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# EXPERIMENTAL ANALYSIS OF THE DYNAMIC BEHAVIOUR OF A REAL WATER DISTRIBUTION SYSTEM

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## ABSTRACT

Water distribution networks are traditionally modelled, designed and managed assuming steady flow conditions considering at most Extended Period Simulation (EPS) approach. However, water distribution systems are actually subject to unsteady flow phenomena. The resulting pressure oscillations can potentially cause structural damage to the systems as well as water quality problems due to the intrusion of contaminants or untreated water. Consequently, it is crucial to conduct a reliable evaluation of the unsteady flow phenomena in order to assure the pipe system integrity and security. However, examples of experimental analyses of the dynamic behaviour of a real water distribution network are very limited to date and mainly focused on the impact of important operations such as valves or pumps manoeuvres.

This paper shows the results of the monitoring and analysis of the dynamic behaviour of a real water distribution network, Gorino Ferrarese (FE, Italy), under ordinary operational conditions. Both pressure and flow were monitored for two days. The dynamic behaviour of the system is thus characterized by an analysis of the pressure fluctuations in the measurement sections. The analysis highlights that all the system is characterized by some predominant low frequencies, related to the network geometry and characteristics. On the other hand, very short pressure oscillations were observed at the measurement sections: they differ according to both the location of the measurement sections – characterized by different density of user connections – and the time of day. These high-frequency pressure signal components can be related to the system management and user demand.

**Keywords:** Hydraulic transients, unsteady flow, water distribution systems, field data

## 1 INTRODUCTION

Water distribution systems are traditionally modelled, designed and managed assuming steady flow conditions or at most considering a succession of steady-state flow with the Extended Period Simulation (EPS) approach. Actually, distribution networks are subjected to transients that significantly stress them in terms of either excessive but occasional or small but continuous pressure variations which could both be very dangerous for the systems.

In fact, transients may occur both in the water mains and in the distribution systems, due to accidental or programmed manoeuvres of pumps, valves or, more generally, regulating devices, and also to users water demand (Meniconi et al. 2017). In extreme cases, the pressure variation resulting from a water hammer can cause the pipeline to break and damage to the joints. In presence of low or negative transient pressures, a condition that often occurs in real networks (Collins et al. 2012; Ebacher et al. 2011), the disintegration of pipe concrete coating, the collapse and the implosion of the pipe and the resuspension of particles can occur as well as the detachment of biofilms due to high cutting intensities, cavitation, the desorption of previously dissolved gases and also the intrusion of untreated water, air or contaminants and pathogens through flanged connections, gaskets or breaks in the water distribution system, with a consequent health risk (Fox et al. 2014; Gibson et al. 2019; Yang et al. 2011).

The complexity of the pressure transient phenomenon is due to multiple factors. In fact, generation and development of a transient phenomenon are influenced by a number of relevant aspects, from the physical characteristics of the system, i.e., system configuration and pipe materials, to the characteristics of the manoeuvre, timing of events and initial conditions (Karney and McInnis 1990). Given the complexity and the potential effects of the phenomenon, it is evident the importance of investigating and characterizing the dynamic behaviour of water distribution systems in order to guarantee the integrity and security of the networks.

The monitoring of the characteristic quantities such as pressure and discharge is the first step in the process of characterization of a system: in order to capture pressure fluctuations during transient regimes, the sampling frequency of pressure data is higher (from tens of Hz to hundreds of Hz) than the one normally adopted for real networks monitoring – typically hourly or daily – (Chen et al. 2008).

