. With respect to sensor precision, manufacturers calibrate equipment; the flow service provider really doesn’t. This term is very general and used industry wide, though somewhat misleading. In practice, a calibration compares a manual sensor value with the meter sensor value. While a graduated depth tool (ruler) might be a sufficient standard, a manual velocity (i.e. electromagnetic) is not really a standard, just another device. Among manufacturers, the returned meter velocity values differ. Some are acquire localized point velocities, some obtain the peak value and others derive an average of the returned values.

2. **Confirmation** (compares sensor values) – a manual measurement used to evaluate sensor precision, not flow accuracy. This is often used interchangeably with the term calibration. In practice, it is used to determine if the returned depth and velocity sensor values are “close enough” to another device.

3. **Hydraulic Profile Calibration** (flow rate accuracy) – measurements used to determine flow rate accuracy by comparing a manual derived flow rate to the meter’s calculated flow rate. It is often shortened to a Hydraulic Profile and incorrectly shortened to the term “velocity profile,” which is just one component of the Hydraulic Profile. A Hydraulic Profile involves (a) a manual depth of flow measurement, (b) a velocity profile, and (c) geometric measurements of the flow cross-section.
   a. Manual Depth – measurement from the bottom of the pipe invert to the surface of the flow
   b. Velocity Profile – a set of velocity readings integrated to produce an average velocity throughout the entire cross section of flow
   c. Geometric measurements of the flow cross-section – the cross sectional area of the pipe (generally fixed) and the level of siltation (dynamic). Both are needed to develop the cross-sectional area of the flow, which will change over time due to changing silt levels.

4. **Verification** – a client specific term. In some cases, it refers to a hydraulic profile, in others a confirmation. In most cases, it compares sensor values.

**What is Accuracy?**

Accuracy is determined by an instrument’s precision and its bias. Precision (repeatability) is how close the returned values are to each other, whereas bias (deviation) is how far the value is from the actual (true) value. An accurate device must have high precision and low bias.

As an example, surface velocity sensors tend to be highly precise (repeatable); they are highly likely to return the value they are designed to acquire, over and over again. But, does this mean they...
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are accurate? On the other hand, pressure sensors are rather imprecise, but can hover around the correct depth values for some time.

Since accuracy also requires an understanding of bias, we need to ask, “What is the correct answer?”

The Correct Answers

**Average Velocity and the Wetted Area**

The continuity equation is the product of the Area (A) and the **average velocity** within a cross-section, not just a velocity. It requires a sensor to return the average velocity values or provide the ability to reliably and consistently interpolate an average from the returned values. Without average velocities, hydraulic conditions of backwater, reverse flow, pressurized flow, undertow, eddies and transverse flow will go unrecognized and severely reduce the accuracy of the measured flow rate. The continuity equation is:

$$Q_c = V_{\text{avg}} \times \text{Area}$$

**Velocity Measurements**

Various technologies are used for the measurement of the velocity in open channel, gravity flow applications. Despite the technology, the correct value for use in the continuity equation is the average velocity rather than a velocity. For this discussion, the technologies have been segregated into two groups, Multiple Point and Point velocity.

**Multiple Point Velocity Technologies**

These technologies penetrate the cross-sectional area to obtain an average velocity.

**Continuous-wave Doppler**

Primary manufacturers include HACH, ISCO, FloWav, ADS and Badger. These technologies measure the frequency shift (Doppler Principle) as sound is reflected from particles within the flow. A beam of sound penetrates the cross section of flow where a velocity spectrum is generated from each firing. Different algorithms are used by each manufacturer to process the signals to derive the average velocity.
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The effective range of Continuous-wave Doppler velocity technologies that use a “fixed beam” is less than thirty inches (30”). Exclusive to ADS, “adjustable” velocity parameters enable the user to ramp up the sensitivity for use in larger depth of flow applications, up to one-hundred inches (100”), depending on turbidity.

The stated effective range varies among manufacturers, along with the repeatability. Most have stated velocity ranges between 0.5 fps to 15 fps. However, only a couple products can measure reliably above speeds of 7.5 fps. Some, not all manufacturers offer the ability to also record reverse velocity. Relative accuracies for recording average velocity for most Continuous-wave Doppler technologies are achievable to within +/- 10%.

