# Circulating Fluidized Bed System Identification

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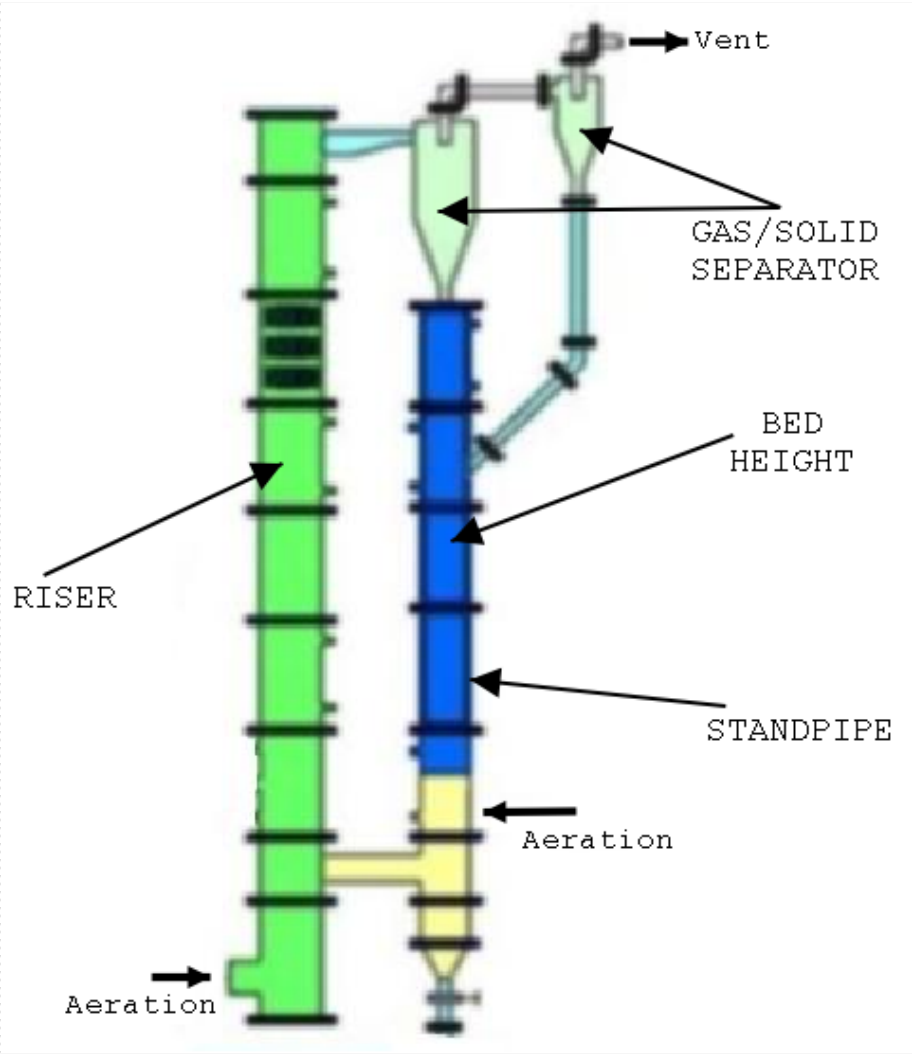
# Research Objectives

- Characterize dynamic model of Circulating Fluidized Bed (CFB)
- Identify variables of the model
- Develop algorithms to estimate the states
- Identify and characterize the control variables
- Develop and test algorithms to optimally control the CFB

- Determining the Circulating Fluidized Bed (CFB) height is essential
  - for assessing system performance
  - To prevent high temperature operation
- Determining the solid circulation rate enables
  - circulation rate control
  - optimal control

# The Circulating Fluidized Bed




Simplified process flow diagram for the cold flow circulating fluidized bed

- Flows up in the riser.
- Separates from the gas in Gas/Solid Separator
- Accumulates in the standpipe to create bed height

