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INCORPORATING THE EFFECTS OF ENTRAPPED AIR IN SWMM5+ MIXED FLOW MODELING

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Mixed Flow in Stormwater Drainage Systems

- Mixed flow condition: free surface + pressurized flow
- Transients arise when free-surface → pressurized (full pipe)
- Air can get entrapped.

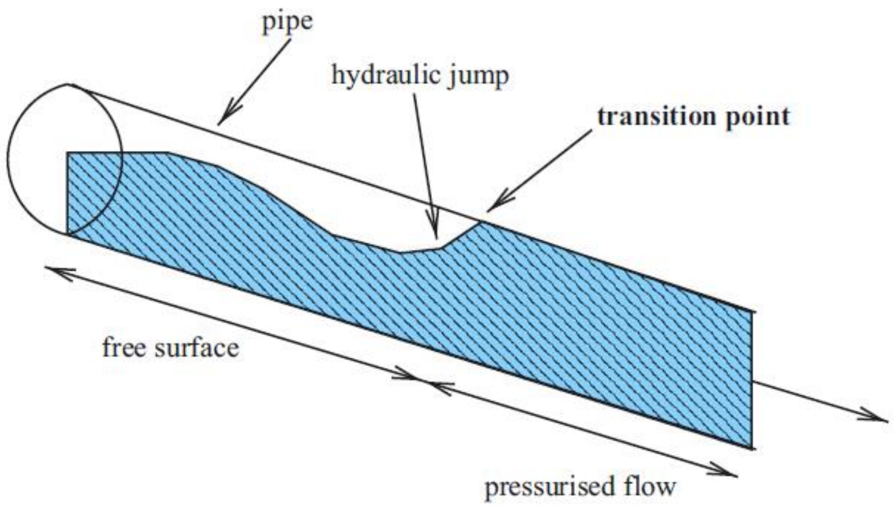

Figure: Mixed flow condition [1]

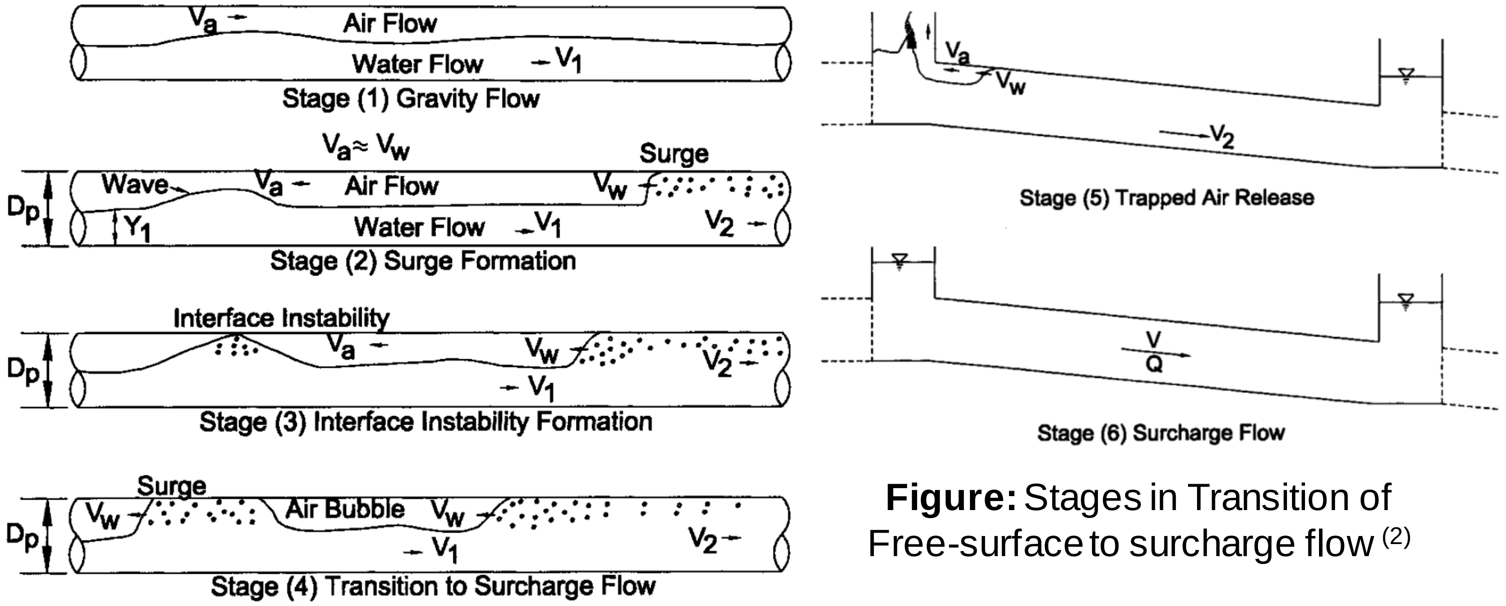

Figure: Stages in Transition of Free-surface to surcharge flow [2]

[1] Bourdarias, C., & Gerbi, S. (2007). A finite volume scheme for a model coupling free surface and pressurised flows in pipes. *Journal of computational and applied Mathematics*, 209(1), 109-131.
[2] Li, J., & McCorquodale, A. (1999). Modeling mixed flow in storm sewers. *Journal of hydraulic Engineering*, *125* (11), 1170-1180.

Air pocket Formation in Pipe Systems

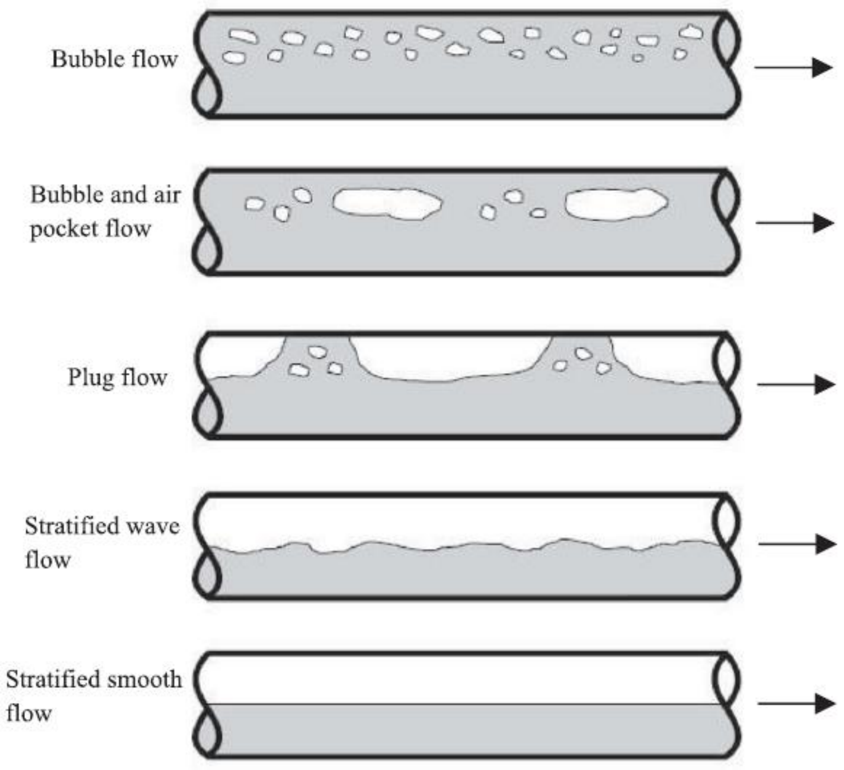

Figure: Air pocket formation at Trunk profile at Gallagher Hill Park [5]

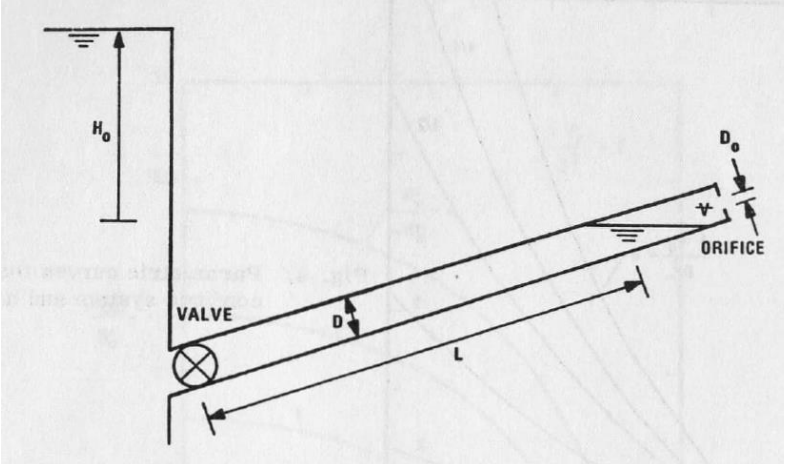

Figure: Entrapped air pocket example from Martin (1976) [4]

