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Characterization of the Flow in a Gully: Average Velocity

Characterization of the Flow in a Gully: Average Velocity, Turbulence and Air Entrainment

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ABSTRACT: The goal of this work is to characterize the flow on a gully, occurring on both drainage and surcharged conditions. To do so, measurements of flow velocity were made using an acoustic Doppler velocimeter on a 1:1 scaled model of a gully, as well as video recordings. The flow fields and turbulence were quantified. In addition a qualitative analysis of the air inside the gully is given, based on the recordings. Similarities were found between the flow rates, for both drainage and surcharged flows, namely: for surcharged flow, a strong anticlockwise is observed on the left side of the gully, while the right side displays almost negligible velocities; for drainage flow there is one large vortex above the orifice, which ascends with the increase of the flow rate, and larger quantities of air are present which are then subsequently reduced with the increase of the flow rate; finally, for the drainage flow, the turbulence increases along the horizontal axis.

Keywords: urban drainage, gully, surcharged flow, direct flow

1 INTRODUCTION

A gully is one of the linking elements between the surface and the sewer of an urban drainage system. Its function is to conduct the excess rainfall from the surface to the sewer, but sometimes, when the incoming flow of an upstream sewer pipe is higher than the discharge capacity of the downstream sewer pipe, the flow is reversed. This may happen during an intense precipitation event or a flood. In this case, the drainage system will be contributing to the flood, instead of mitigating it. The study of a drainage system thus implies the study of its linking elements.

Several studies regarding gullies have been made. The hydraulic efficiency of gullies was studied by Goméz and Russo (2007) and Goméz and Russo (2009). The latter studied longitudinal gullies. These studies focused on the effect of the gratings on the hydraulic efficiency, but only for drainage conditions. Djordjević *et al.* (2011) used experimental results of drainage and surcharged flows to determine discharge coefficients and to compare with numerical simulations.

Under the Multiple Linking Elements project, taking place on the University of Coimbra, several numerical simulations have been made, including Carvalho *et al.* (2011) and Carvalho *et al.* (2012), who studied the hydraulic behavior of a gully with drainage and surcharged flow. Martins *et al.* (2012) and Lopes *et al.* (2012) presented 3D numerical simulations of the gully under drainage and surcharged flow conditions, respectively, whose results were compared with experimental water heights obtained on the 1:1 scaled model also used in this work.

Continuing the works above mentioned the present work aims to characterize the direct and reverse flow in a gully, using a 1:1 scaled model. Flow velocity was measured on several points inside the gully, using a Nortek AS[®] 10MHz acoustic Doppler velocimeter (NDV). This data was used to characterize the average flow velocity and turbulence of the flow, for the drainage flow. A qualitative analysis of the air entrainment is also presented, based on 30 s videos of each flow rate.

2 EXPERIMENTAL FACILITY

A 1:1 scaled model of a gully was set up inside the multipurpose hydraulic channel at the Hydraulics Laboratory on the Civil Engineering Department of Coimbra University. The water was supplied to the channel by a constant head tank, and then it flowed through a 50 cm wide, 50 cm deep and 10 m long acrylic channel, with a 1% slope. The gully model is a 30 cm wide, 30 cm deep and 60 cm long acrylic box, with a circular orifice at the center of the bottom of the box, 8 cm in diameter, and an additional 6 cm long tube connected to the orifice. The top opening is uncovered. When simulating the surcharged flow, a gate was set upstream the box, as well as a PVC pipe connecting the upstream flow to the gully orifice. Figure 1 presents a scheme of the experimental facility.
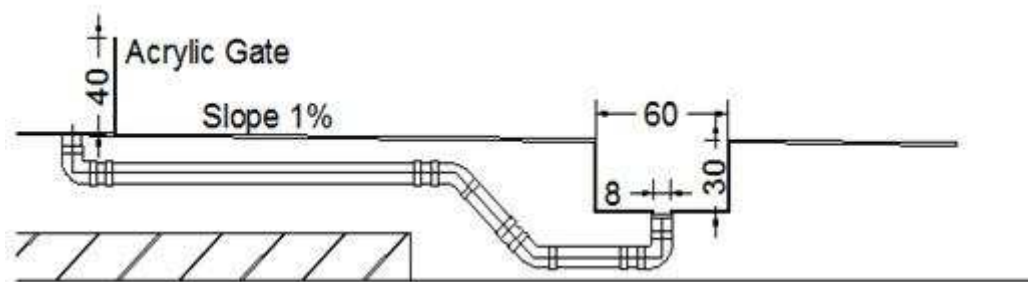