Examples of experimental analyses of the dynamic behaviour of real water distribution networks, and therefore of complex systems, are currently limited; in fact, this type of analysis is typically performed on elementary systems (Benson et al. 1963; Choon et al. 2012; Izquierdo and Iglesias 2002; Yu and Gray 1969). Furthermore, the literature dealing with distribution networks under unsteady flow conditions tends to focus on theoretical approach or guidelines (Boulos et al. 2005; Ghidaoui et al. 2005; Jung et al. 2007; Karney and McInnis 1990; Pothof and Karney 2012) and example of analysis of complex system can be found based on field data (Meniconi et al. 2015), on comparison between field data and modelled data (Chen et al. 2008; Ebacher et al. 2011; Li et al. 2018; McInnis and Karney 1995) or relying on numerical model (Fan et al. 2018; Kwon 2007; Skulovich et al. 2014; Wood et al. 2005) but mainly considering the systems subjected to extraordinary or very significant manoeuvres (e.g., switching on/off of the pumping devices). The characterization of water distribution systems subjected to transient regimes becomes important also taking into account some studies that prove some positive correlation between pressure variation in the pipelines and failures (Kwon and Lee 2008; Rezaei et al. 2015). From this perspective, the impact of repetitive and moderate unsteady flow phenomena that can equally lead to damage to the system, in a process of weakening of the pipes in the long term, has been less investigated: transients induced by user activity are much more frequent than expected and their impact in terms of changes in pressure must not be overlooked (Stephens et al. 2017).

This paper shows the results of the monitoring and analysis of the dynamic behaviour of a real water distribution network, Gorino Ferrarese (FE, Italy), under ordinary operational conditions. Both pressure and flow were monitored for two days. The dynamic behaviour of the system is thus characterized by an analysis of the pressure fluctuations in the measurement sections, managing to highlight which areas of the network are potentially the most stressed. Finally, some concluding remarks are reported.

## 2 THE CASE STUDY: THE REAL NETWORK AND THE MEASUREMENT CAMPAIGN

The real system monitored is the water distribution network serving the urban centre of Gorino Ferrarese (FE, Italy), managed by the C.A.D.F. (Consorzio Acque Delta). This small town is positioned in the north of Italy, along the river Po di Goro and overlooks the Adriatic Sea. The network is connected by a single supply pipe to the wider network that serves the centre of Goro, located nearly 6 km upstream (

Figure 1). Both Goro and Gorino Ferrarese systems are fed by a tank and a pumping station located in Goro. The pumping station is equipped with variable-speed pumps with inverters that are set to maintain a constant pressure immediately downstream of the pumping station itself with different setting values during the day and the night. The pipes of the Gorino Ferrarese network have diameters ranging from 60 mm to 160 mm for a total length of about 15 km; their materials are fibre-reinforced concrete and PVC. The water distribution system of Gorino Ferrarese serves around 300 domestic and small-scale commercial users. The pattern of total consumption, and thus the inlet discharge observed is characterized by a typical residential shape: high consumptions during the day, and in particular in the morning and evening, ranging from 0.5 L/s to 2.5 L/s and lower consumptions during the night, ranging from 0.2 L/s to 0.5 L/s.

The campaign of measurements was carried out between 15 and 17 January 2018: three data loggers, for the simultaneous acquisition of pressure with the acquisition frequency of 100 Hz – already tested at the Water Engineering Laboratory of the University of Perugia (Italy) – were installed in three strategic points of the network, hereinafter referred to P1, P2 and P3 (see

Figure 1 and Figure 2). As highlighted in Figure 2 where an aerial view of Gorino Ferrarese and the location of the measurement points are reported, P1 is located at a dead-end in the downstream part of the network, P2 is located in the middle of the urban centre in a highly looped part of the system, characterized by many user connections, whereas P3 is placed on the transmission main that comes from Goro, 590 m upstream of the looped network serving the urban centre of Gorino Ferrarese.

Furthermore, for the entire duration of the measurement campaign, other quantities have been monitored:

(a) pressure and discharge at the outlet of the pumping station with a 15-minute step. This monitoring system is also set up in order to acquire pressure and flow data within every 15-minute step in case of pressure and flow variation larger than 2 m and 2 L/s, respectively;
(b) pressure and discharge at P3, acquired by the network manager's remote control system every 5 seconds and every 1 minute respectively;
(c) water consumption of all users in Gorino Ferrarese with 1-minute time step: the volumes delivered are obtained through the installation at each user of magnetic smart meter.

With regard to pressure signal at P3, it is worth noting that the pressure variations correspond to the daily manoeuvres at the upstream pumping station which takes place respectively at 07:15 am and at 11:00 pm.