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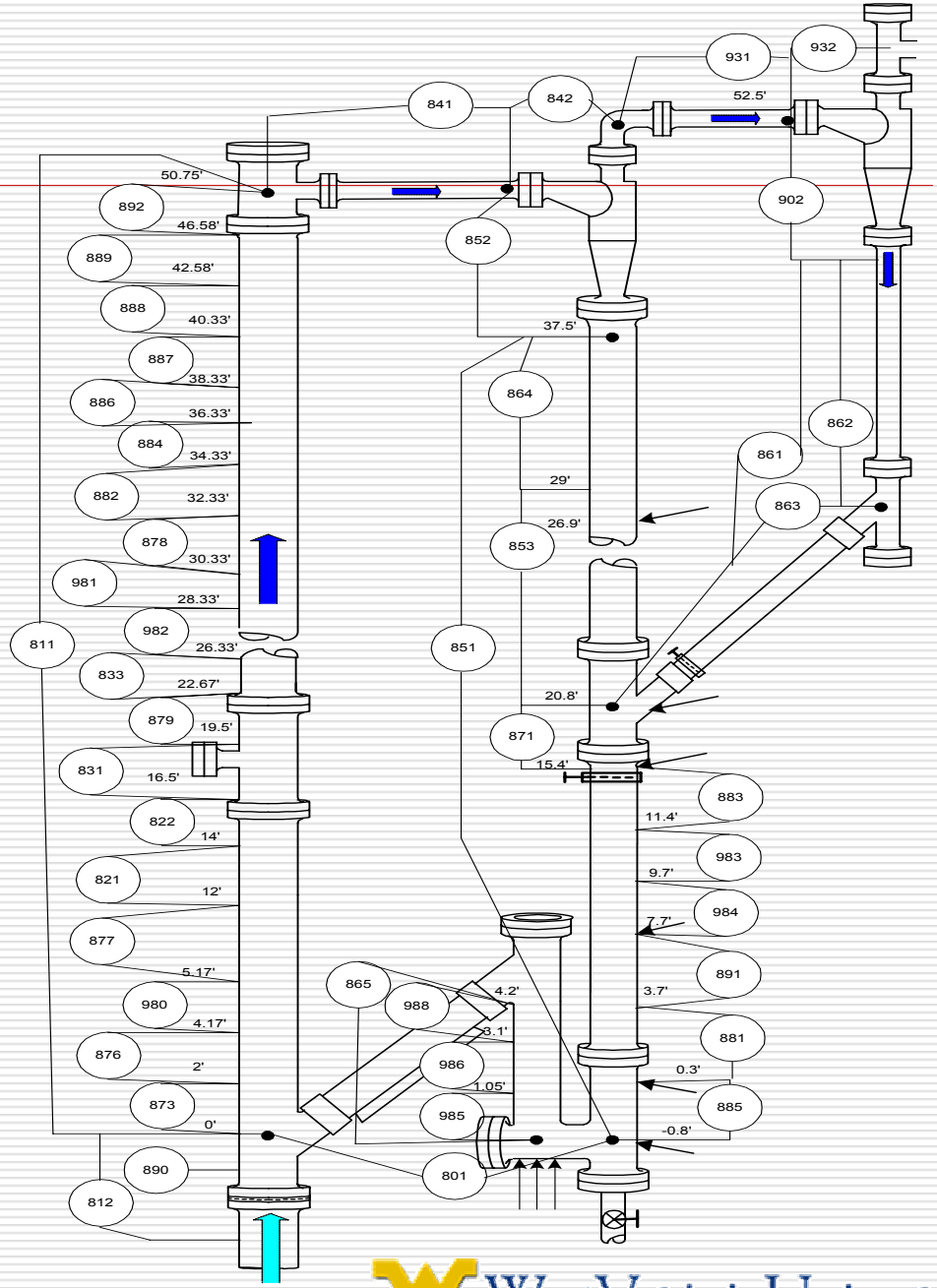
- They have been used by industry since at least the 1940's.
- The most prominent example of a CFB is a catalytic cracker used by the petroleum industry to turn high molecular weight compounds (like oil) into lighter compounds (like gasoline).
- Fluidized bed research at NETL was initiated in 1960s.
- Can increase energy efficiency and decrease environmental pollution

# CFB at NETL

- 50 feet high and one foot diameter
- See through construction of some sections
- Well instrumented with partial pressure measurements
- Equipped with a spiral for solid mass flow measurement

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# Methods

- Dynamic model based methods
  - Obtaining dynamic model of a standpipe
  - Obtaining dynamic model of a riser
  - An extended Kalman filter
  - An $H_\infty$ (infinity) estimator method
- Data based methods
  - 2-region model to estimate bed height
  - Using system identification to estimate the solid circulation rate