Figure 1. Experimental facility set up for surcharged flow. For drainage flow, the pipe and the gate are removed. The water flows from left to right.

3 METHODOLOGY

A 3D side looking Nortek AS® 10MHz acoustic Doppler velocimeter (NDV) was used to collect data to calculate the average velocity field and turbulence, for the central longitudinal plane. The sampling frequency was set to 1 Hz to the surcharged flow, and since this would return very low correlations for the drainage flow, it was set at 25 Hz for the latter. The sampling time was always 180 s. The mesh consists of points distanced 3 cm from each other. The NDV configuration did not allow measuring any point from the bottom up to 5 cm height. The highest points were measured at 29 cm, whenever possible. On the surcharged flow, the gully was always submerged, allowing these measurements, but for the drainage flows it was not always possible, since the water height inside the gully varied and in some cases it did not allow the NDV to be submerged. On the reverse flow the jet area presents high turbulence, making the NDV measurements less reliable. For this reason, the mesh was adapted and there are no points in the centre of the box and the two columns nearer the jet, one on each side, were moved 1 cm away from the jet, which means they are 2 cm away from the others, on the horizontal direction, as presented on Figure 2 (left).

The turbulence parameters were calculated only for drainage flow and for a smaller number of points: near the walls, at the center of the gully and at the center of each side of the gully and at 5, 14 and 23 cm height, as presented in Figure 2 (right). Considering that only the longitudinal plane is being studied, the turbulence was calculated only on the streamwise and the vertical directions.
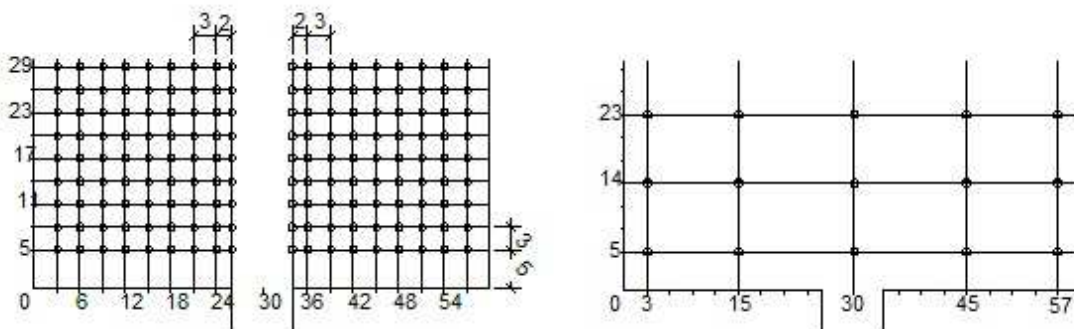

Figure 2. Mesh used for surcharged flow (left) and turbulence (right).

Videos of each flow rate were recorded, using a Panasonic DMC-FS16 camera with 14 Mega Pixels fixed on a tripod. The recordings were made on automatic mode with natural light. The frame rate was 30fps for the surcharged flow and 24 fps for the drainage flow; the shutter speed was always 1/30 s and the aperture varied from f/4 to f/4.8. The videos lasted 30 s and were used to analyze the air inside the gully, specifically the minimum and maximum air concentration observed.

The flow rates tested were 4, 5 and 6 l/s for the surcharged flow, and 15, 22, 32 and 42 l/s for the drainage flow. These choices depended on previous works and their conclusions. For the surcharged flow, flow rates lower than 4 l/s presented very low average velocities and the experimental facility limited the maximum flow rate. For flow rates lower than 15 l/s, the drainage flow presented an air concentration inside the gully so high that would not allow good measurements with the NDV. For flow rates higher than 42l/s, most of the water would flow across the gully, and the results would not return any additional information (Martins, 2011).