Because this equipment is submerged, it is prone to debris and requires more frequent maintenance than non-contact sensors.

**Pulse Doppler**

Primary manufacturers include ISCO, ADS and Sontek. Derived from ocean wave measurement applications, this technology refines the Continuous-wave Doppler technology by associating the readings to their locations within the measured cross-section. Instead of a single velocity spectrum from Continuous-wave Doppler, Pulse Doppler incorporates multiple velocity spectra (“bins”) to integrate an average.

The effective range of this technology requires a minimum of nine inches (9”) of flow depth to transmit and receive reading location measurements. For this reason, this technology is better suited for large pipe applications.

Relative accuracy outperforms “fixed beam” Continuous-wave Doppler technologies for flow depths in excess of thirty inches (30”) and compares favorably to adjustable continuous-wave.

**Chordal velocity**

Primary manufacturers include Badger Meter and Accusonics. Also referred to as “time-of-flight,” this technology measures the sound signal lag between a transmitter and receiver induced by the speed of the flow. Multiple chords are used to capture the average velocity across multiple velocity contours.

Developed initially for hydropower applications, this technology is generally limited to larger pipes above forty-eight inches (48”) to provide sufficient space for the transmitters and receivers, and sufficient minimum flow depth above the lowest beam location. Multiple beams are required to increase the accuracy. This is the most expensive of the technologies evaluated, however accuracies within 5% are achievable.

**Point Velocity Technologies**

These technologies measure a specific point within the flow and require interpolation to derive an average velocity.
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Electromagnetic

Primary manufacturer is limited to HACH. Derived from potable water applications, this technology measures the voltage drop induced by the flow current. The effective range for electromagnetic sensors is within a magnetic flux of approximately three inches (3”) at the location of the probe. Installed along the wall at the bottom of the pipe, it measures the slowest velocities despite changes in depth. For this reason, this technology has been abandoned as a viable continuous measurement of velocity because of its limited and isolated range of measurement. On occasion, this technology creeps into unsuspecting flow monitoring programs only to result in additional analysis efforts and highly questioned data by modelers and end users.

Since the effective area of electromagnetic velocity sensors is within a three inch (3”) magnetic flux zone, they are highly proficient at obtaining discrete velocities for use in developing an average velocity profile.

Non-Contact Velocity

Primary manufacturers’ products include ADS CS5, HACH FlowDar and ISCO Laser. Also marketed as microwave and laser, non-contact velocity sensors capture a surface velocity value, penetrating less than a half inch (½”). The ISCO Laser claims to penetrate four to six inches (4-6”), which still limits the measurement of the entire cross section for large pipe applications.

These measurements are not the average velocity needed for the continuity equation. Instead, they are “point velocities,” capturing the speed of the flow at only a specific location, the surface. Localized readings must be interpolated into an average. This becomes increasingly more error prone the deeper the depth of flow. For example, if only the first half inch (½”) within sixty inches (60”) of flow is measured, the average velocity for the remaining 59 ½ inches of flow is indeterminate.

This methodology is very similar to the application of electromagnetic velocity readings, which have been long-regarded as inferior and unfit for use in gravity sewer installations. Errors in the “point” velocity readings alone can exceed three-hundred percent (300%) due to the difficulty in deriving a depth to discharge relationship from only an isolated measured location.

Since point velocity devices fail to capture the average velocity, each meter velocity value must be correlated to an average at
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various depths, from shallow to full pipe. This requires an extensive amount of “hydraulic profiles” to develop a depth to discharge relationship based on the correlation of each point velocity reading to a manually calculated average. Still yet, the technology is incapable of accounting for non-uniform flow characteristics beneath the surface such as backwater, undertow, swirling, in addition to the effects of head pressure and pump stations.

These devices are installed in the manhole chamber where the depth sensor is not within the same plane of measurement as the measured sensor. Error is introduced, especially where the manhole transition is not uniform or where there is a wide range of flow depths. This can be overcome by installing a secondary in-line ultrasonic depth sensor, if available by the manufacturer.

**Optimal Use on Non-Contact Velocities**

Like electromagnetic sensors, non-contact surface velocity sensors are not fit for use as the primary velocity measurement device for most applications. Failing to measure the velocities below the surface induces significant errors in volatile hydraulic locations prone to non-free flow conditions.