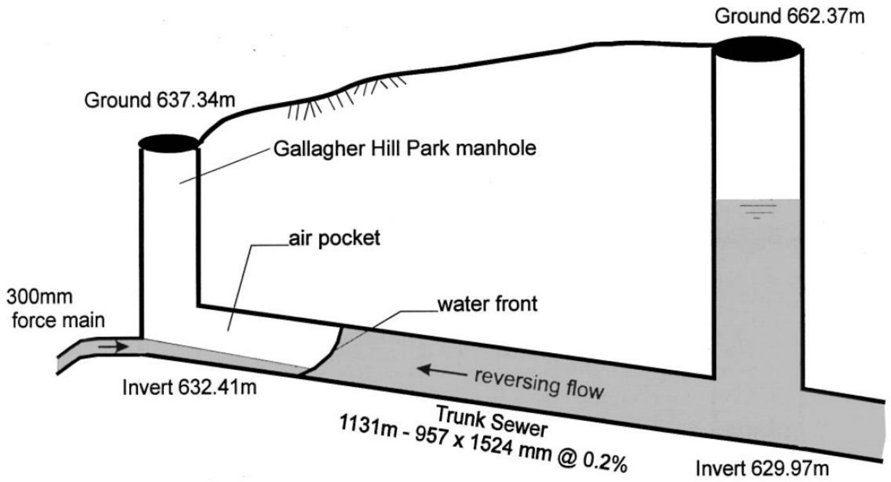

Figure: Air pocket formation at Trunk profile at Gallagher Hill Park [3]

[3] Zhou, F., Hicks, F. E., and Steffler, P. M. (2002). “Transient flow in a rapidly filling horizontal pipe containing trapped air.” *Journal of Hydraulic Engineering*, 128(6), 625–634.
[4] Martin, C. S. (1976). “Entrapped air in pipelines.” *Proc., 2nd Int. Conf. on Pressure Surges*, Cranfield, UK, British Hydromechanics Research Assoc, 15–28.
[5] Fuertes-Miquel, V. S., Coronado-Hernández, O. E., Mora-Meliá, D., and Iglesias-Rey, P. L. (2019). “Hydraulic modeling during filling and emptying processes in pressurized pipelines: A literature review.” *Urban Water Journal*, 16(4), 299–311.

Modeling Approach

- Air pocket detection algorithm: vented conduit
- Martin (1976) polytropic model,

$$\frac{dH_a^*}{dt} = -\kappa \frac{H_a^*}{\forall_a} \frac{d\forall_a}{dt} + \kappa \frac{H_a^*}{m} \frac{dm_a}{dt}$$

- Air pocket continuity,

$$\frac{d\forall_a}{dt} = Q_{\text{inflow}} - Q_{\text{outflow}}$$

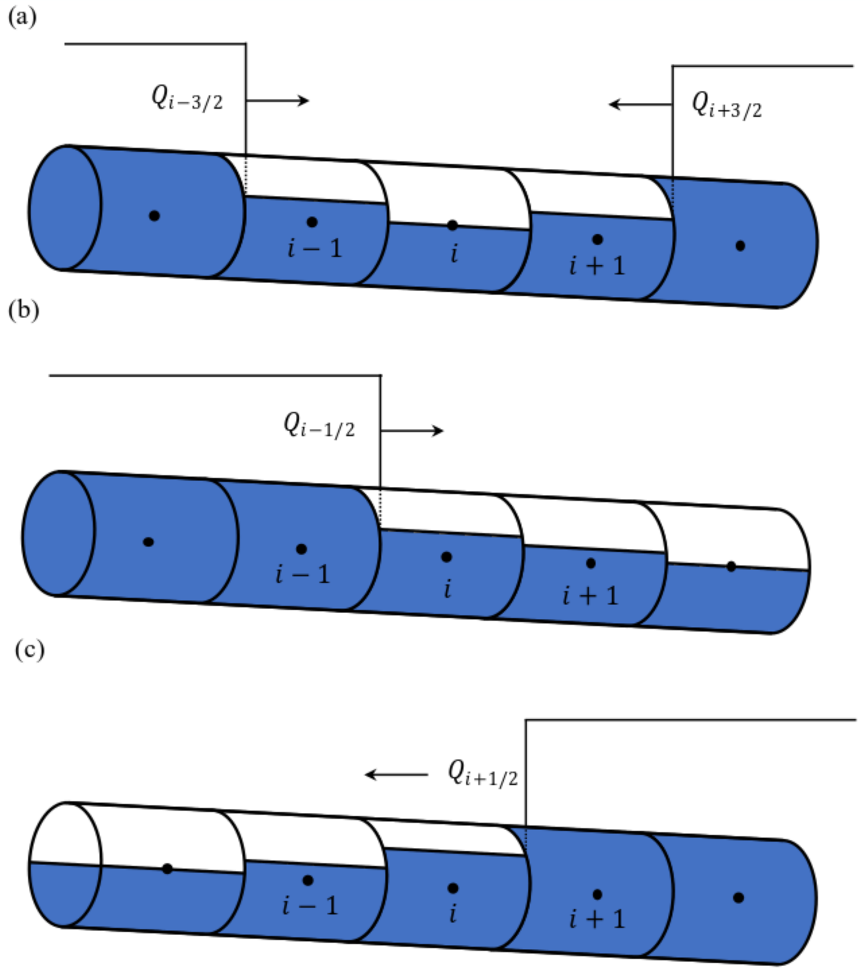

Figure: Detection of possible air pocket formation in a finite-volume discretized conduit: (a) air pocked formed without any ventilation, (b) air pocket with downstream vent, (c) air pocket with upstream vent.

Modeling Approach: Air Release

- Air release modeled using Zhou (2002) orifice equations.
  - Subsonic air release,

$$\frac{\mathrm{d}m_a}{\mathrm{d}t} = C_d \rho_a A_o Y \sqrt{2g \frac{\rho_w}{\rho_a} \left(H_a^* - H_{\mathrm{atm}}^*\right)}$$

  - Critical air release $(H_a^*/H_{\mathrm{atm}}^* > 1.89)$,

$$\frac{\mathrm{d}m}{\mathrm{d}t} = C_d \rho_a A_o \sqrt{g \frac{\rho_w}{\rho_a} H_a^*} \sqrt{\kappa \left(\frac{2}{\kappa + 1}\right)^{(\kappa+1)/(\kappa-1)}}$$

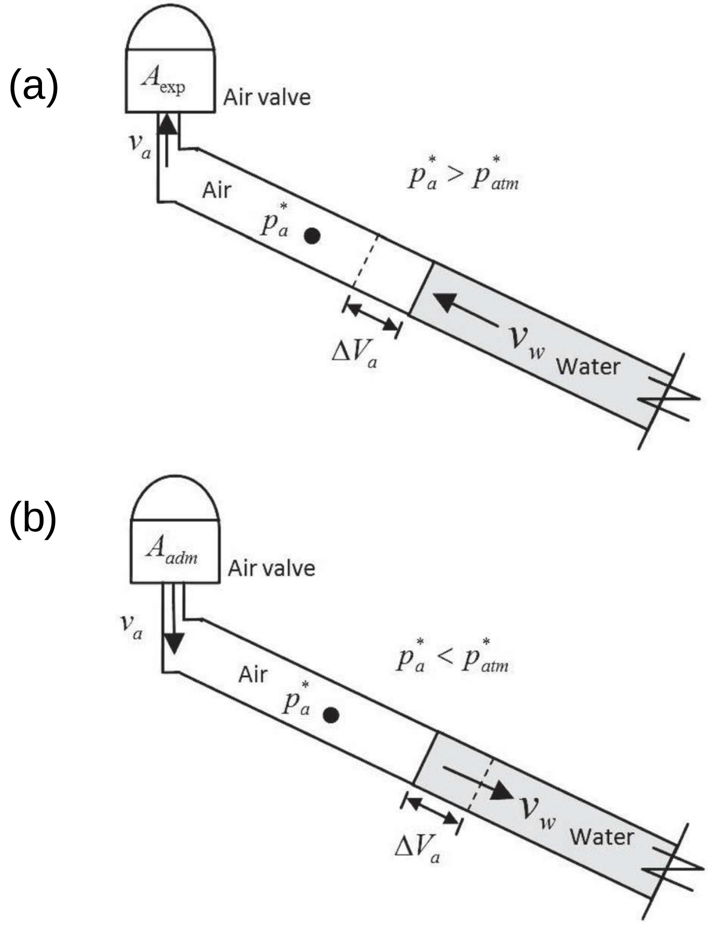

Figure: Effects of air valve behavior during (a) air release/outflow (b) air inflow

(5) Fuertes-Miquel, V. S., Coronado-Hernández, O. E., Mora-Meliá, D., and Iglesias-Rey, P. L. (2019). "Hydraulic modeling during filling and emptying processes in pressurized pipelines: A literature review." *Urban Water Journal*, 16(4), 299–311.