The Reynolds number (calculated as $Re = Ud/v$ and as $Re = UH_u/v$ for the drainage flow) varied from $6.4\text{x}10^4$ to $11\text{x}10^4$ for the surcharged and from $8\text{x}10^4$ to $11\text{x}10^4$ for the drainage flow, and the Froude number (calculated as $Fr = U/(gd)^{0.5}$ and $Fr = U/(gH_u)^{0.5}$ for the surcharged and drainage flow, respectively) was comprised between 0.90 and 1.34 for the surcharged flow and 1.80 and 2.00 for the drainage flow. The summary of the experimental conditions is shown on Table 1. The water depth was measured upstream, and the average velocity was calculated for the orifice with diameter d=0.08 m, on the surcharged flow, and upstream, on the drainage flow.

Table 1. Flow rate, water depth, average velocity, Reynolds number, Froude number, and sampling frequency and time for surcharged and drainage flow.

		Q (l/s)	H_u (m)	U (m/s)	Re (-)	Fr (-)	f (Hz)	t (s)
Surcharged	Q_4	4	0.76	0.80	$6.4\text{x}10^4$	0.90		
	Q_5	5	0.825	0.99	$8.0\text{x}10^4$	1.12	1	
	Q_6	6	0.905	1.19	$9.5\text{x}10^4$	1.34		
								180
Drainage	Q_{15}	15	0.030	0.99	$8\text{x}10^4$	1.80		
	Q_{22}	22	0.037	1.18	$9\text{x}10^4$	1.94		
	Q_{32}	32	0.047	1.36	$11\text{x}10^4$	2.00	25	
	Q_{42}	42	0.059	1.43	$11\text{x}10^4$	1.89		

The data obtained by the NDV were post-processed using WinADV, version 2.028 (Wahl, 2000). The post-processing included the elimination of spikes, using the phase-space threshold despiking method proposed by Goring and Nikora (2002) and modified by Wahl (2003), the elimination of points in the data series that presented a signal to noise ratio (SNR) lower than 5dB for the surcharged flow and 15dB for the drainage flow (Lohrman *et al.*, 1994), and the elimination of points that had lower correlation coefficients. For the calculation of the average velocity, the correlation coefficient can be as low as 30% (Sontek, 2001), but it was decided to apply a stricter filter first. For the calculation of the turbulence parameters, and considering that Wahl (2000) suggests that samples with correlation coefficients lower than 70% can provide good data when SNR is high and the flow is turbulent, samples with correlation coefficients as low as 50% were not eliminated, which is a similar approach to that of Romagnoli *et al.* (2012), who considered correlations as low as 45%.