The use of these sensors is limited to locations where hydraulics remain uniform throughout the expected range of depths; where the ratio of the measured point velocity to the average does not vary. Such conditions are constrained to shallow, slow hydraulics where variances from the fastest to the slowest velocities remain constant. However, these sensors are poor candidates in locations where the flow depths or velocities increase significantly beyond shallow, slow flow rates.

Non-contact velocity sensors may be used as redundant devices to measure velocities and lower flow depths where submerged sensors may be incapable (less than 1 ½-inches) or where siltation may affect the performance of submerged sensors.

Non-contact velocity sensors are often used in caustic environments where submerged equipment may get damaged.

**Wetted Area**

In the continuity equation \(Q_c = V_{avg} \times \text{Area}\), the Area refers to the wetted cross-section. The wetted area requires geometric measurements of the pipe, siltation and the depth of flow to determine the resultant cross-sectional area of the flow.

The industry standard for the primary depth measuring device is an ultrasonic level sensor. Manufacturers offer two types of ultrasonic sensors: (1) “down-looking” and (2) “up-looking.”
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Both types of sensors must be mounted parallel to the surface of the flow. A “down-looking” ultrasonic is installed at the crown of the pipe, while an “up-looker” is placed at the bottom-center of the pipe.

_Ultrasonic Technology_

Primary manufacturers include ADS, ISCO, HACH, Sontek and FloWav. Ultrasonic technology operates by measuring the elapsed time for an ultrasonic signal to travel to the flow surface and back. Using the speed of sound and pipe geometry, the elapsed time is used to compute a distance to derive a depth of flow.

_Single-Crystal Ultrasonic_

These sensors have a significant “deadband” where they are incapable of measuring the depth. This occurs because the sensor must function as a transmitter and transceiver. It must transmit a sound wave, turn itself off, wait until the sound vibration has dissipated, turn itself back on and then receive the signals. This period of time generally correlates to a distance of about six inches (6”).

Manufacturers have been able to reduce the impacts of a single crystal deadband through the use of reflectors and mounting the sensor horizontally.

_Multiple-Crystal Ultrasonic_

These sensors significantly reduce the deadband by having one sensor transmit the sound wave while the other receives. As a result, the deadband can be reduced to about a half inch (½”).

_Installation/Operation_

The ultrasonic sensor is typically installed within the pipe and does not record depths above full pipe, unless it is installed as a “surcharge mount” (higher up the manhole). Manufacturers have different methods to engage a pressure sensor technology when the flow level compromises the effective range of the ultrasonic sensor.

- ADS meters continuously measure redundant depths with one or two ultrasonic sensors and a pressure sensor to derive a composite depth entity. The result is a seamless depth through surcharge situations.
- HACH meters activate the pressure sensor once the ultrasonic has been compromised and patches the depth entities. This method leaves a void in the depth data entity as the equipment switches from an ultrasonic to pressure based depth.
- ISCO meters must be manually substituted in the event the ultrasonic sensor is not functioning.
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Pressure Transducers

Pressure sensors are offered by most flow meter manufacturers. This technology measures the pressure differential between ambient air pressure and the head pressure induced by the depth of flow. The deflection of the transducer is measured and converted to a depth of flow.

Pressure sensors have long been regarded as inferior for use in continuous flow monitoring programs. Because these sensors are mechanical devices, they are prone to drift and hysteresis from sensor fouling, moisture and exceeding their maximum design pressure. Sensor precision is 0.5% of full scale for most manufacturers, where full scale is the maximum capable measured depth. So, a sensor rated to 15 psi would have an effective range of about thirty-five feet (35') and its stated accuracy would be around two inches (+/- 2”). In eight inches (8”) of flow, this would equate to more than a twenty-five percent (25%) error in the calculated flow rate.

Manufacturers include various techniques to prevent moisture from entering the sensor including hydrophobic filters and oil chambers. These methods can provide some benefit for limiting moisture, but are not effective long term.

Because of these issues and the inherent inaccuracy, pressure transducers should only be used as redundant depth devices.

Are Calibrations Necessary for Gravity Flow Monitoring?