Modeling Approach: Time March

- θ-method time march within SWMM5+ RK2 scheme

$$\alpha = \kappa \frac{1}{\forall_a} \frac{d\forall_a}{dt}$$

$$\beta = \kappa \frac{1}{m} \frac{dm}{dt}$$

$$\frac{H_a^{*n+1} - H_a^{*n}}{\Delta t} = (\beta - \alpha)\left[\theta H_a^{*n+1} + (1-\theta) H_a^{*n}\right]$$

$$H_a^{*n+1} = H_a^{*n}\left[\frac{1 + \Delta t (1-\theta)(\beta - \alpha)}{1 - \Delta t \theta (\beta - \alpha)}\right]$$

$\theta = 1 \rightarrow$ Forward difference
$\theta = 0 \rightarrow$ Euler
$\theta = 0.5 \rightarrow$ Crank-Nicolson

- Add the air gauge head to solved piezometric head.

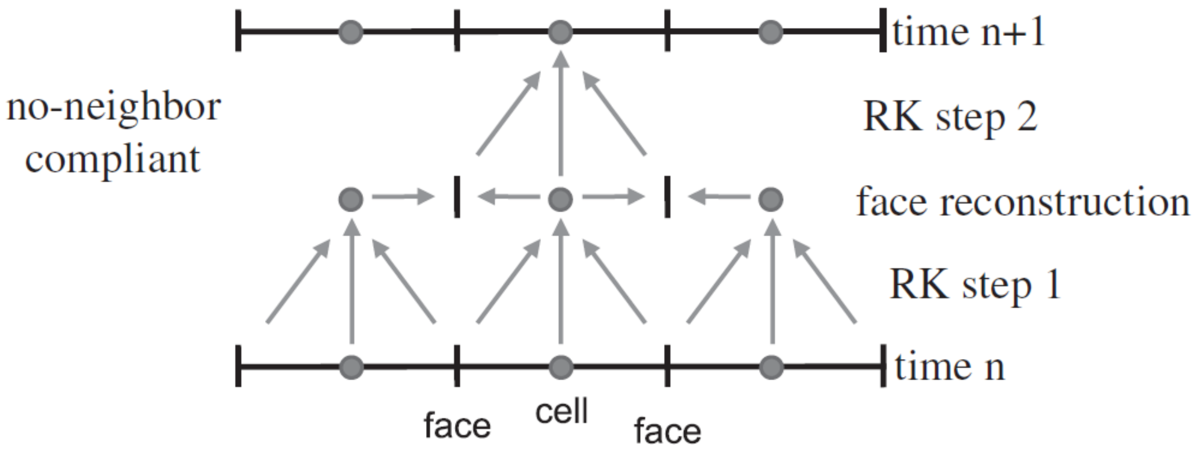

Figure: SWMM5+ RK2 time march.

Test Case: Ferreira et al. (2023) Experiments

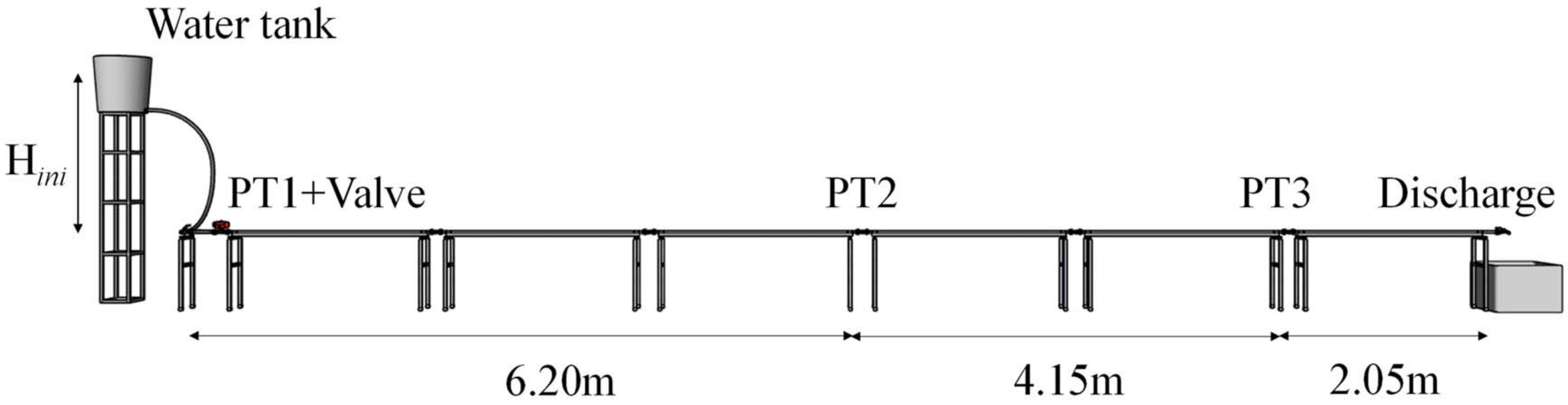

Figure: Ferreira et al. (2023) experimental setup (16)

Table: Ferreira et al. (2023) experimental tests, steady-state flowrate, orifice openings, and Reynolds number (16)

	Dead end		Small orifice				Large orifice			
	d = 0 mm		d = 1.1 mm		d = 2.2 mm		d = 10 mm		d = 21 mm	
H_{ini} (m)	Q	Re	Q	Re	Q	Re	Q	Re	Q	Re
0.35	0	0	0	0	0	0	0.28	4,715	0.37	6,231
1.50	0	0	0.03	488	0.08	1364	1.02	17,178	1.23	20,715

(6) Ferreira, J. P., Ferras, D., Covas, D. I., and Kapelan, Z. (2023). “Improved SWMM modeling for rapid pipe filling incorporating air behavior in intermittent water supply systems.” *Journal of Hydraulic Engineering*, 149(4), 04023004.

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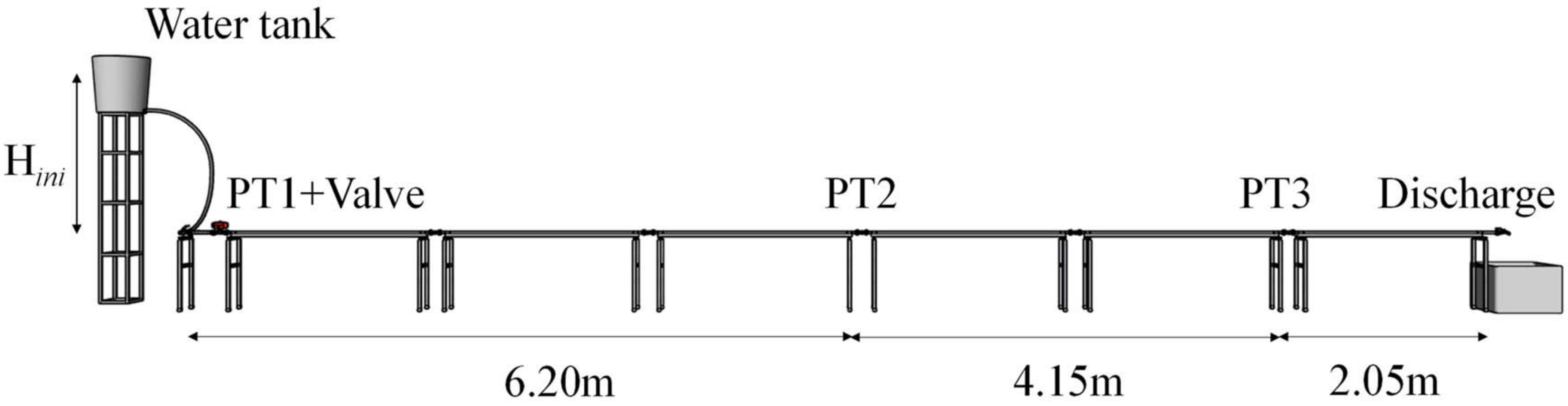