4 RESULTS AND DISCUSSION

4.1 *Correlation coefficient*

The average correlation coefficients obtained during the samplings are presented in Figure 3. The values vary from more than 80% to as low as 20%, as seen on the surcharged flow. The presence of turbulence decreases the correlation coefficient. Its value was lower where it was expected the turbulence to be higher, namely near the jet, for the case of the surcharged flow, and near the surface. The areas where water is entering the box also present low correlations, specifically the upper left side for the surcharged flow and the side for the drainage flow. For all cases, the correlation coefficient is higher near the walls.
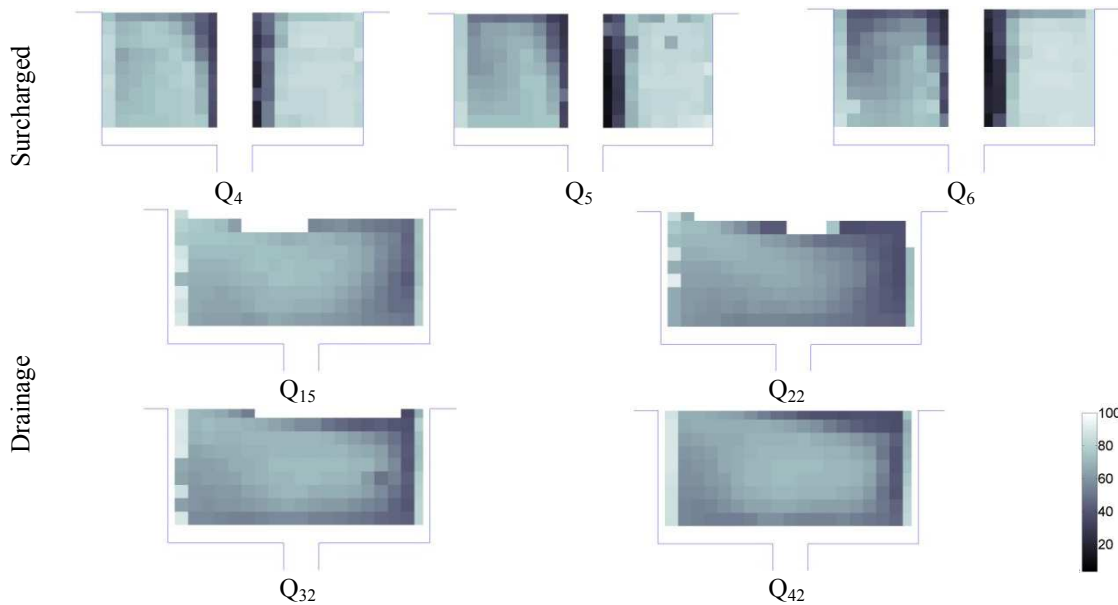
Figure 3. Correlation coefficients for surcharged (above) and drainage (below) flows.

4.2 *Average velocity field*

The average velocity fields are shown on Figure 4, for both surcharged and drainage flows. The maximum average velocity is presented for each flow rate. There is a similarity between the flow rates analyzed for the surcharged flow and for the drainage flow either.
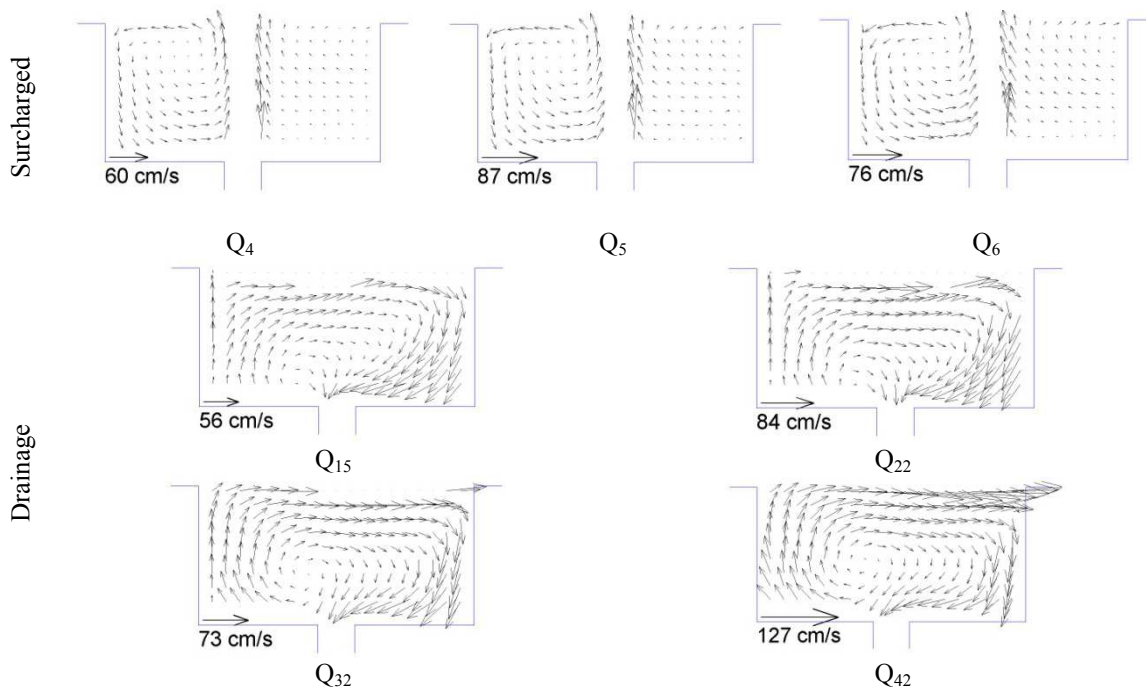

Figure 4. Average velocity fields for surcharged (above) and drainage (below) flows.