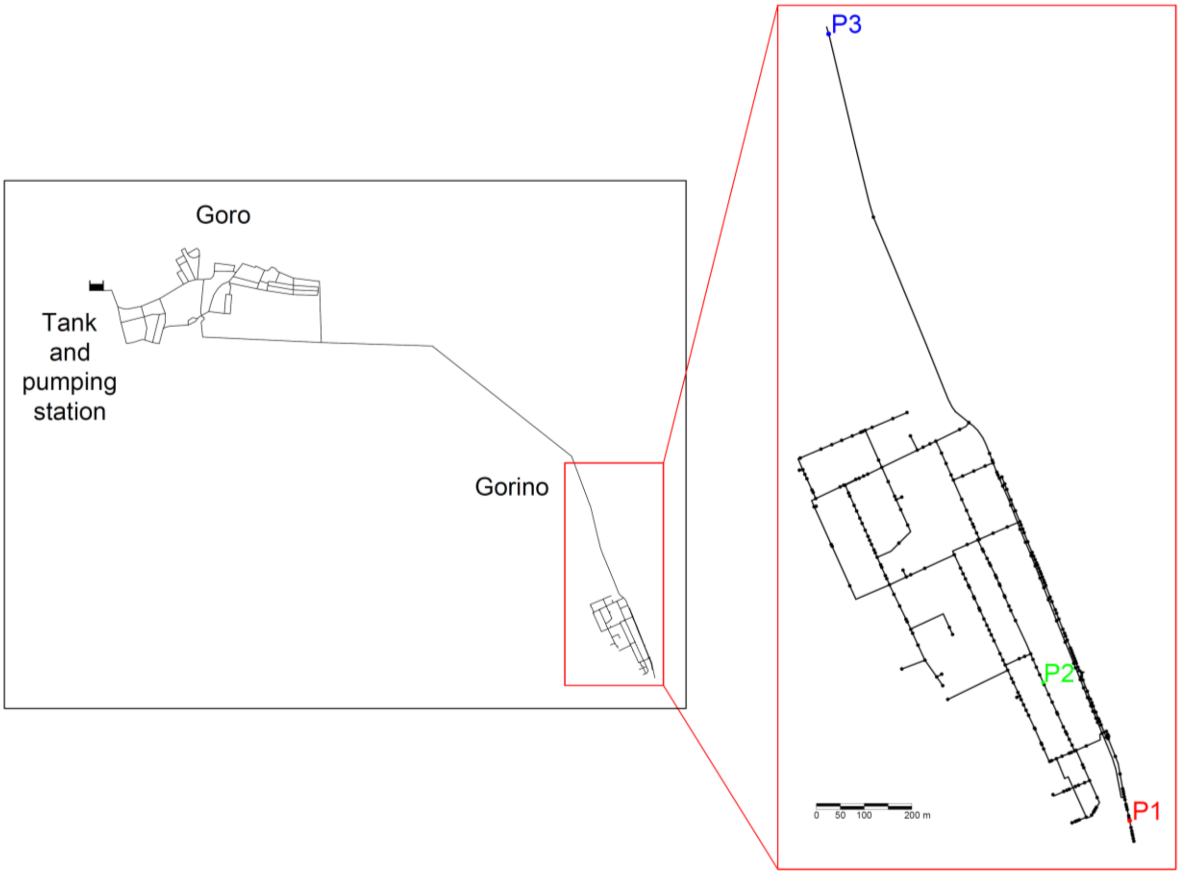

Figure 1. Layout of the water distribution network that serves the urban centres of Goro and Gorino Ferrarese. The pressure measurement sections P1, P2 and P3 are also indicated.

**Figure 2.** Aerial view of Gorino Ferrarese and location of pressure measurement sections P1, P2 and P3.

## 3 ANALYSIS OF PRESSURE SIGNALS

For the sake of brevity, the pressure signals acquired at the three measurement sections P1, P2 and P3 are reported in Figure 3 for a time window of ten-minutes (16:10 – 16:20, 16/01/2018). Firstly, it is evident that pressure trends are not stationary. Indeed, both rather long pressure oscillations and instantaneous or very short oscillations can be observed, leading on the whole to pressure values oscillating in a rather large band of around 4 meters. More in details, it can be observed that there is a good correspondence for long-term fluctuations between the three measurement points: periods with values between 80-100 seconds (see Figure 3) are actually recognizable in all the points. Thus it seems that the whole network has a common long-term behaviour related to the geometric characteristics of the network itself.