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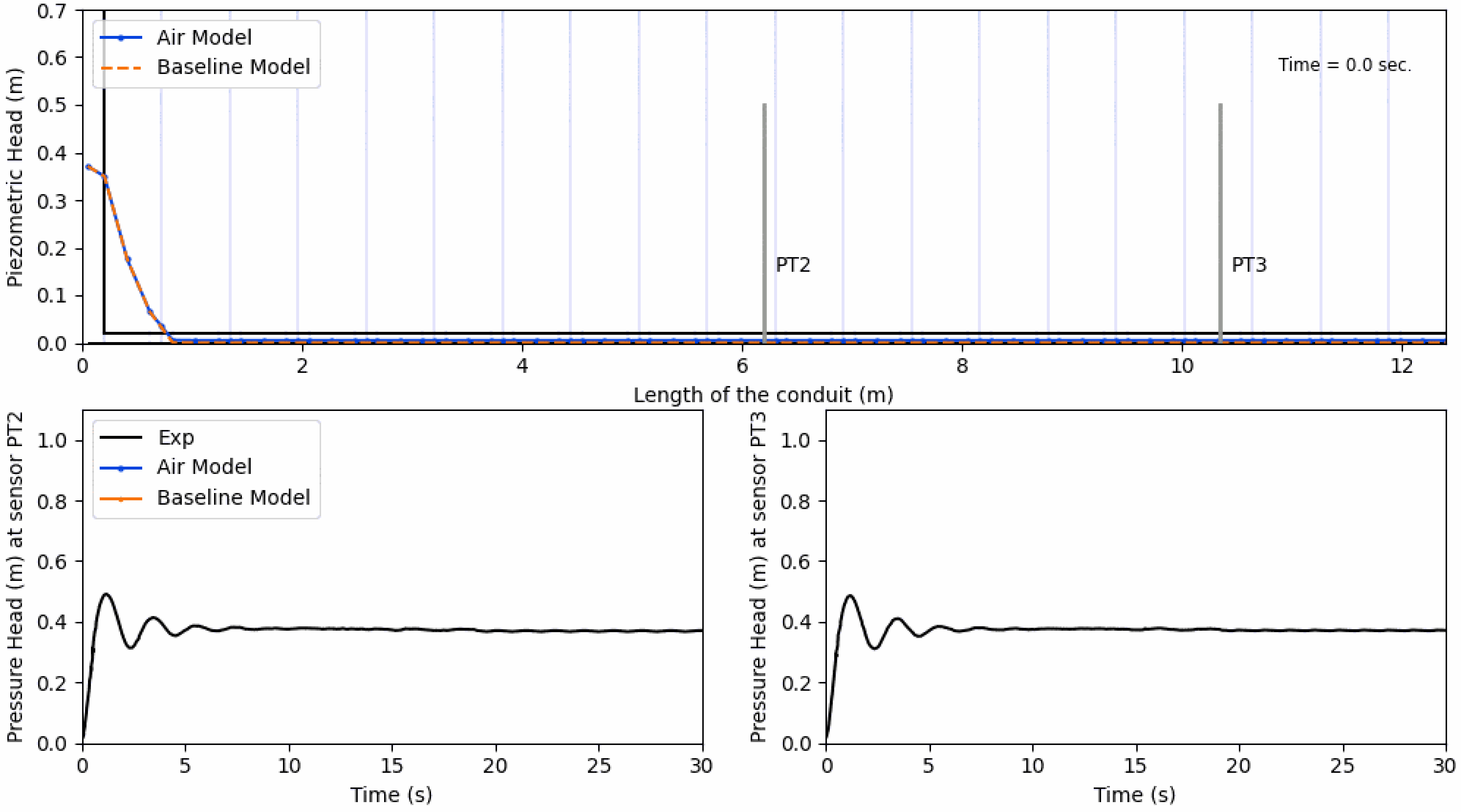
Ferreira et al. (2023) Experiments: No Air Release



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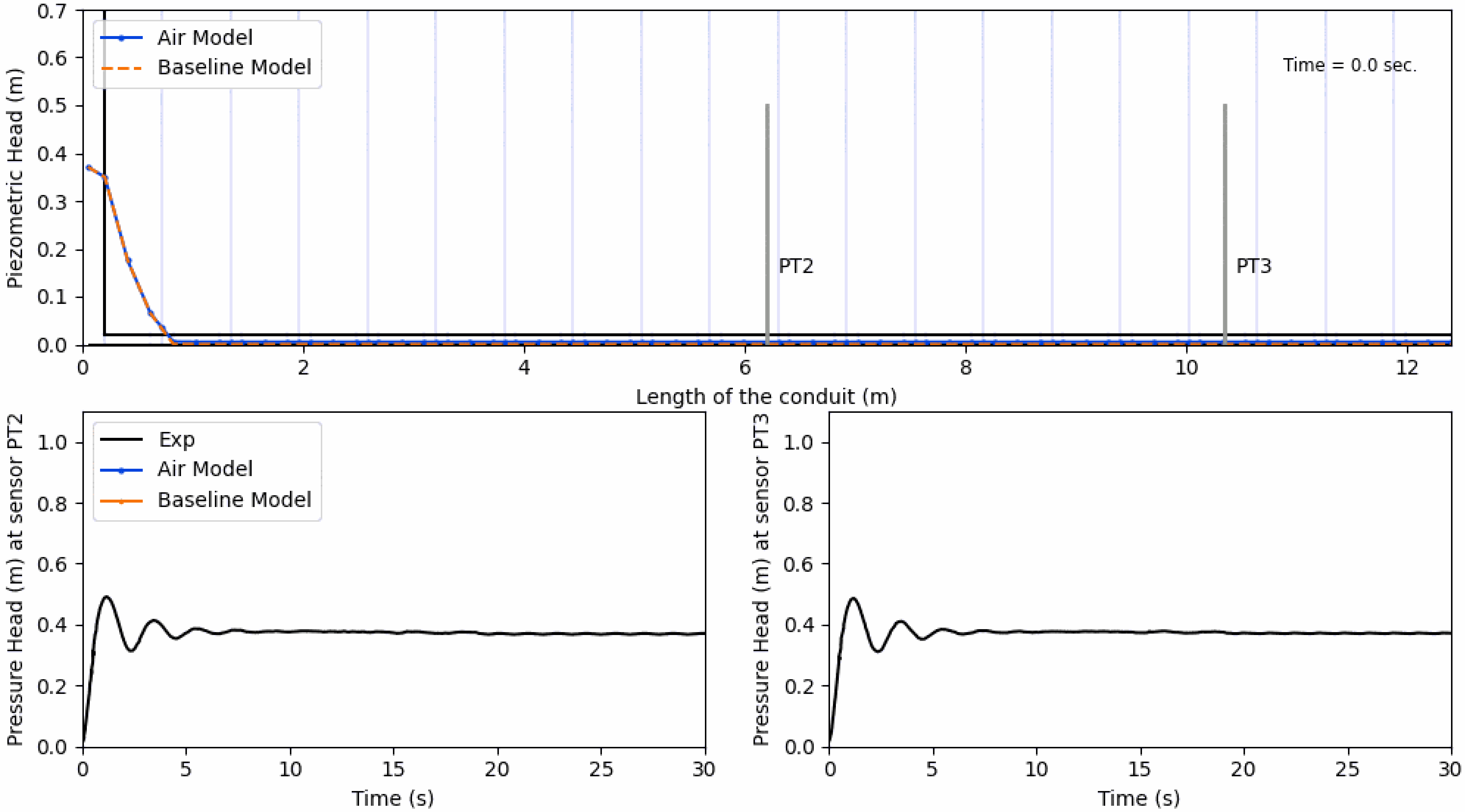