The surcharged flow presents an anticlockwise vortex on the left side of the box that illustrates the entrance of water in the gully. On the right side the velocities are quite low. Near the jet the velocities are almost vertical and are the highest on the gully. There is an increase on the average velocities with the increase on the flow rate, despite the fact that the highest maximum velocity was measured on Q_5 instead of Q_6, as expected. This could be explained with the fact that the maximum velocity is located near the jet, an area where the correlation coefficients are quite low, which makes the data less reliable.

The drainage flow is composed of only one clockwise vortex, and its center is located 20 to 25 cm away from the upstream wall. With the increase in flow rate the vortex center "ascends", and so do the horizontal velocities near the bottom, that then become visible. The water entering the gully flows across it, directly to the downstream wall. Here, part of it flows downwards into the gully, and the rest flows out of the gully. The former is the main contributor to the flow exiting through the bottom orifice. There is a

hydraulic jump and its position influences the velocity field. With the increase in flow rate, the jump moves downstream, causing the velocity near the surface to become more horizontal. The velocities increase with the flow rate, and the highest velocities are located on the surface and near the downstream wall. The highest velocity on Q_{22} is higher than on Q_{32}, but on this case this can be explained by the differences on the mesh used: it is possible that on the points that were eliminated (on the Q_{32} flow) the velocities were higher than the ones measured on both Q_{32} and Q_{22}.

4.3 *Air entrainment*

The qualitative analyses performed focused mainly on the maximum and minimum values observed and on the entrance points. Figure 5 consists of frames of the recording videos that were considered to best illustrate the variation of the air concentration inside the gully.
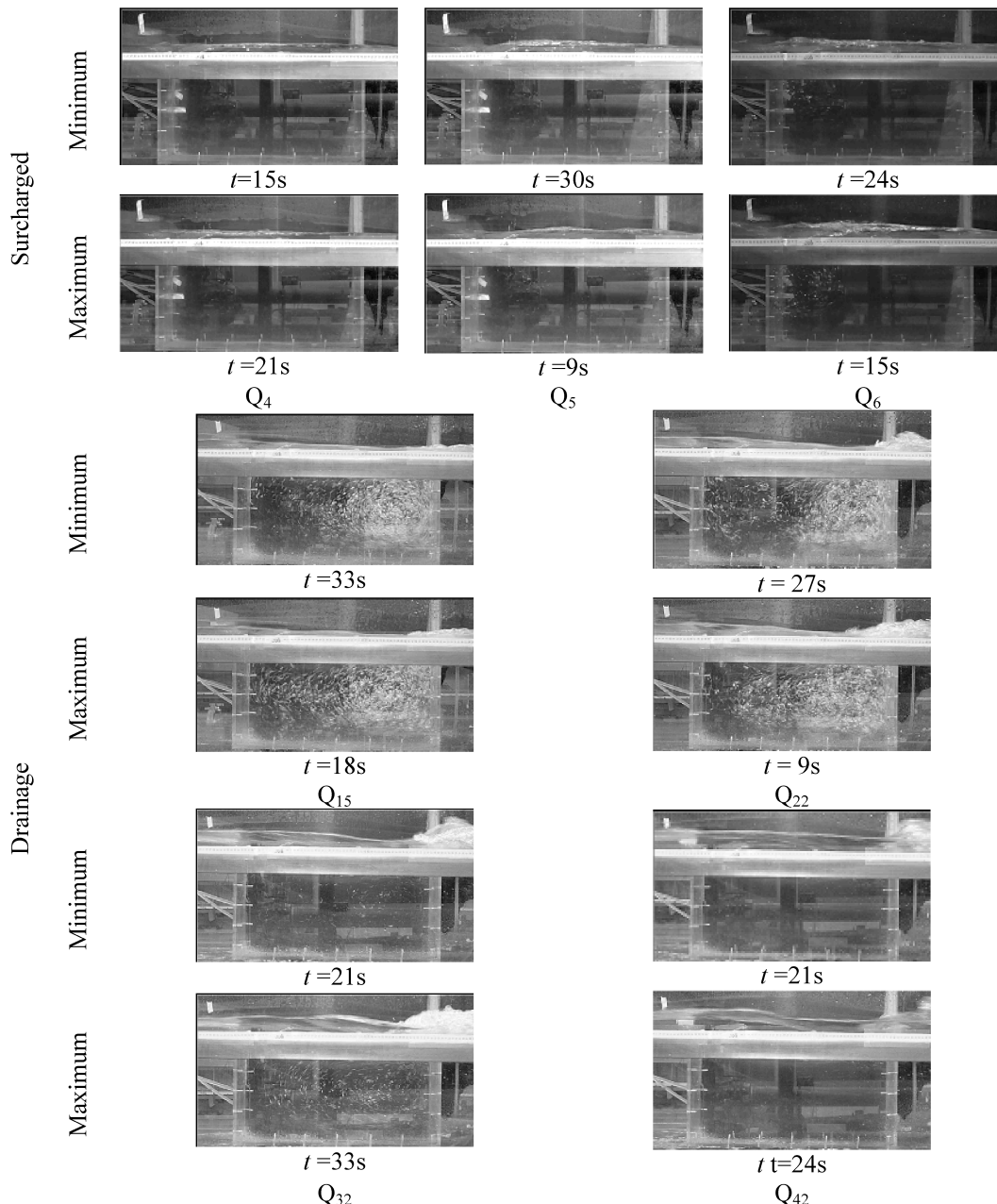

