

Considerations for the Hydraulic Design of Gravity-Fed Water Conduits in Areas with Rugged Terrain

Rodrigo Ruíz-Santos¹, Humberto Silva-Hidalgo^{1*}, María Socorro Espino-Valdés¹, Adán Pinales-Munguía¹, Cornelio Álvarez-Herrera¹, Álvarez Jorge-Lucero²

¹Faculty of Engineering, Autonomous University of Chihuahua, Chihuahua, Mexico

²Faculty of Animal Science and Ecology, Autonomous University of Chihuahua, Chihuahua, Mexico

Email: rruiz@uach.mx, *hsilva@uach.mx

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Abstract

The design of gravity-fed hydraulic systems in mountainous terrain profiles still has challenges, especially in rural areas. The steep topography can induce air in pipes, leading to a change of flow regime, hydraulic area reduction, and hydraulic head losses. Furthermore, the transition between pressurized and free-surface flow, which frequently occurs in pipelines with steep slopes, that is, in which this article focuses, can significantly reduce the hydraulic head and drastically decrease the flow capacity. This experimental work demonstrated that the actual conveyance capacity in a physical model was reduced by up to 75% compared to the theoretical value. Failure to consider this problem in the design of conveyance systems in steep terrain can lead to the incorrect application of mathematical models and conventional hydraulic design software, which do not account for flow regime transitions such as single-phase pressurized flow (liquid), two-phase pressurized flow (liquid and gas), or free-surface flow (liquid at atmospheric pressure). This analysis documents a problem that can be common in conveyance systems in rugged terrain, especially low-flow systems serving small mountain communities. It also highlights the urgent need to integrate advanced and specific criteria into the design of gravity functioning conveyance systems to ensure a safe and efficient water supply.

Keywords

Water Availability, Water Sources, Accessibility to Water Resources, Topographic Conditions

1. Introduction

Humanity cannot develop without access to sufficient quantities of safe water; there-

fore, social well-being depends on the availability of this vital resource. The World Bank [1] has recognized that “inadequate sanitation and lack of access to clean water affect millions of people worldwide”, making it necessary to implement immediate measures to address poverty.

According to the OMS-UNICEF [2], the greatest gap is in rural areas, as in 2015 only 55% of the world’s rural population had access to safely managed water services, compared to 85% in urban areas. In Mexico, in 2020, drinking water coverage in rural areas was 89%, while in urban centers it reached 98%. In neither case was it specified whether the service was safely managed [3].

In addition to these socio-demographic challenges, many rural communities in mountain areas face other technical problems that can hinder or delay the safe management of drinking water services in accordance with Sustainable Development Goal 6 [4] in its target 6.1: Achieve by 2030, universal and equitable access to safe drinking water at affordable cost.

Among the most significant technical challenges are: 1) the decrease in the availability of surface and groundwater in these regions, 2) the sources of drinking water supply are progressively located at greater distances, adversely affecting accessibility to the water resource; 3) the presence of air in pressurized water conveyance systems, related to the previous challenges; and 4) more rugged topographical conditions for the development of water conveyance projects.

In relation to the latest engineering challenge, this work focuses on identifying the problems that arise in the design of water conveyance systems for supplying populations in hilly terrain (mountains), analyzing the limits of conventional hydraulic modeling methods in these scenarios, and demonstrating, through an experimental physical model, the discrepancies between the flow regime assumptions of traditional hydraulic analysis and the observed behaviors.

In relation to this engineering challenge, the present study focuses on determining under which conditions a gravity pipeline, designed as a total length pressurized system, may fail when operating under mixed flow regimes, in water-supply systems serving hilly terrain (mountains). Additionally, the limitations of conventional hydraulic modeling approaches under these scenarios are assessed, and, through a physical experimental model, evidence of the failure mode and its effect on the actual conveyance capacity compared to the theoretical discharge is presented, contrasting conventional modeling assumptions with the observed hydraulic behavior.

The hydraulic engineer must consider these issues to avoid underestimating the pipe diameter, which leads to a water pipeline with less conveyance capacity, compared to results obtained from conventional theoretical solutions.

2. Challenges in Water Supply in Mountainous Areas

2.1. Decreasing Availability of Surface and Groundwater

With the increase in the world’s population, water availability has decreased sig-

nificantly, leading to a water crisis in some places [5]. Per capita water availability in Mexico fell from 18,035 m³/capita/year in 1950 to 4416 m³/capita/year in 2007 [6]. It is estimated to have decreased to 3663 m³/capita/year in 2020 and is projected to reach 3358 m³/capita/year by 2030 [7].