Moreover, it can be noted that pressure data observed in P1 and P2 are more reactive and characterized by more pressure peaks (of around 1 m) in comparison to P3. In fact, P1 and P2 are very close to many active users; thus the more hysterical behaviour of the pressure signals in P1 and P2 can be associated to both user activities and system configuration, because of the continuous reflections from dead ends and no active users. On the other hand, the third measurement section P3, which is not surrounded by users, seems to be less affected by pressure peaks, although long-term fluctuations are quite evident.

These aspects have been more extensively investigated considering the whole daytime period (09:00 – 21:00, 16/01/2018) and night period (02:00 – 05:00, 16/01/2018) and excluding the early morning and late evening period when both the pressure lowering and pressure increase manoeuvres carried out by the upstream pumping station occur.

Operatively, in order to characterize the peculiarity of pressure fluctuations, starting from the pressure signal acquired at 100 Hz, the one-second average of the pressure signal and the fluctuations of 100 pressure data falling in that second with respect to the corresponding average are calculated (short-term fluctuation). This operation has been done for each of the three measurement points and for both the day and night period defined above. The analysis of pressure data in terms of short-term fluctuations can be useful to evaluate the influence of the users' activity that causes transients of moderate entity and short duration that are processed and reflected by the system. In Figure 4, frequency histograms of pressure signal short-term fluctuations are reported for P1, P2 and P3 for both the day and night periods. Considering first of all the day period, it can be observed that P1 and P2 present a more dispersive distribution of the short-term pressure fluctuations than P3. Moreover, short-term pressure fluctuations result more significant for the first two points of measurement, reaching values of three-four meters. These results confirm the more hysterical nature of pressure signal observed in P1 and P2. Pressure data measured in P3 shows short-term fluctuations that are on average less dispersive with respect to the other two points and characterised by values in the order of one meter: P3 appears to be the least disturbed point probably because it is located on the feed pipe that hydraulically connects Goro and Gorino Ferrarese, not within the town centre, and waves produced by user activity tend to be damped along the way.

Considering the night period, it can be observed that in general, short term pressure fluctuations are reduced. Different characteristics of pressure signals between the three measurement points are no longer so markedly detectable, and even though the dispersion of short-term pressure fluctuations is lower in the night period than in the day period in all the points, the most important reduction is observable at points P1 and P2. It is worth noting that one of the aspects that distinguishes P1, P2 and P3 is precisely the density of active users around them, and in the night period this activity is reduced a lot and sometimes is annulled in the whole network. Frequency histograms of short-term fluctuations for the night period (Figure 4) confirm that short-term pressure oscillations are reduced for the three measurement points but above all in P1 and P2, which in the daytime are instead characterized by more user water consumption activities and thus marked fluctuations.