Figure 5. Air entrainment for surcharged (above) and drainage (below) flow. For each flow the minimum and maximum registered concentrations of air are presented.

Air enters the gully dragged by the water, so on the surcharged flow, it enters on the upper left corner, and on the drainage flow, it is dragged on the right side. The air quantity depends on the flow rate: on the surcharge flow, it increases with the flow rate, and for Q_4 there are no air bubbles inside the gully; Q_5 showed a few air bubbles, but on some occasions there are none visible; air was always present on Q_6, and it varied from some bubbles near the upstream wall to air occupying 20 cm (horizontally) of the gully. For the drainage flow, the opposite happens: the air concentration diminishes with the increase in

the flow rate, and this can be related with the position of the hydraulic jump, as well as the water height inside the gully.

The hydraulic jump also influences the air concentration variation for each flow rate. As it moves downstream, the air quantity entering the box diminishes, and for Q_{42} there were no air bubbles visible, but the increase in the water height had also an influence, since it made it difficult for the air to enter. The air distribution inside the gully depended on its quantity, and there was always air present on the right side of the box, whereas on the left side its presence was not constant.

4.4 Turbulence

Turbulence parameters were normalized with U^2, being U the average velocity as presented on Table 1. Normal stresses are presented on Figure 6, for the streamwise ($<u_xu_x>$) and the vertical ($<u_zu_z>$) direction. Shear stresses ($<u_xu_z>$) and turbulent kinetic energy (k) are shown on Figure 7. Like it was previously mentioned, the turbulence parameters were calculated for three different heights and for five points on the horizontal direction.
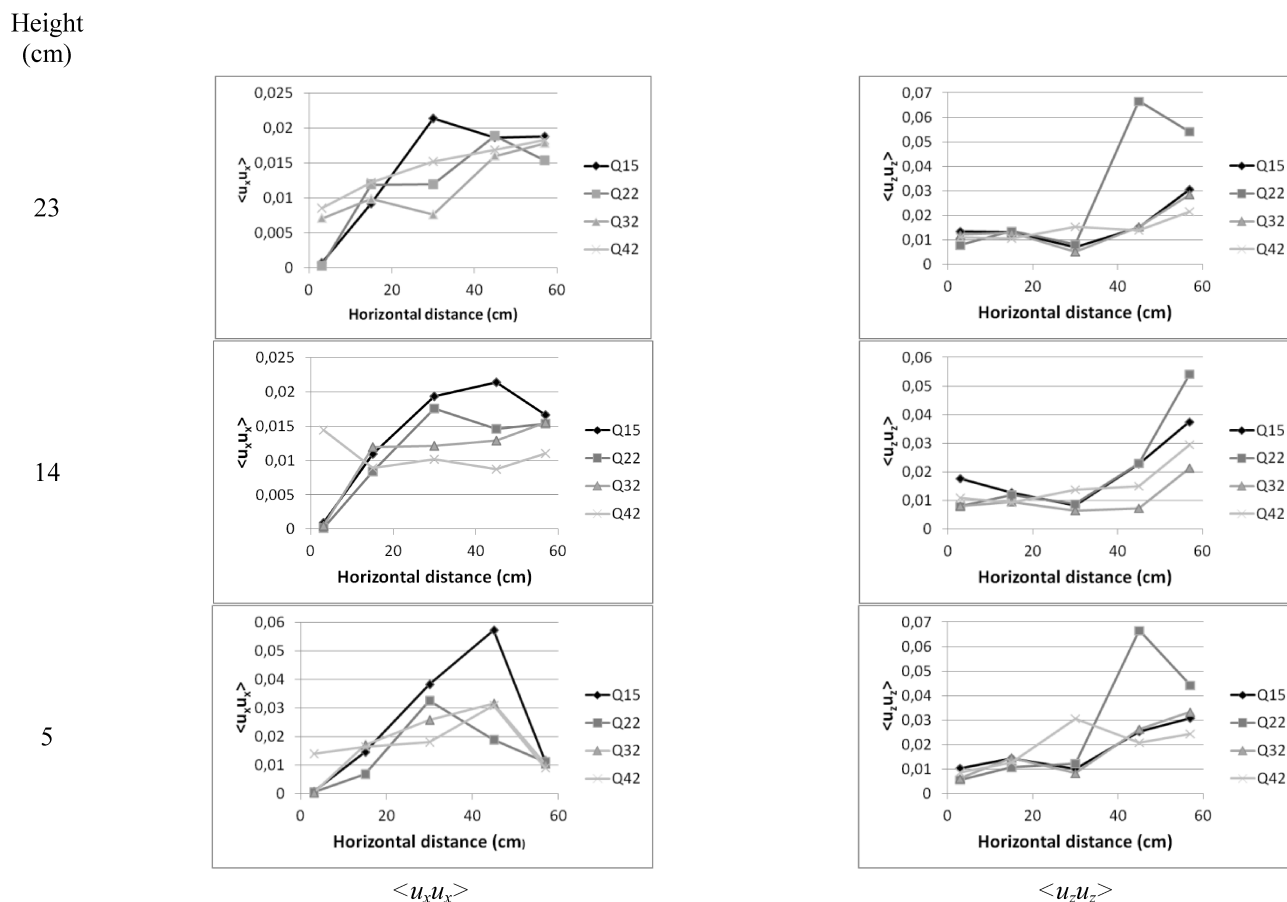

Figure 6. Normal stresses: streamwise (left) and vertical direction (right).

Considering the evolution along the horizontal distance, there is an increase in the normal stress for all four flow rates, although the maximum doesn't take place in the downstream wall, with the exception of normal stress in the vertical direction at 14 cm height, as seen in the centre right chart. In fact, the maximum value is mostly on the point distancing 45 cm from the upstream wall.