2.2. Accessibility of Resources Due to Distance from Supply Sources

In Integrated Water Resources Management, two fundamental aspects are water availability and efficient use [8]. Supply sources, basins, and aquifers are affected in their water availability by increased demand or extraction, which can lead to the depletion of some water intake structures. In these cases, the sources will need to be replaced by others located in more distant areas, where social pressure on water resources has not yet affected surface flows or the yield of groundwater extraction. This process translates into a change in the conditions of accessibility to the water resource, which entails the construction of longer water conveyance systems and, in many cases, routes along winding and rugged topographic profiles.

2.3. Air in Pressurized Water Conveyance Systems

Air entrainment in pressurized water conveyance systems can occur in installations operating under both pumping and gravity flow conditions. However, it is essential to recognize that potable water conveyance systems are designed to transport only liquid, in order to maintain consistency with the hydraulic design principles governing pressurized conduits. These principles are grounded in the laws of conservation of mass and energy [9]. The theoretical framework underlying this design assumes that the fluid completely occupies the cross-section of the conduit [10] [11].

Considering the above, a pressurized potable water system should ideally not contain air. However, in reality, air can be present due to improper filling or emptying operations, as well as physical or design flaws, such as incorrect placement or inadequate sizing of air intake and exhaust devices. Construction problems can even allow air to enter through pipe joints with special fittings and connections when pressures in the system are below atmospheric [12].

Air in drinking water pipes can also be generated by the release of gas when the pressure in the liquid decreases or as the temperature increases, as well as at the points of water entry into the system, such as the intake structure in a spring or in a body of water, as well as in pumping equipment due to inadequate submergence conditions [13].

Air trapped in pressurized pipelines gives rise to two-phase flow, which can cause, among other issues, flow capacity reduction [14]. In gravity-fed pressurized systems, air accumulated at the high points of the topographic profile reduces the effective hydraulic cross-section and increases flow resistance, thereby significantly diminishing the nominal flow capacity [15], as illustrated in **Figure 1**.

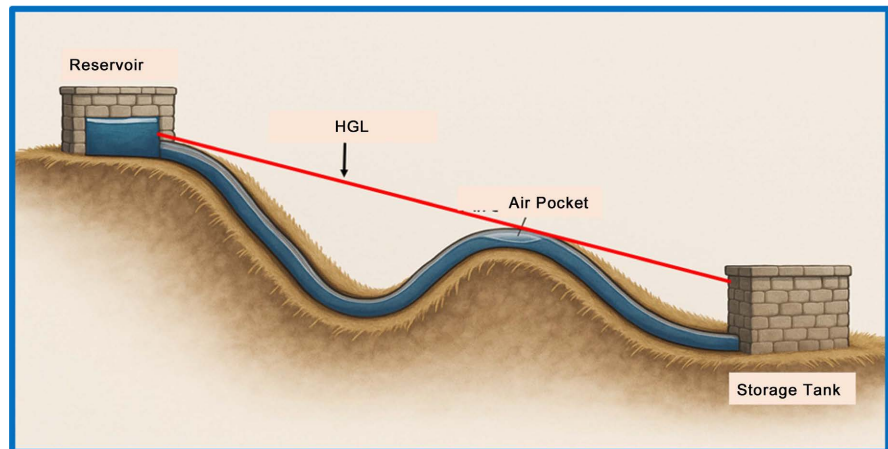


Figure 1. Typical air accumulation in a gravity-fed pressurized water conveyance system.

2.4. Rugged Topographic Conditions

When encountering rugged topographic conditions with steep slopes and uneven terrain, hydraulic design can be a significant challenge. This is due to the changing conditions that may fall outside the scope of conventional hydraulic engineering, especially in gravity-fed systems.

In these cases, trapped air is relatively common in pressurized water conveyance systems. However, in profiles with very steep slopes, a transition between pressurized and free-surface flow can occur (**Figure 2**). Stormwater drainage systems frequently observe this phenomenon [16]. In these situations, part of the pipe operates under free surface pressure (subjected to atmospheric pressure), which differs from a pressurized pipe with trapped air, where the liquid and gas pressures are different from atmospheric pressure **Figure 2**.

