Discussion of "Pressure Surges Following Sudden Air Pocket Entrapment in Storm-Water Tunnels" by Jose G. Vasconcelos and Gabriel M. Leite

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First, the authors are to be congratulated on their paper. It is an accomplishment to have experimentally investigated such a complex phenomenon, particularly one that has received only minor attention to date in the associated literature. This paper differs from other work presented in this realm in that the pipe system permits a water column that is not initially at rest and one that can convey a considerable amount of kinetic energy. This initial kinetic energy embodied in the water column, as shown in the original paper, makes a considerable difference to the system's transient response.

The authors have nicely studied the influence of a number of key parameters on the transient pressure response and on the subsequent pressure damping following both partial and complete stoppage of flow; the parameters investigated include the initial velocity of water column, the size of air pocket, the pipe slope, and the degree to which the flow is restricted at the end valve.

However, there are a couple of points that this discussion would like to help to clarify. In particular, the discussers believe that both the initial air void fraction and the system wave speed (representing the elastic nature of the water column and the pipe) are sometimes more important issues than the paper implies. In other words, under particular circumstances, both of these factors can significantly affect the transient pressures. It is perhaps not surprising that these special cases were not noted, because the test conditions were such that the contributions of these two important factors remained hidden; the tests were all conduced in a range of response that was insensitive to these features. But to avoid a too generalized conclusion, the following discussion aims at shedding some light on these occasionally important sensitivities. Because both air void fraction and elasticity tend to be more influential in cases of complete flow blockage, they are both discussed here in that context only.

To better understand the important role of initial kinetic energy of a water column, it is insightful to quickly review a 1976 study by Martin. In particular, Martin (1976) numerically explored the pressurization of a horizontal frictionless pipe system and concluded that for a given reservoir height, the maximum pressure following sudden pressurization at a downstream air pocket is constant for any arbitrary choice of water column length and air pocket volume. The pipe system considered only included an initially stagnant water column, along with the constant head upstream reservoir and an air pocket at the downstream side. For such a system, energy considerations directly confirm that if rigid column theory is assumed and in the absence of friction, all energy (i.e., flow work) admitted to the system from the upstream reservoir must be absorbed by the air pocket by the time the water column is again brought to rest against the compressed air pocket. Obviously, for a given sized air pocket, the air pressure will tend to increase in direct response to increased compressive energy from the reservoir.

In Martin's (1976) case, an increase in the size of the air pocket increases the total quantity of energy admitted from the reservoir because a larger air pocket allows the water column to accelerate for a longer duration and thus to extract more energy from the reservoir; yet conversely, a larger air pocket requires more energy to be compressed to a specific pressure. It turns out that these two contrary tendencies are perfectly balanced, accounting for the observed independence between the maximum air pressure and the initial air pocket size for a given reservoir height.

In the current case, however, the energy by which the air pocket is compressed is not only dependent on the size of the air pocket, but also depends on the initial energy of the water column, a value that is in turn dependent on both the velocity and length of the moving water column. For a given velocity and air pocket size, as the water length increases, the air pocket will be compressed with more energy, and thus gain a higher pressure. As the water column increases further, so does the maximum pressure; it is only control of the initial velocity of the water column that practically limits the resulting air pocket pressure.

All these physical insights can be easily confirmed numerically. To this end, the discussers created a rigid column model (RCM) based on the same set of equations presented by the authors. The RCM was applied to a hypothetical example consisting of a horizontal frictionless pipe, a constant head upstream reservoir, and an initially fully open valve at the downstream side. Geometrical and hydraulic characteristics of the system are as follows: initial air pocket size $= 1\ \mathrm{m}^3$, initial water column velocity $= 2\ \mathrm{m/s}$, pipe diameter $= 1.129$ m (giving a cross-sectional area of unity), reservoir height $= 0.204$ m (a value chosen to compensate for the velocity head), polytropic exponent $= 1.2$, atmospheric pressure head $= 10.4$ m, and initial air pocket pressure $= 0$ m.

Fig. 1 depicts the calculated maximum air pressure as a function of the initial water column length. As can be seen for the given air pocket size, the maximum air pressure grows without bound as the initial velocity and kinetic energy water column progressively increases. This confirms that the water column plays a crucial role in the transient response of the system and should be considered in

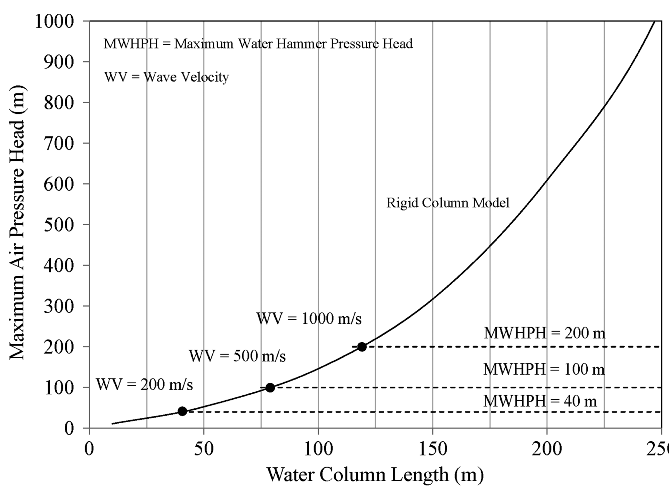

Fig. 1. Effect of water column length on maximum air pressure head

both system and experimental design. However, Fig. 1 demonstrates that beyond a specific length of water column, the calculated maximum pressure tends to exceed what is called maximum water hammer pressure, which is obtained by the Joukowsky formula, $H = (a/g)V$. Obviously in this case, for a given initial water column velocity, acoustic wave velocity markedly and directly affects the maximum pressure.