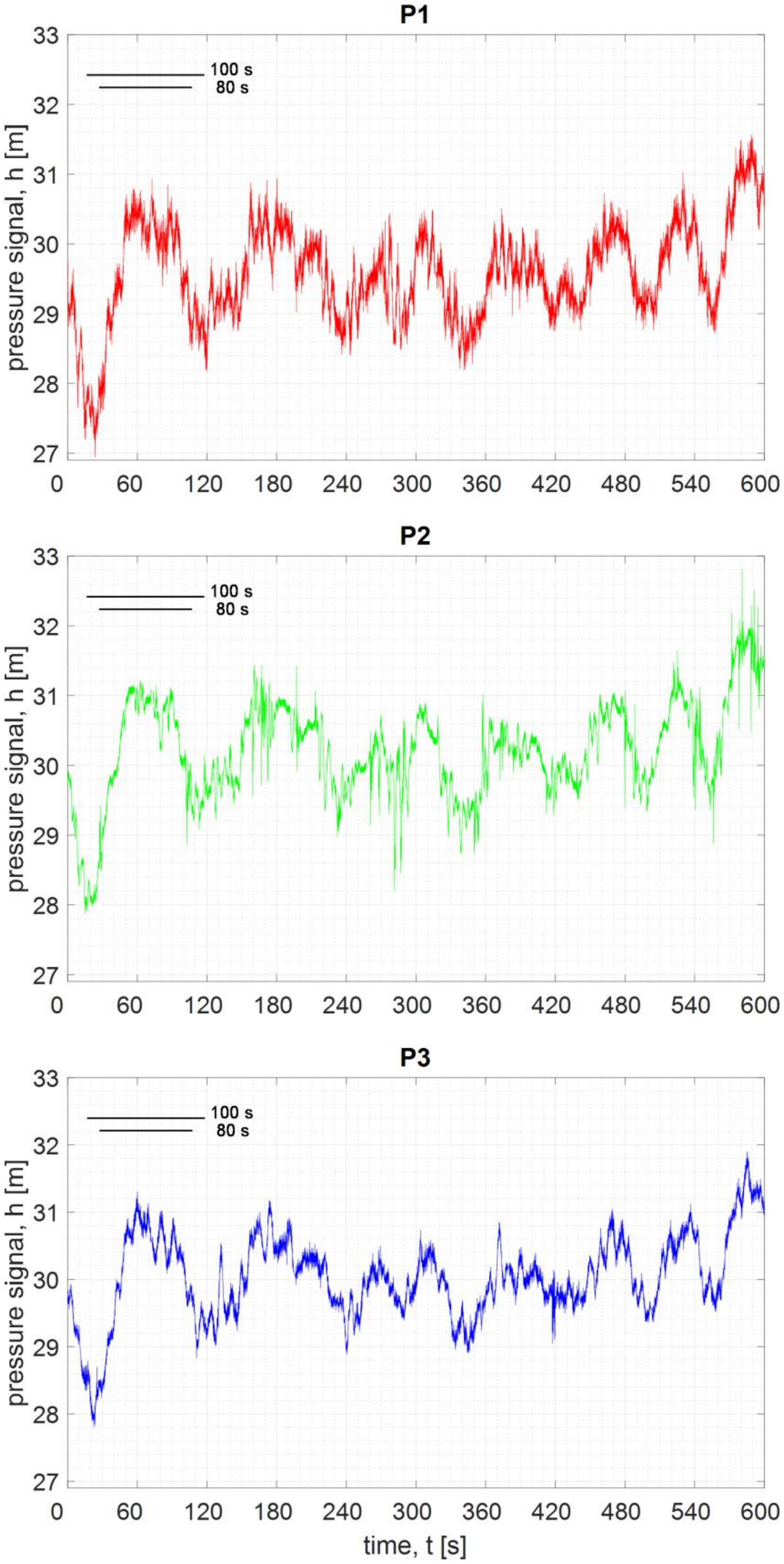

**Figure 3.** Pressure signals acquired at sections P1, P2 and P3 in a ten-minute window (16:10 – 16:20, 16/01/2018). In order to visualize long-term periods characterizing the signal, segments corresponding to periods of 80 s and 100 s are also reported.