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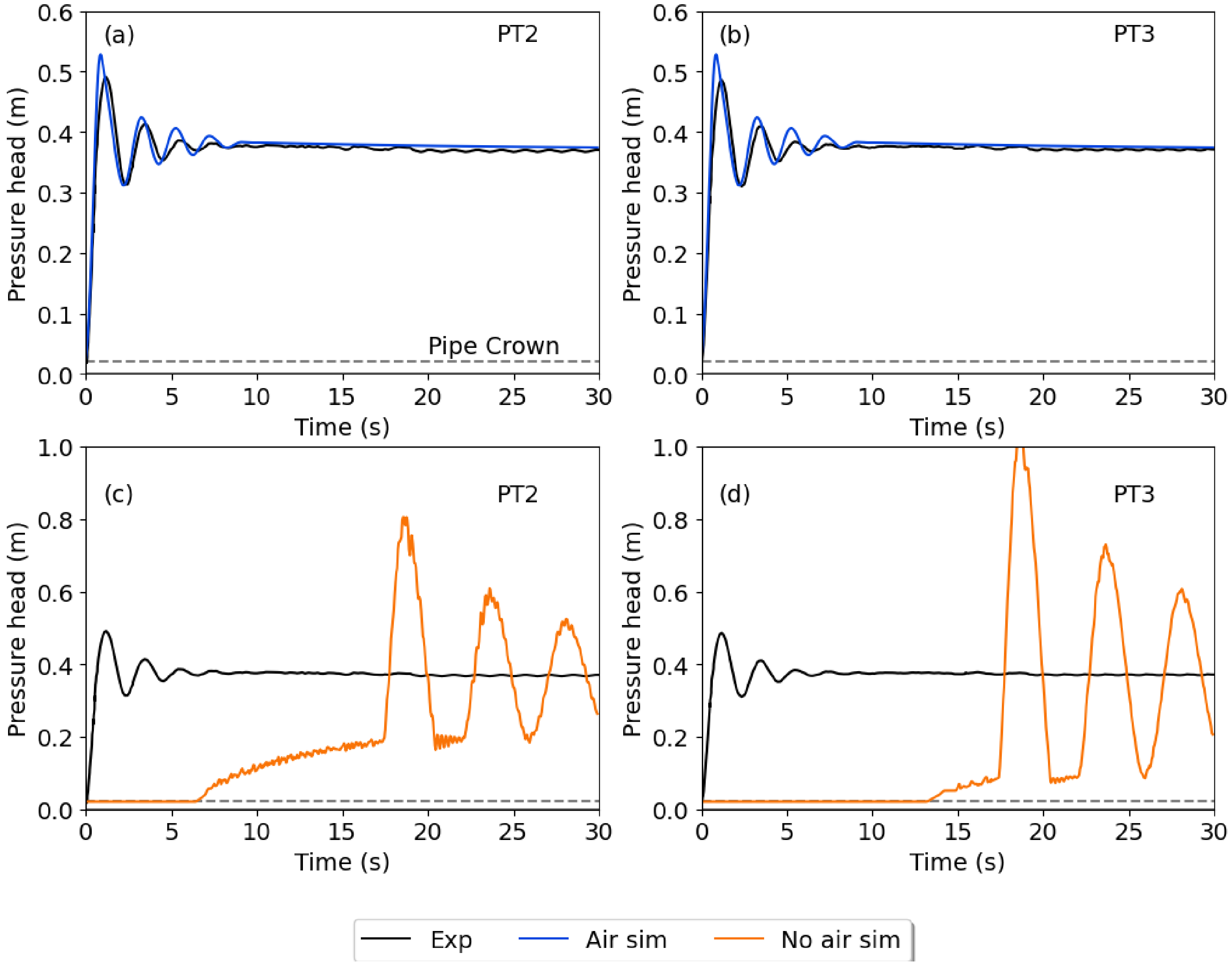
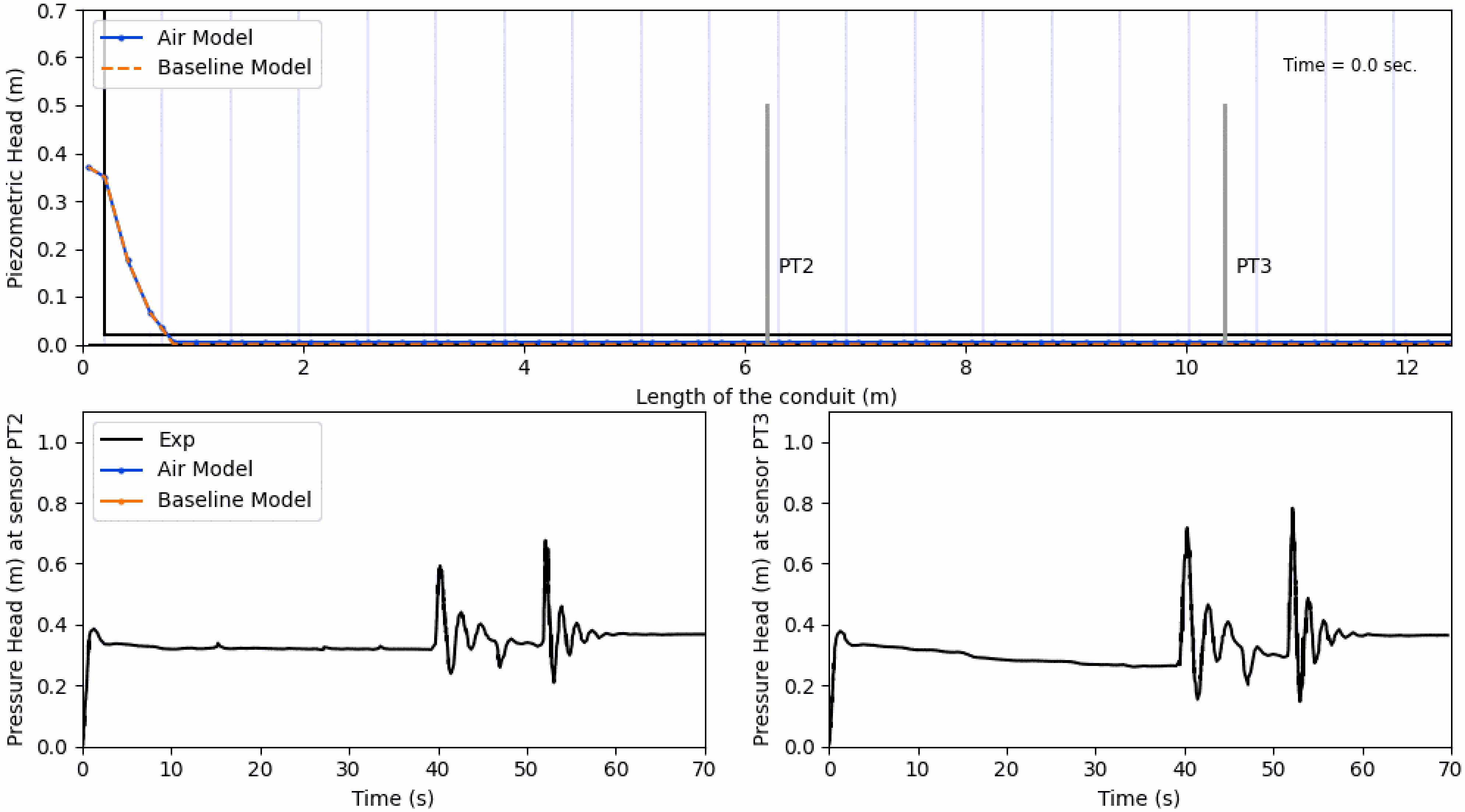
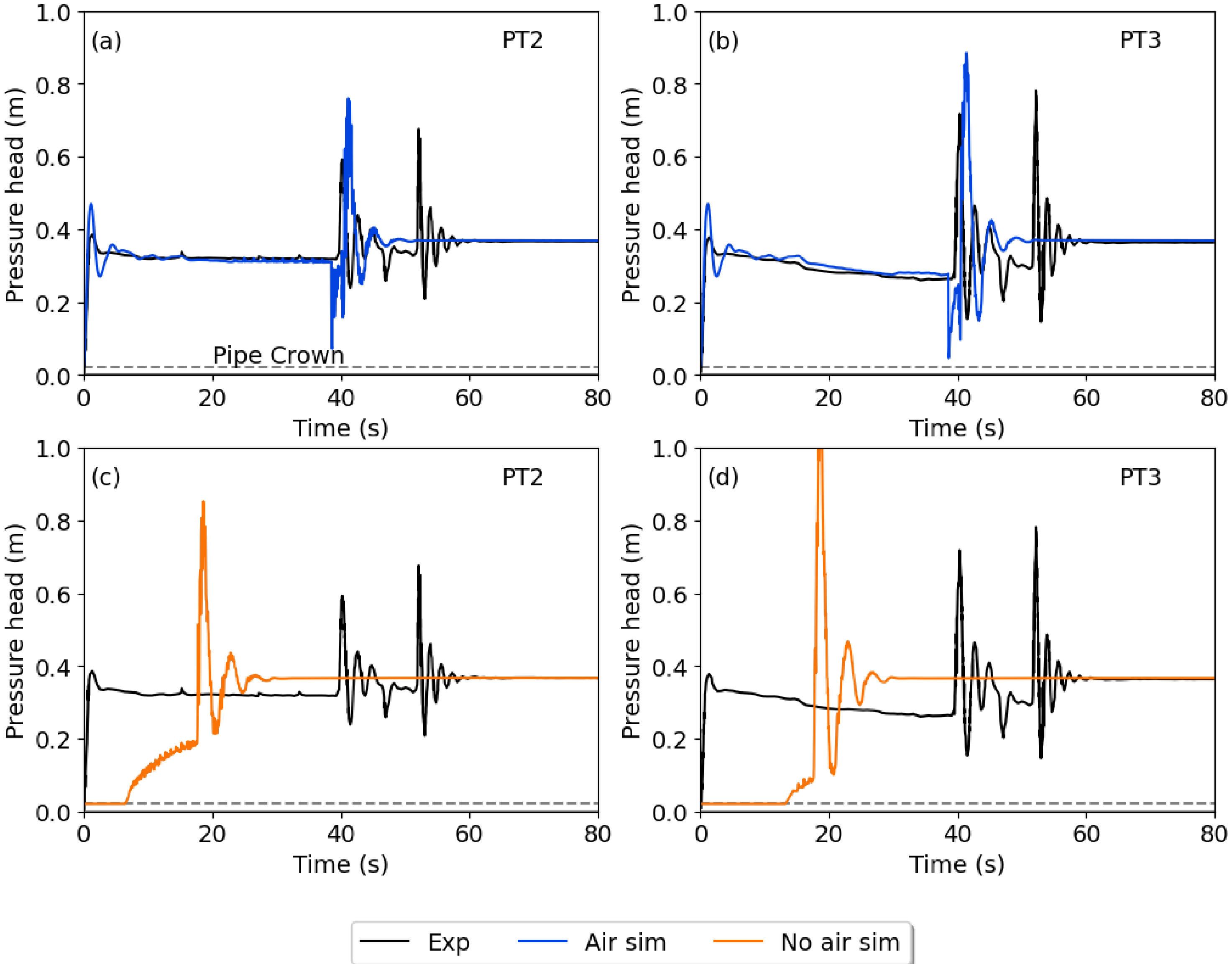