# Dynamic model of standpipe

- Mass conservation and $\varepsilon_g + \varepsilon_s = 1$

  $$j_0(t) = j_g(z,t) + j_s(z,t)$$

- Use modified Richardson-Zaki correlation

$$\xi(\varepsilon) = \begin{cases} 0 & \text{if} \quad \varepsilon \le \varepsilon_{pb} \\ \dfrac{\varepsilon_{mf}^{n-1}}{\varepsilon_{mf} - \varepsilon_{pb}}\left(\varepsilon - \varepsilon_{pb}\right) & \text{if} \quad \varepsilon_{pb} < \varepsilon < \varepsilon_{mf} \\ \varepsilon^{n-1} & \text{if} \quad \varepsilon \ge \varepsilon_{mf} \end{cases}$$

- Non-linear state equation

$$\varepsilon_k^i = \varepsilon_{k-1}^i + \frac{\Delta t}{\Delta z}\left(j_{k-1}^{i-} - j_{k-1}^{i+}\right)$$

- Determine volumetric gas flux according to wave speed

$$j_{k-1}^{i-} = j_0 \varepsilon_{k-1}^{i-1} + V_t g\left(\varepsilon_{k-1}^{i-1}\right) \quad if \quad \lambda^{i-} > 0,$$

$$j_{k-1}^{i-} = j_0 \varepsilon_{k-1}^{i} + V_t g\left(\varepsilon_{k-1}^{i}\right) \quad if \quad \lambda^{i-} < 0$$

where

$$\lambda^{i-} = j_0(t) + V_t g'\left(\left(\varepsilon_{k-1}^{i-1} + \varepsilon_{k-1}^{i}\right)/2\right)$$

$$g(\varepsilon) = \varepsilon(1-\varepsilon)\xi(\varepsilon) \quad , \quad g'(\varepsilon) = \frac{dg(\varepsilon)}{d\varepsilon}$$

- Use truncated Ergun Eq. to find pressure profile

$$p_k^i = \frac{1}{2} C_1 V_t \sum_{l=i}^{N-1} \left(z_{l+1} - z_l\right) \left\{ q\left(\varepsilon_k^l\right) + q\left(\varepsilon_k^{l+1}\right) \right\}$$

$$q(\varepsilon) = \frac{(\varepsilon - 1)^2}{\varepsilon^2} \xi(\varepsilon)$$

# An extended Kalman filter

$$\varepsilon_k = f_{k-1}\left(\varepsilon_{k-1}\right) + w_{k-1}$$

$$p_k = h_k\left(\varepsilon_k\right) + v_k$$

Assign Q & R
Set Initial Conditions.

$$F_{k-1}\left(\hat{\varepsilon}_k(+)\right) = \left.\frac{\partial f_k(\varepsilon)}{\partial \varepsilon}\right|_{\varepsilon=\hat{\varepsilon}_{k-1}(+)}, \quad H_k\left(\hat{\varepsilon}_k(+)\right) = \left.\frac{\partial h_k(\varepsilon)}{\partial \varepsilon}\right|_{\varepsilon=\hat{\varepsilon}_k(-)}$$

$$P_k(-) = F_{k-1}\left(\hat{\varepsilon}_k(+)\right) P_{k-1}(+) F_{k-1}\left(\hat{\varepsilon}_k(+)\right)^T + Q$$

$$K_k = P_k(-) H_k\left(\hat{\varepsilon}_k(-)\right)^T \left\{H_k\left(\hat{\varepsilon}_k(-)\right) P_k(-) H_k\left(\hat{\varepsilon}_k(-)\right)^T + R\right\}^{-1}$$

$$\hat{p}_k = h_k\left(\hat{\varepsilon}_k(-)\right)$$

$$\hat{\varepsilon}_k(+) = \hat{\varepsilon}_k(-) + K_k\left\{p_k - \hat{p}_k\right\}$$

$$P_k(+) = \left\{I_N - K_k H_k\left(\hat{\varepsilon}_k(-)\right)\right\} P_k(-)$$

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# $H_\infty$ Estimator

- Kalman filter has many inherit tuning variables
- Kalman filter failed with some data sets
- Need more robust estimator with less tuning variables
- $H_\infty$ (infinity) is a candidate

# An $H_\infty$ estimation method

$$\varepsilon_k = f_{k-1}\left(\varepsilon_{k-1}\right) + w_{k-1}$$

$$p_k = h_k\left(\varepsilon_k\right) + v_k$$

Assign Q,W,V, $\gamma$
Set Initial Conditions.