This question is the most differentiating question when it comes to the selection of appropriate technologies in gravity sewers. While the question most often pertains to validating the accuracy of the calculated flow rate, responses highlighting the accuracy of the instrumentation are misleading.

There is a common misbelief the instrumentation should be capable of consistently and accurately measuring the flow rate with limited periodic calibrations, much like pressurized water systems. Although the continuity equation is used for both gravity and pressurized systems, the ability to capture the necessary parameters of depth and velocity greatly differ.

For pressurized systems, the area is fixed; it’s the cross-sectional area of the pipe and a depth measurement is unnecessary. For gravity systems, the depths will range from zero to full pipe. Together with an accurate geometric profile, ultrasonic depth sensors are extremely precise and undeviating, resulting in an accurate representation of the wetted area.

Velocity, however, is a much different story. Pressurized systems generally remain stable at depth (full pipe) and have a predictable and consistent uniformity of flow. Technologies such as electromagnetic, magnetic induction, polysonic and transit-time are highly capable of measuring the average velocity throughout the full pipe cross section; emphasis being on average velocity. However, these technologies become highly inaccurate if the depth is not at full pipe, much like gravity systems.
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Unlike full-pipe pressurized systems, the average velocity of a partially filled pipe is non-uniform and highly unpredictable. Furthermore, the technologies vary widely in what parameters they measure.

Hydraulic Calibrations are used to validate both the accuracy of each sensor and the flow rate. Some manufacturers contend calibrations are not necessary for their devices, claiming their sensors are accurate, that they do not need constant calibration and that they remain calibrated. At the sensor level, this is a valid claim. There devices are accurate (precise).

But, flow rate accuracy requires both a precise sensor and one with low bias, undeviating from measuring the correct answer. The continuity equation requires the wetted area, cross-sectional area of the flow. When silt is introduced or washed away from a measured pipe section, the cross-sectional area will change. The continuity equation also requires the average velocity, obtainable from multiple-point velocity technologies but not point velocities.

For calculating flow rates, the claim that [hydraulic] calibrations are not necessary is simply untrue and grossly misleading.

Summary

Flow rate accuracy requires that the sensors be both precise and undeviating. Their results must be repeatable and capable of measuring the correct parameters to calculate the flow rate.

HighAccuracy

Chordal velocity, Pulse Doppler and magnetic induction (inverted syphon) technologies are the most accurate technologies for measuring the average velocity. Ultrasonic sensors are the most accurate for measuring the depth of flow. Each of these technologies are highly repeatable and undeviating (high precision and low bias).

AcceptableAccuracy

Continuous-wave Doppler technologies have high success in many applications, but require continuous validation (calibrations) to account for the highly dynamic flow regimes found in gravity sewers. Manufacturers that offer an adjustable velocity range provide greater applications than fixed continuous-wave technologies.

UnacceptableAccuracy

These technologies are incapable of measuring the average velocity and should not be used as primary velocity measuring devices where high accuracy is required. These point velocities include electromagnetic and non-contact surface velocity, weirs and depth only technologies. Although these technologies are precise in what
they measure, they fail to measure the correct average velocity parameter. For depth, pressure sensors lack in both repeatability and deviation.

Conclusion

1. Accurate flow rates require high sensor repeatability, low deviation and the ability to measure the intended parameter (depth and average velocity)

2. There is no one technology that fulfills all application requirements in gravity sewers and each must be correctly used within their optimal performance envelopes

3. Calibrations are necessary to ensure the sensors remain **precise** and **undeviating** in a highly volatile and dynamic flow environment

4. Hydraulic profile calibrations differ from sensor calibrations and are necessary to validate the accuracy of the calculated flow rate

5. Calibrations must include silt measurements to account for changes in the cross-sectional area

6. Multipoint velocity technologies including Continuous-wave Doppler, Pulse Doppler and chordal are the most appropriate technologies for measuring the average velocity

7. Point velocities, including non-contact surface velocity and electromagnetic technologies should not be used as primary velocity devices if accuracy is a prerequisite

8. Ultrasonic sensors are the most appropriate technologies for measuring the depth of flow

9. Pressure sensors should not be used as primary depth devices if accuracy is a prerequisite