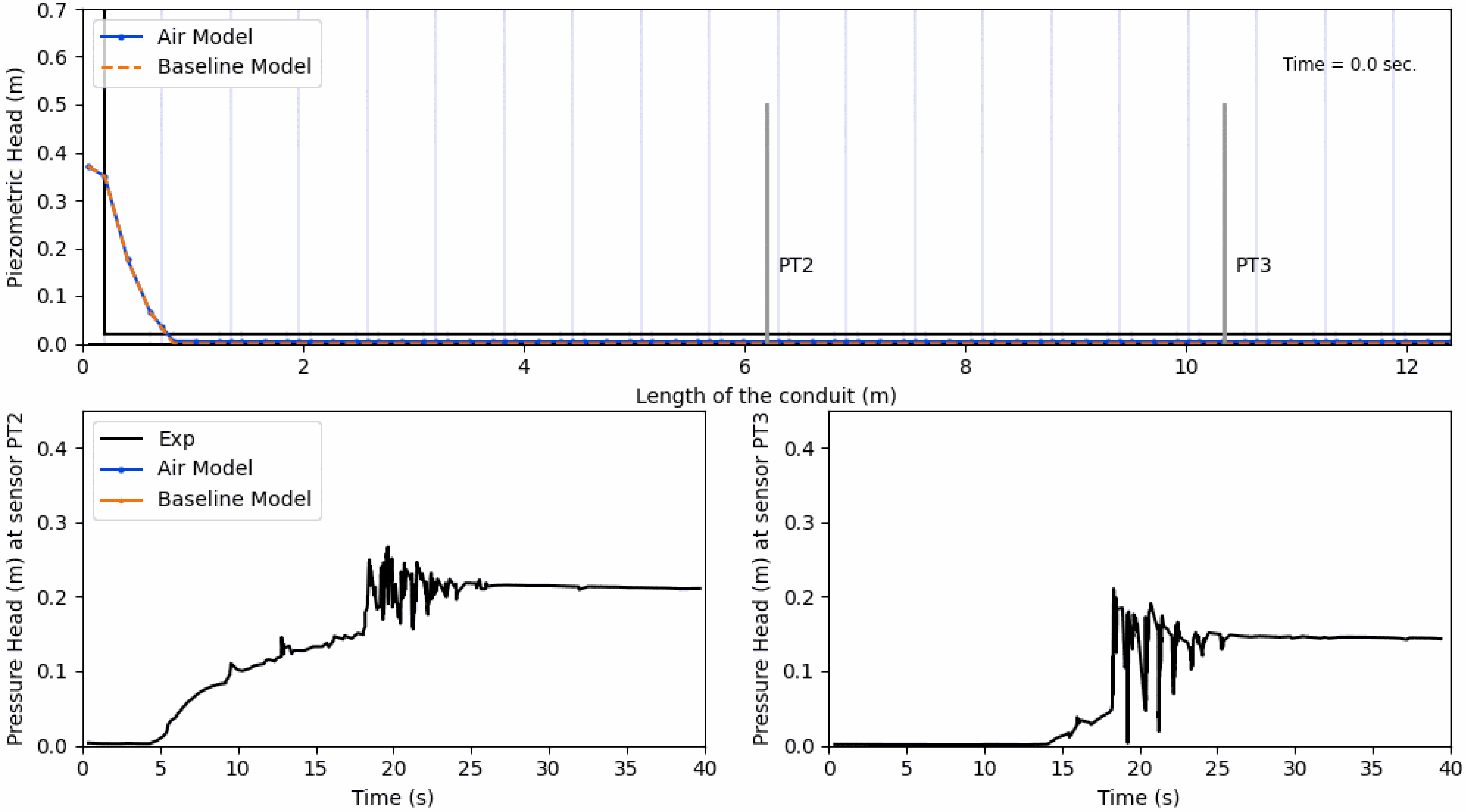
Ferreira et al. (2023) Experiments: Small Orifice Air Release (1.1 mm)



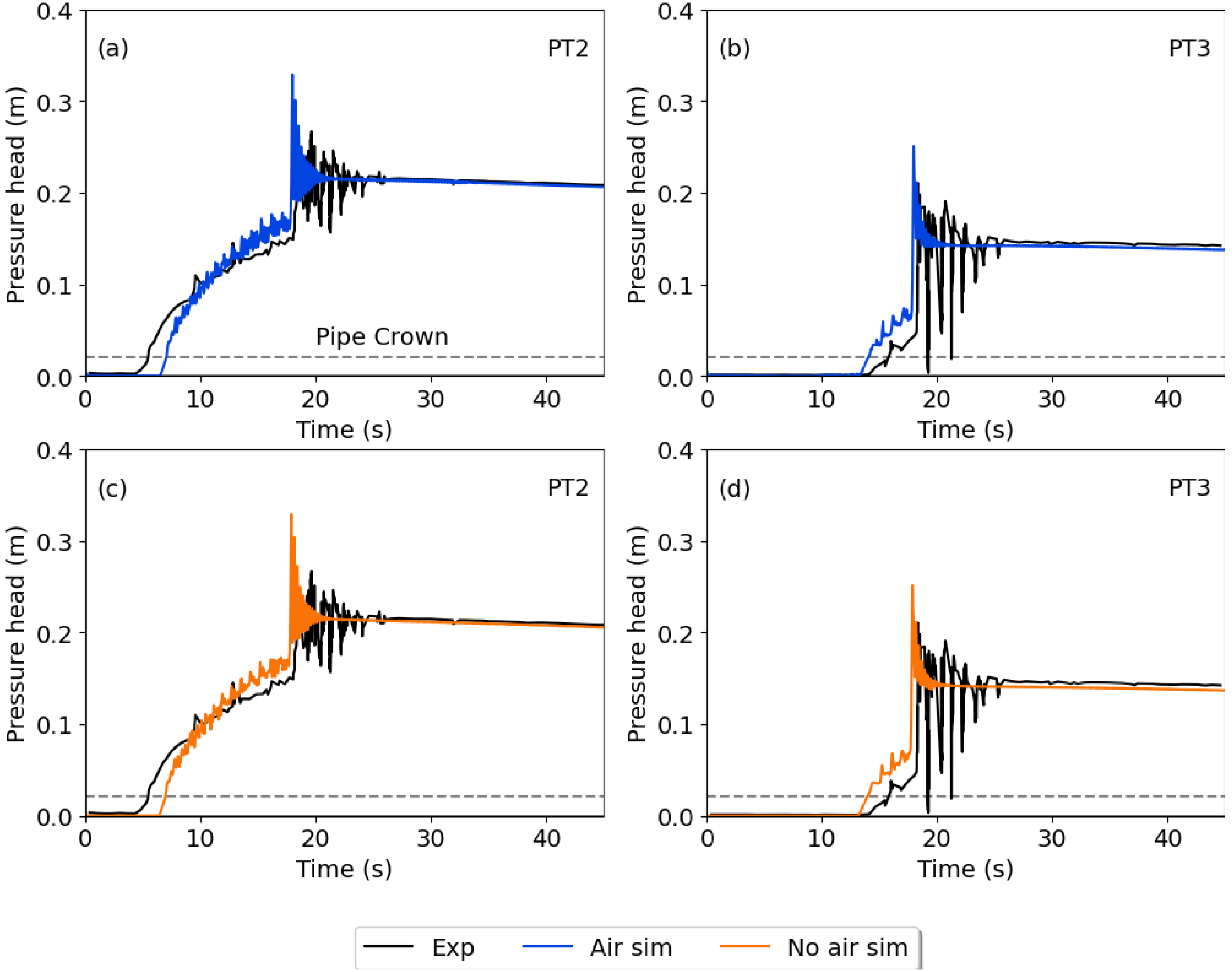
Ferreira et al. (2023) Experiments: Small Orifice Air Release (1.1 mm)



Ferreira et al. (2023) Experiments: Large Orifice Air Release (21 mm)



Ferreira et al. (2023) Experiments: Large Orifice Air Release (21 mm)



Tunnel Test

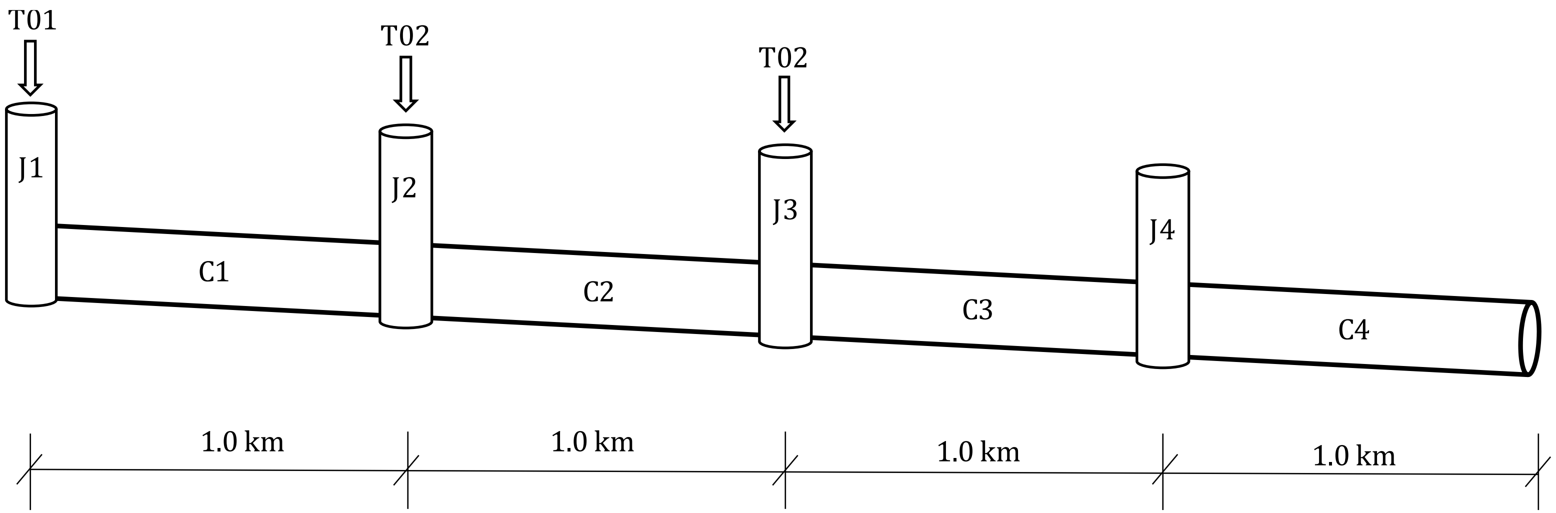


Figure: Tunnel test case layout. T01 and T02 are the inflow time-series. Conduits C1-C4 are 1 m diameter, smooth concrete (Manning's n of 0.01). Junctions J1-J4 are 1.21 m in diameter and allow a maximum surcharge height of 10 m before overflowing. The downstream end of C4 is a SWMM outfall node with a free-overflow boundary condition.