$$F_{k-1}\left(\hat{\varepsilon}_k(+)\right) = \left.\frac{\partial f_k(\varepsilon)}{\partial \varepsilon}\right|_{\varepsilon=\hat{\varepsilon}_{k-1}(+)}, \quad H_k\left(\hat{\varepsilon}_k(+)\right) = \left.\frac{\partial h_k(\varepsilon)}{\partial \varepsilon}\right|_{\varepsilon=\hat{\varepsilon}_k(-)}$$

$$L_k = \left(I - \gamma Q P_k + H_k\left(\hat{\varepsilon}_k(-)\right)^T V^{-1} H_k\left(\hat{\varepsilon}_k(-)\right) P_k\right)^{-1}$$

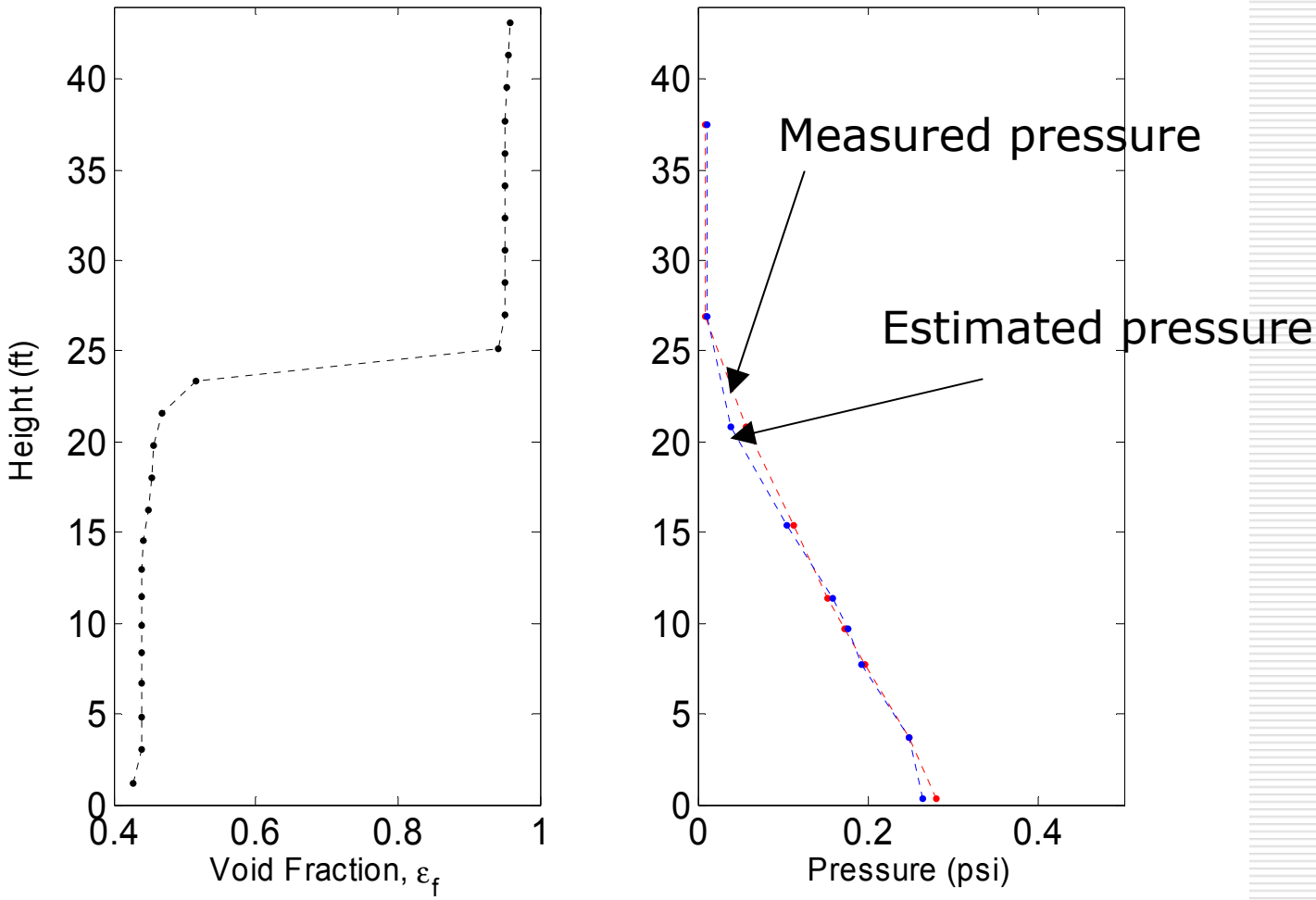
$$K_k = F_{k-1}\left(\hat{\varepsilon}_k(+)\right) P_k L_k H_k\left(\hat{\varepsilon}_k(-)\right)^T V^{-1}$$