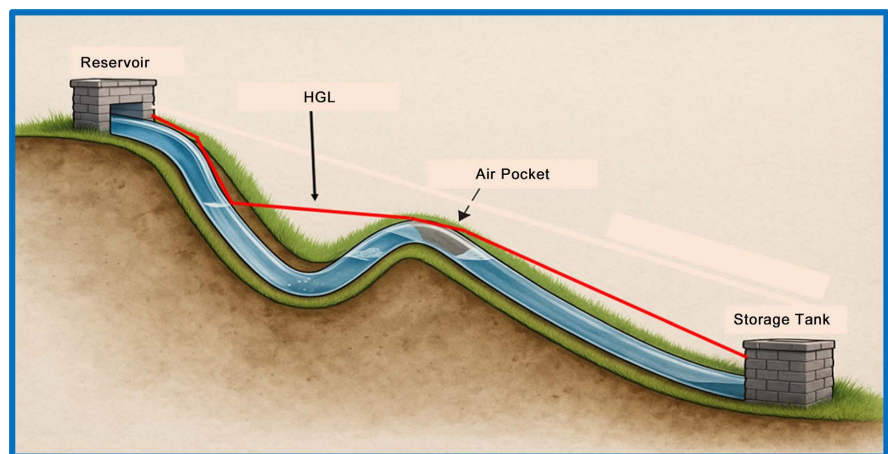


Figure 2. Partially pressurized and free surface (along its length) water conveyance system operating by gravity.

3. Case Study

To document the problem, a physical model was constructed in the hydraulics

laboratory of the Faculty of Engineering at the Autonomous University of Chihuahua (UACH), based on the pipeline profile shown in **Figure 3**. The setup consists of a transparent plastic pipe with an internal diameter of 19.05 mm and a total length of 14.06 m, instrumented with three piezometers to record the hydraulic grade line (HGL) under different inlet heads, considering air management at high points using air valves. The theoretical flow capacity and the piezometric line of the pipe were determined using the mass conservation equation (Equation (1)) and the energy conservation equation (Equation (2)). The profile presents descending slopes between of 68.3% and 10.16%, which are representative of hilly topographic conditions. For its application, the assumptions governing its use [9] were considered and applied to the control volume, which in this case is the water pipeline, which can be discretized into segments for analysis at points of interest.

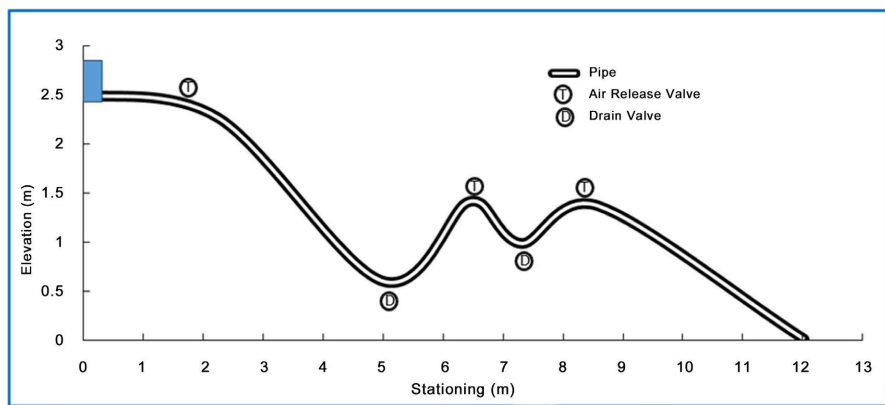


Figure 3. Driving profile of the case study.

$$V_1 A_1 = V_2 A_2 \tag{1}$$

$$z_1 + h_1 + \frac{V_1^2}{2g} - h_f - h_a = z_2 + h_2 + \frac{V_2^2}{2g} \tag{2}$$

The flow velocities are represented by V_1 and V_2 , the cross-sectional areas in the pipeline by A_1 and A_2 , the hydraulic heads by h_1 and h_2 , and the elevations of the pipeline by z_1 and z_2 . The subscripts 1 and 2 represent the initial and final analysis locations, respectively; h_f represents friction losses (Equation (3)), and h_a , fitting losses (Equation (4)):

$$h_f = K L Q^2 \tag{3}$$

where $K = \frac{10.3n^2}{\varnothing^3}$, n is the roughness coefficient of the pipe material, and \varnothing is the pipe diameter and

$$h_a = k \frac{V^2}{2g} \tag{4}$$

where k is the coefficient for calculating losses due to accessories or premises.

Considering the profile in **Figure 3**, the pipeline operates by gravity and has a

favorable difference in elevation between the initial point (1), with a storage tank providing a hydraulic head of 0.25 m, and the discharge point (2), which is subject to free discharge (atmosphere). To meet the stated assumptions, the pipeline must be pressurized along its entire length, so the piezometric line must always be above the pipe's crown elevation profile. In other words, there should be no negative pressures, since if they occur, the flow rate would be lower than required [9] and Equations (3) and (4) could be out of boundary conditions in some segments, if the pipe is not completely full of water and working pressurized all length.