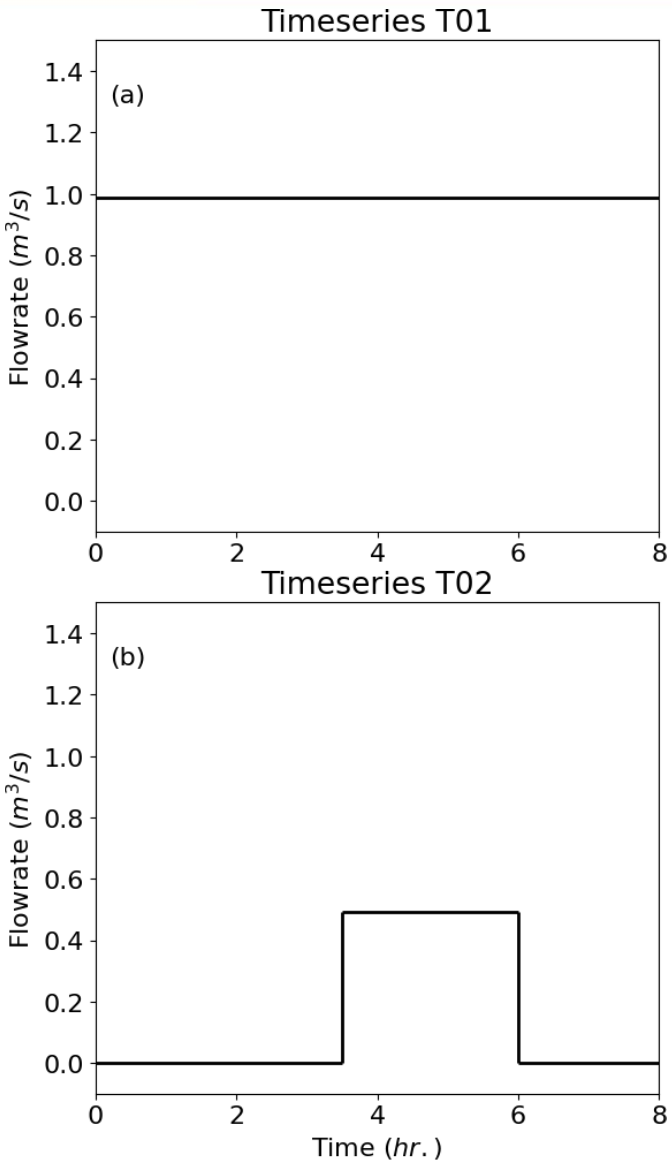
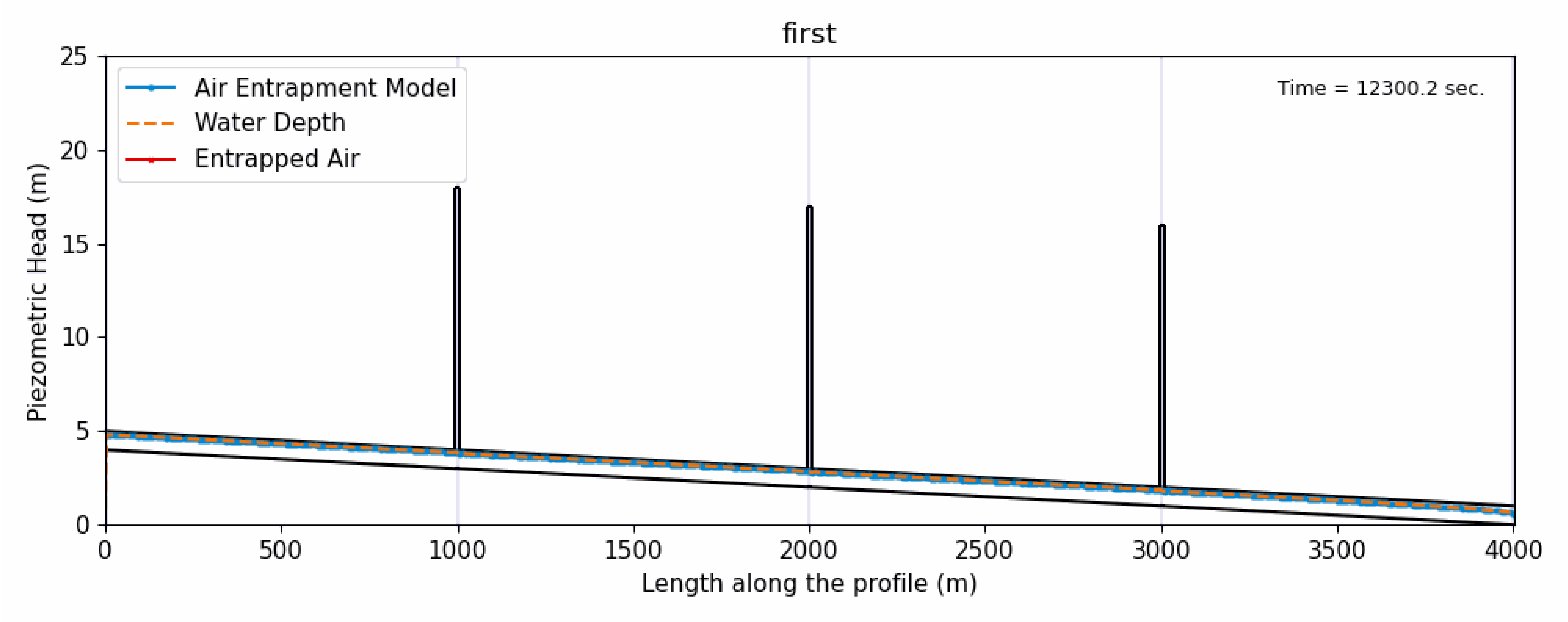


Figure: Inflow time series used in the tunnel test case: (a) T01 inflow into J1, (b) T02 inflow into each of J2 and J3.