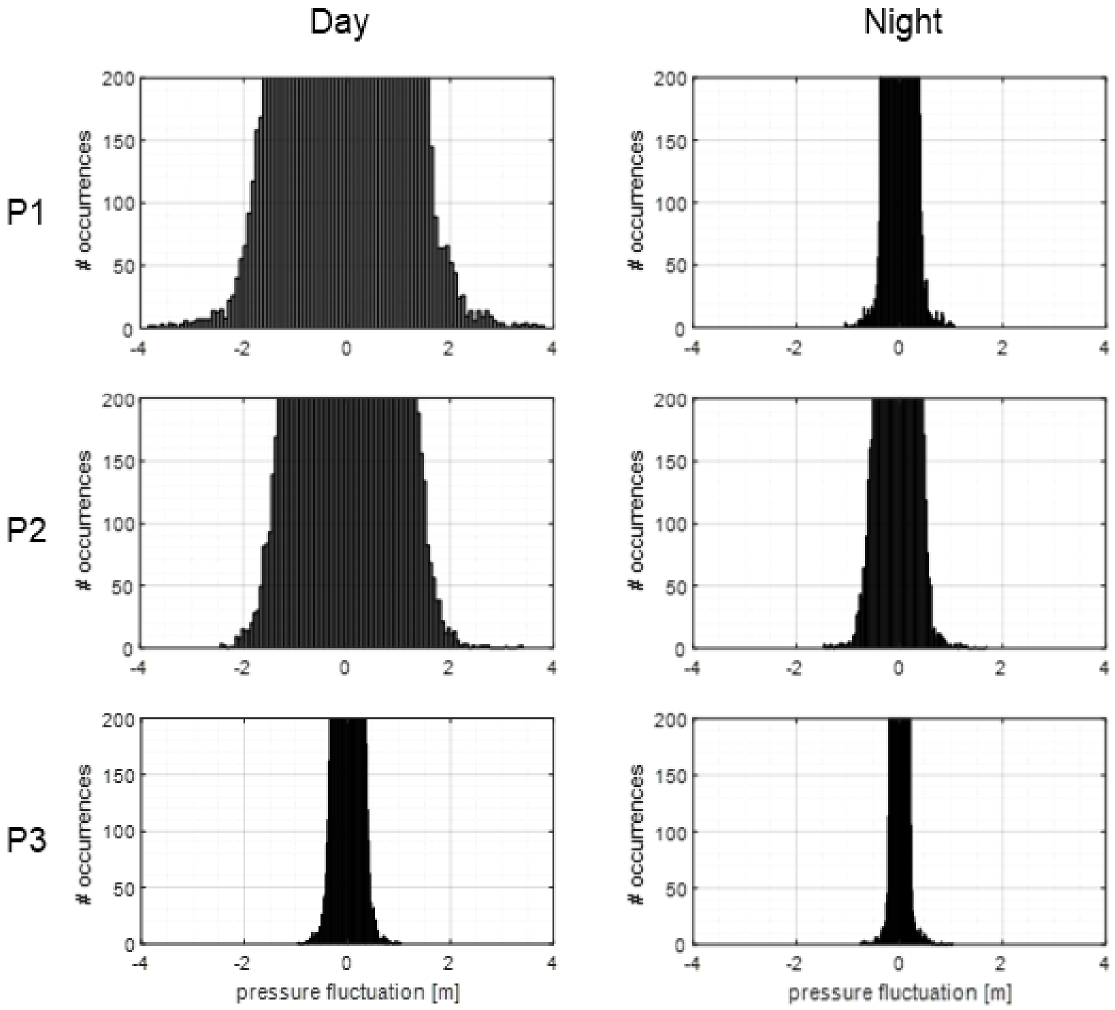

**Figure 4.** Histograms of short-term pressure fluctuations in the day and night period for the three measurement sections P1, P2 and P3.

## 4 CONCLUSIONS

This work is aimed at characterizing the water distribution network that serves the urban centre of Gorino Ferrarese under transient regimes in ordinary operational conditions considering high frequency (100 Hz) pressure signals collected at three points, two within the urban centre and one in transmission main. Observed pressure data are characterised: on one hand, a good correspondence for long-term pressure signal trend is observed between the three points. On the other end, short-term pressure fluctuations seem to distinguish the three measuring points. Indeed, pressure signal observed in points within the urban centre experimentally present more hysterical pressure data, probably due to both user activity and system configuration which tends to favour pressure wave reflections in downstream areas of the network: short-term pressure fluctuations reach values of almost three-four meters. The third measurement point located in feeding pipe seems to be less affected by the user activity and characterized by short-term fluctuations in the order of one meter. Considering the night period, short-term pressure oscillations are reduced for the three measurement points and their dynamic response becomes similar. So, considering the short-term pressure fluctuations, during the day, the measurement sections located in the urban centre present more reactive pressure signal than the one in the feeding pipe, while during the night the behaviour in all the three sections is quite similar.

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