Through hydraulic analysis, the theoretical hydraulic profile shown in **Figure 4** was obtained, corresponding to a flow rate of 0.22 L/s. It is important to note that this is the maximum flow rate that can theoretically be conveyed without negative pressures occurring (piezometric line at an elevation lower than the top of the pipe) along the pipeline. This means that the head loss due to conveyance and accessories estimated through Equations (3) and (4) does not lead to negative pressure (using Equation (2)) along the pipeline, especially in the first 2 m stations of the elevation profile shown in **Figure 4**.

However, as mentioned, the discharge is to the atmosphere, so the piezometric line does not correspond to the free discharge condition. To achieve this, a pressure-sustaining valve (or another device that provides similar results) would be required at the pipeline discharge so that the actual piezometric line matches the theoretical one, but many times the operation and maintenance of these devices are limited for small rural communities in mountainous zones.

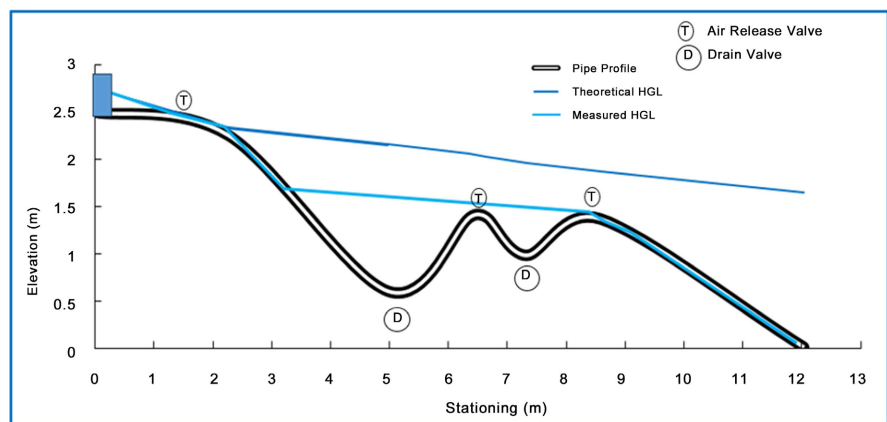


Figure 4. Topographic and hydraulic profiles of the theoretical and observed analysis in the case study.

Figure 4 presents the observed piezometric line, which is consistent with the behavior identified in the physical model. The pipe exhibits a steep slope in two sections, inducing a transition from a pressurized flow regime to a free-surface regime (*i.e.*, a partially full pipe with liquid and gas at atmospheric pressure). This phenomenon is illustrated in **Figure 5**, obtained during the experimental campaign. Under these conditions, the measured flow rate was $0.05465 \text{ L/s} \pm 0.0039 \text{ L/s}$, corresponding to 25.0% of the theoretical flow rate. This reduction can be

attributed to the presence of two segments where flow regime transitions occur due to high descending slopes, and pressurization is lost, causing the system to behave as a pressure-breaking head where the pipe is functioning as a channel with the water surface at atmospheric pressure. Consequently, the available head is dissipated, reducing the pipe's overall flow capacity.



Figure 5. Experimentation using a physical model.

Many rural water conveyance systems were theoretically designed for a specific flow rate; however, in practice, they often exhibit a lower conveyance capacity for the reasons discussed above. This improper sizing constitutes a hydraulic design issue that must be addressed promptly, as it risks the construction of conveyance systems with insufficient capacity to transport the required flow.

4. Limitations of Conventional Design Programs

Conventional hydraulic design programs are typically developed for either open-channel analysis, as in the case of SWMM [17], or for pressurized conduit analysis, as in the case of EPANET [18], both of which are in the public domain. However, these programs cannot model systems in which both flow regimes coexist. As an alternative, efforts have been made to couple programs [19] that can first analyze one regime and subsequently use the results as boundary conditions for analyzing the complementary regime, thereby sequentially adapting the physical conditions of the conduit under study.

5. Conclusions

The hydraulic analysis of gravity-fed pipelines in areas with rugged terrain remains a challenge that has not yet been addressed with sufficient depth and rigor. In some cases, design procedures are implemented without considering that, due to the complex topography, pipeline segments with steep positive slopes (downward in the direction of flow) may operate partially full, with the flow exposed to

atmospheric pressure. This condition can result in the selection of an undersized pipe diameter, as in sections operating under free-surface conditions, the internal pressure dissipates—equivalent to an energy loss—thereby reducing the available hydraulic head. Consequently, the flow capacity is lower than theoretically expected; in the experimental case analyzed, it was approximately four times lower.

The paper shows an area of opportunity for research to address the specific problem of gravity-fed water pipelines in areas with rugged terrain presenting high slope profile segments, which cause transitions in the operation regimen (pressurized-free surface) where a mixed regimen hydraulic model is required.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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