Tunnel Test Case: Drawdown



Tunnel Test Case: Conduit Pressure Heads

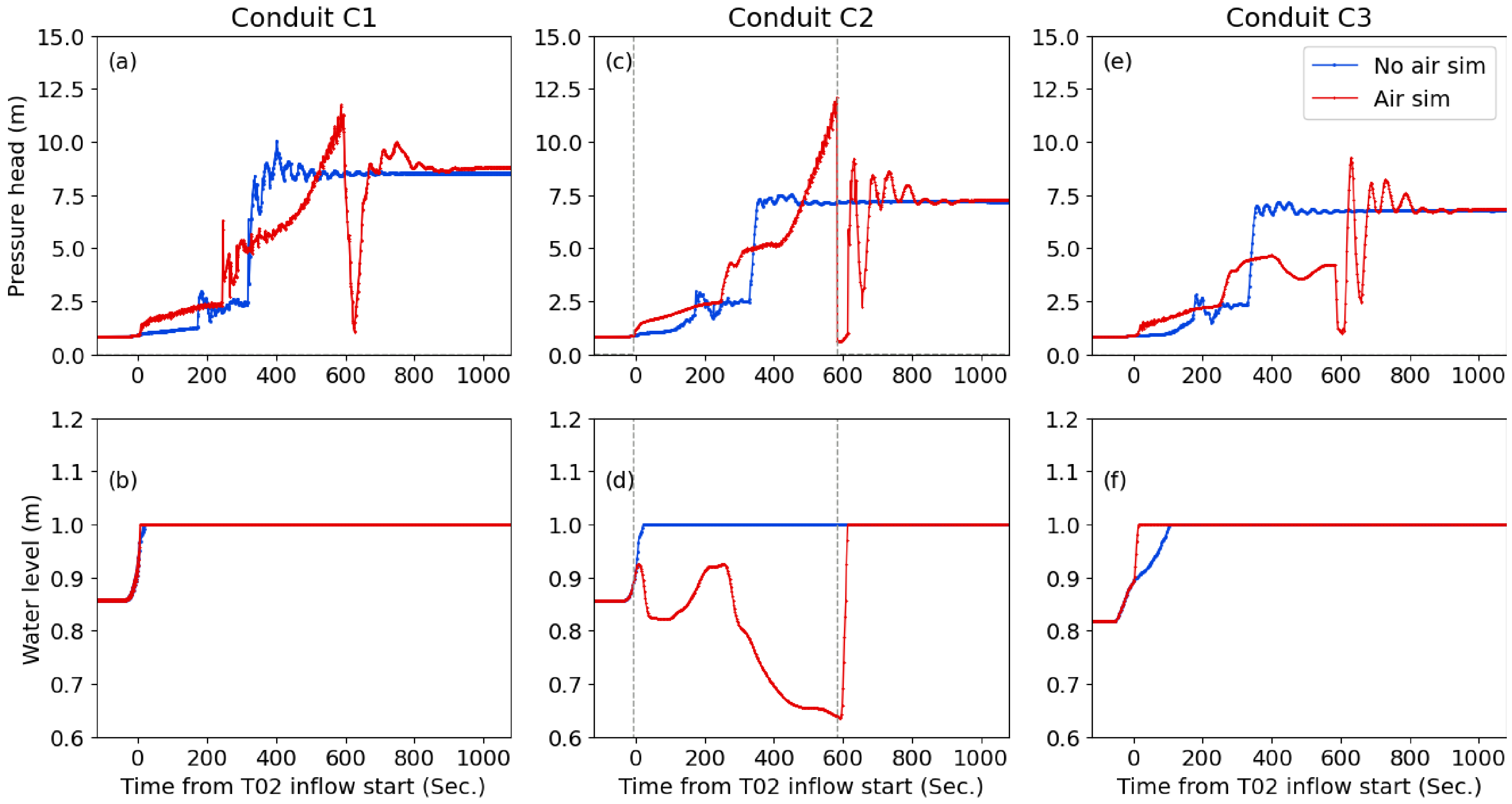


Figure: Simulated pressure heads (upper panels) and water levels (lower panels) at 50m from the downstream end of the conduits; (a,b) Conduit C1, (c,d) Conduit C2, and (e,f) Conduit C3 for both air entrapment and baseline model.

Tunnel Test Case: Junction Pressure Heads

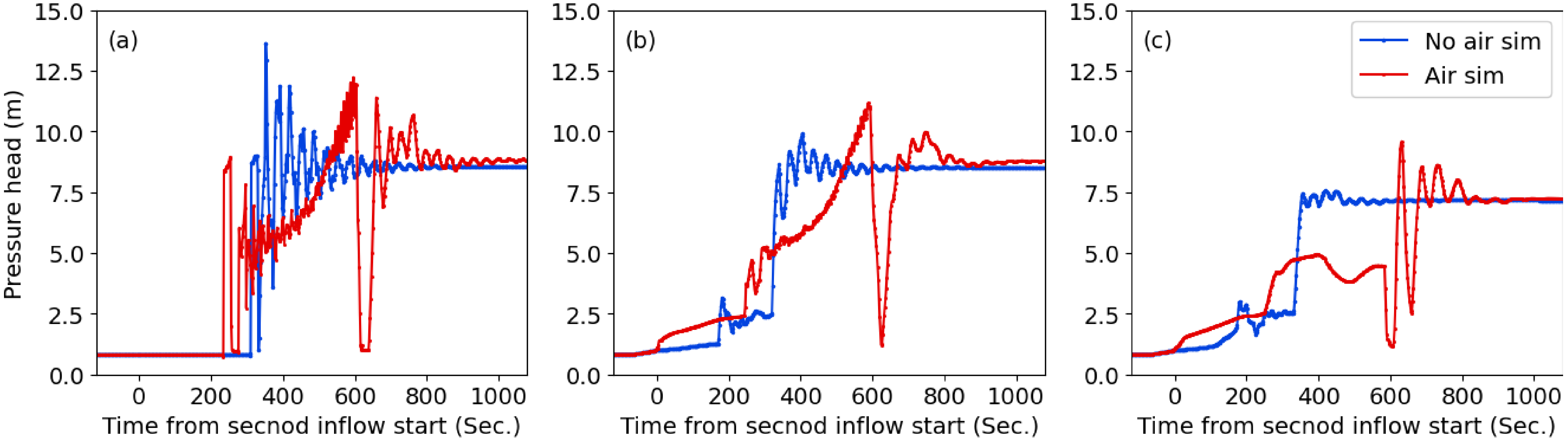
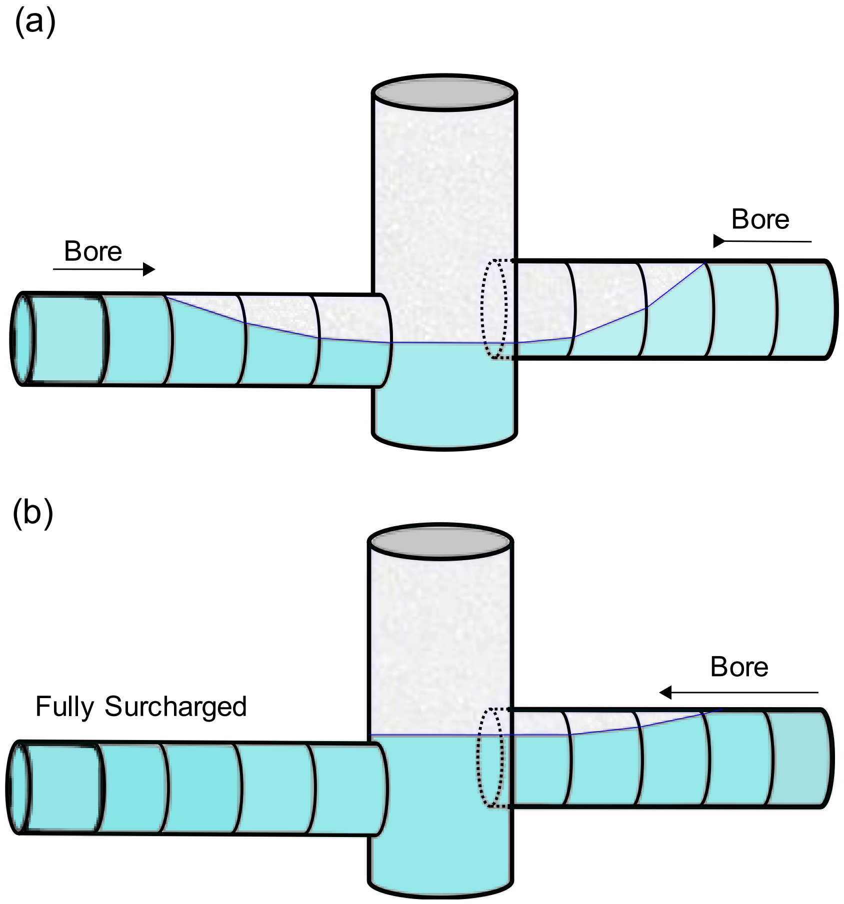


Figure: Simulated pressure heads at (a) Junction J1, (b) Junction J2, and (c) Junction J3 for both air entrapment and baseline model.

Future work: Conduit-junction Integrated Air Pocket

Combined conduit junction air pocket



No air pockets detected

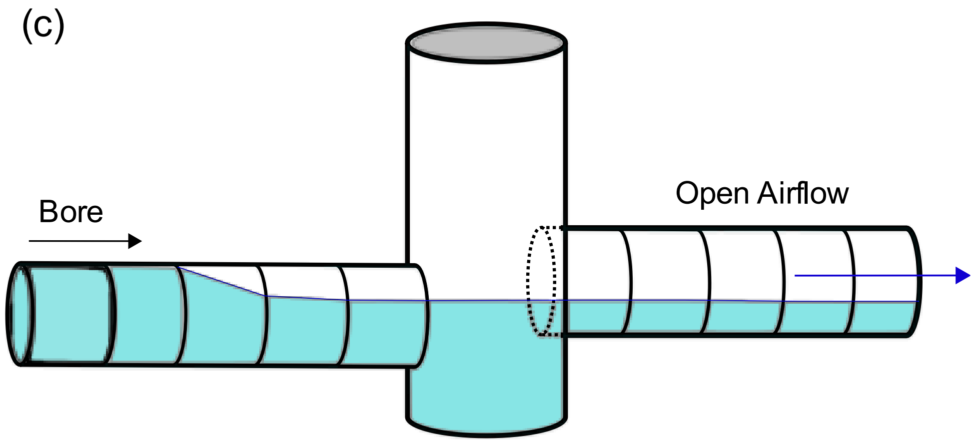


Figure: Combined conduit junction air pockets: (a) entrapped air pocket between two moving bores, (b) entrapped air pocket between a moving bore and closed conduit, and (c) moving bore but an open conduit resulting in no air pocket

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University of Texas at Austin

Center for Infrastructure

Modeling and Management

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US EPA - NCIMM

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SWMM 5+ Open Access Repository

https://github.com/CIMM-ORG/SWMM5plus

Further Questions

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