Streamwise stresses tend to assume a concave growth, while the vertical stresses present a convex growth. Streamwise stresses, for 5 cm and 14 cm height show a decrease on the turbulence with the increase on the flow rate, but there is no clear pattern for the other cases, although the maximum value for the vertical stresses always occurs for Q_{22}, while for streamwise stresses it is always Q_{15} that present it.
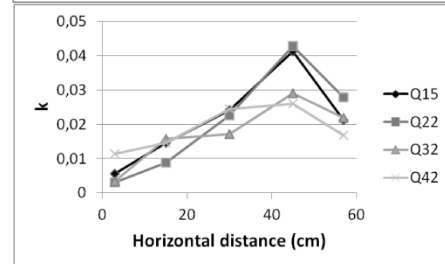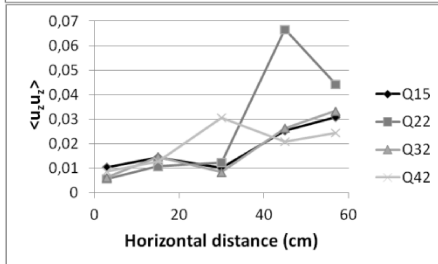
Height
(cm)

23

14

5

$<u_xu_z>$
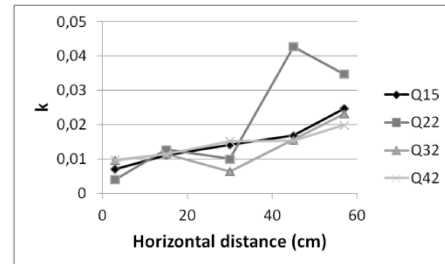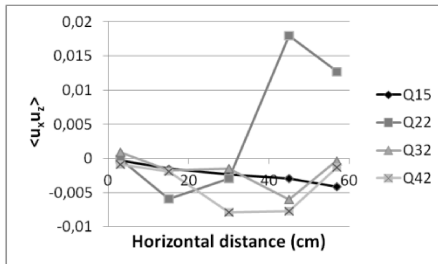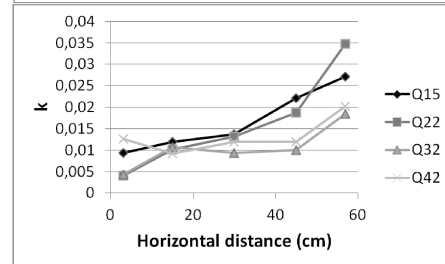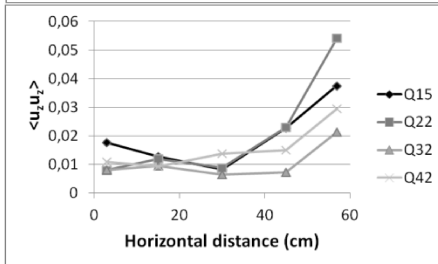
k

Figure 7. Shear stresses (left) and turbulent kinetic energy (right).

Like normal stresses, shear stresses and turbulent kinetic energy present an increase in turbulence along the horizontal distance, except for 23 cm height, where there is no clear pattern, as seen in Figure 7, top left. For both parameters, Q$_{22}$ presents the maximum value, located near the downstream wall at 14 cm height (centre charts) and distanced 45 cm on the top and bottom of the gully.

5 CONCLUSION

The flow occurring on a gully was characterized, for both surcharged and drainage conditions. The average velocity fields were analyzed and a qualitative study of the air inside the gully was performed, as well as the turbulence characterization for the drainage flow. Several flow rates were studied, which showed similarity on their behavior.
− On the surcharged flow there is an anticlockwise vortex on the left side of the gully, whilst on the right side flow velocities are quite low.
− Drainage flow exhibits a big quantity of air drawn into the inside of the gully, but it diminishes with the increase of the flow rate, due to the displacement of the hydraulic jump or the increase of water depth.
− There is only one visible vortex on the drainage flow, clockwise, and its centre is located near the orifice, but it ascends as the flow rate increases.
− Turbulence increases along the horizontal distance, but no clear pattern was identified between the flow rates.
These results are quite important and highlight instabilities that may occur in gullies. They may be used to calibrate and validate numerical models that simulate gullies. This study should be extended in order to integrate channel and buried pipes.

NOTATION

$<u_i u_j>$	Reynolds stresses
d	orifice diameter
f	NDV sampling frequency
Fr	Froude number for the orifice
g	acceleration due to gravity
H_u	water height upstream the gully
k	turbulent kinetic energy
Q	flow rate
Re	Reynolds number
t	time
U	average velocity
v	kinematic viscosity

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