In Fig. 1, the maximum water hammer pressure heads associated with the wave velocities of 1,000, 500, and 200 m/s are marked by three horizontal lines. As can be seen, beyond a threshold water column length, rigid column theory markedly violates the physics of the flow, predicting unrealistic maximum air pressures. Indeed, it is the compressibility of the flow, traditionally associated with water hammer conditions, that actually limits the pressure peak. For example, for an initial water column length of 200 m, the maximum pressure head obtained from the rigid column model is 609.9 m, whereas the maximum water hammer pressure for the wave velocities of 1,000, 500, and 200 m/s are 200, 100, and 40 m, respectively. For a given initial water column velocity, the threshold length depends on the magnitude of the wave speed and reduces as the wave velocity decreases. Obviously, for water column lengths greater than the threshold length, the maximum air pressure remains constant and no longer depends on the water column length.

Such behavior can be explained by considering that in this case, not all kinetic energy of fluid accumulates in the air pocket; rather, it is partitioned between the compressed air and elastic energy associated with the pressure wave in the water column itself. With shorter water columns, the energy accumulated in the water column is a small fraction of that accumulated in the air pocket, so the elastic effect is rendered unimportant, and the rigid column model then provides satisfactory results. However, for longer water columns, a considerable amount of energy is stored in the water column itself and the air pocket is squeezed with lower energy. This causes the maximum air pressures to always be lower than those calculated by the rigid column theory. However, beyond a specific length, the maximum air pressure remains constant at what is called the Jokowsky pressure because at this specific pressure, the kinetic energy in the unit length of the water column is exactly equal to the energy that can be stored in a unit length of the water column. Thus, at this specific pressure, the remaining kinetic energy in the system is directly stored within the water column, and no energy is transferred to the air pocket.

To further justify the foregoing discussion, flow stoppage in the hypothetical example is also simulated by an elastic model possessing the same formulation of that presented by Abreu et al. (1992). Fig. 2 compares rigid column model results with those of the elastic model for different wave velocities. As can be seen, the model results reconfirm all aforementioned discussion, particularly existence of the threshold water column. In this case, the threshold length for the wave velocities of 1,000, 500, and 200 m/s are 300, 150, and 100 m, respectively.

In the case with initially zero water column velocity, the elastic effect also comes into play as the initial void fraction of the system (air pocket volume divided by pipe volume) becomes smaller (Abreu et al. 1991); but in this case, the difference between the maximum air pressure calculated by the rigid column theory and that obtained from the elastic theory remains bounded, even if the

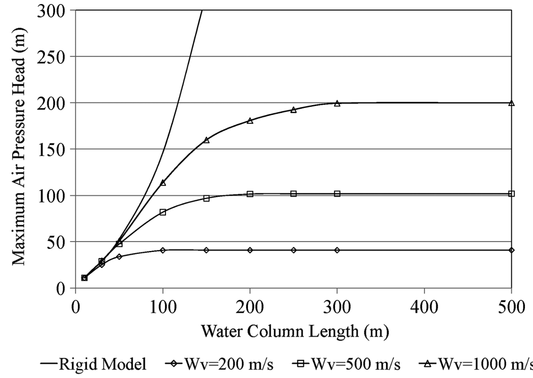

Fig. 2. Comparing rigid column and elastic models

air void fraction tends to zero. However, in the current case, the difference is not bounded and increases indefinitely as the air void fraction approaches zero.

Based on the aforementioned discussion, the following general remarks can be made:

1. For a given air pocket size, the initial water column length is an important factor that should be considered in design and experiments. However, after a specific threshold length, the maximum air pressure becomes independent of the water column length and remains constant at what is called maximum water hammer pressure. For a given air pocket size, this threshold length depends on both the initial velocity of the water column and the acoustic wave velocity of the water column; and
2. Rigid column theory should be cautiously employed in design because it may dramatically overestimate the maximum pressure. This conservatism would be particularly extreme in certain cases, such as when a sewer tunnel is initially operated at a high velocity during pressurization but also has a low acoustic wave velocity because of large content of free gas that could be intruded through tall drop shafts.

Finally, although the following discussion focuses on the complete stoppage of flow, partial blockage of flow may be also affected by both water column length and elastic effect of the system. However, these implications should be elaborated through a detailed study.

The discussers again thank the authors for an interesting and stimulating study and paper.

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