$$\hat{p}_k = h_k\left(\hat{\varepsilon}_k(-)\right)$$

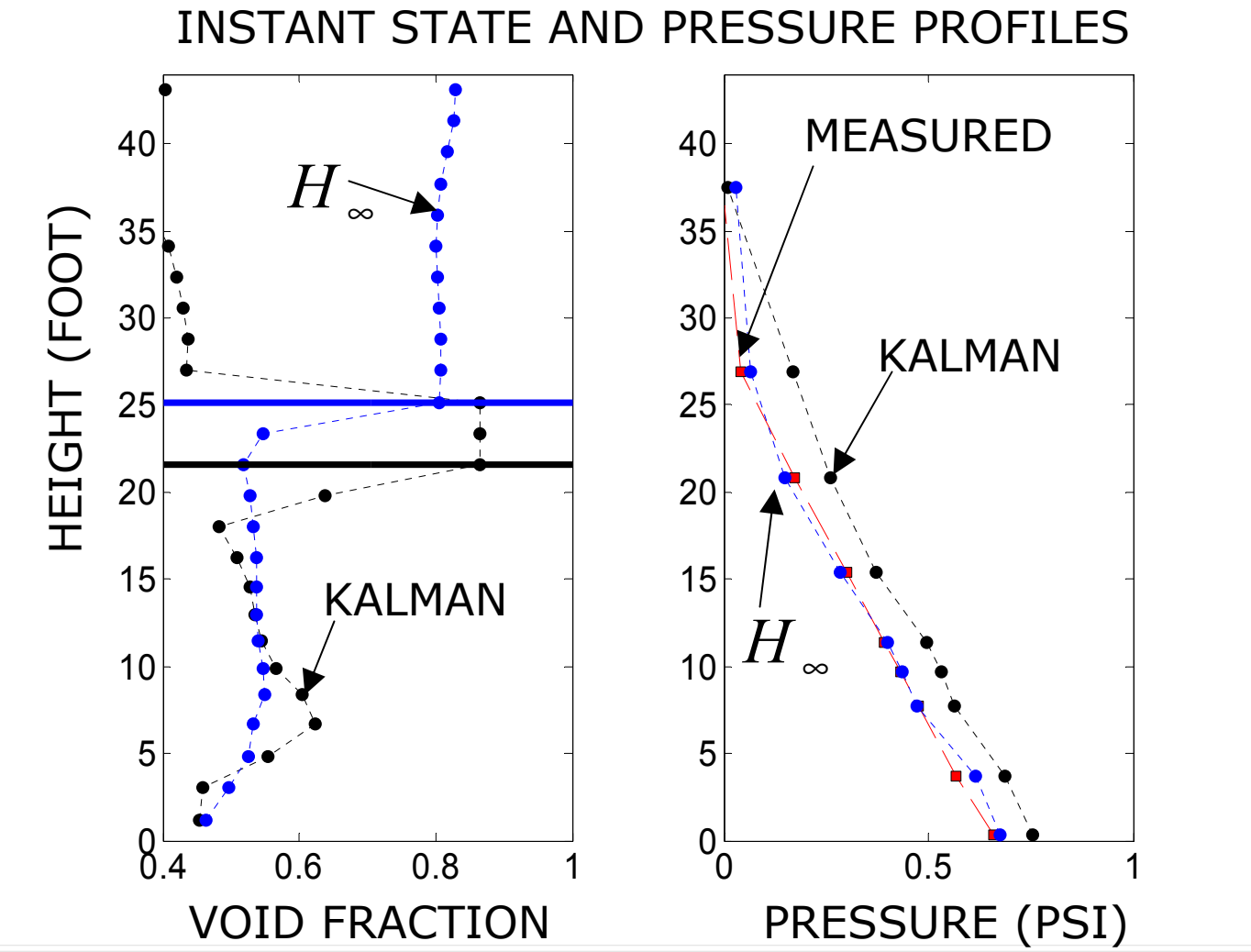
$$\hat{\varepsilon}_k(+) = \hat{\varepsilon}_k(-) + K_k\left\{p_k - \hat{p}_k\right\}$$

$$P_k(+) = F_{k-1}\left(\hat{\varepsilon}_k(+)\right) P_k(-) L_k F_{k-1}\left(\hat{\varepsilon}_k(+)\right) + W$$

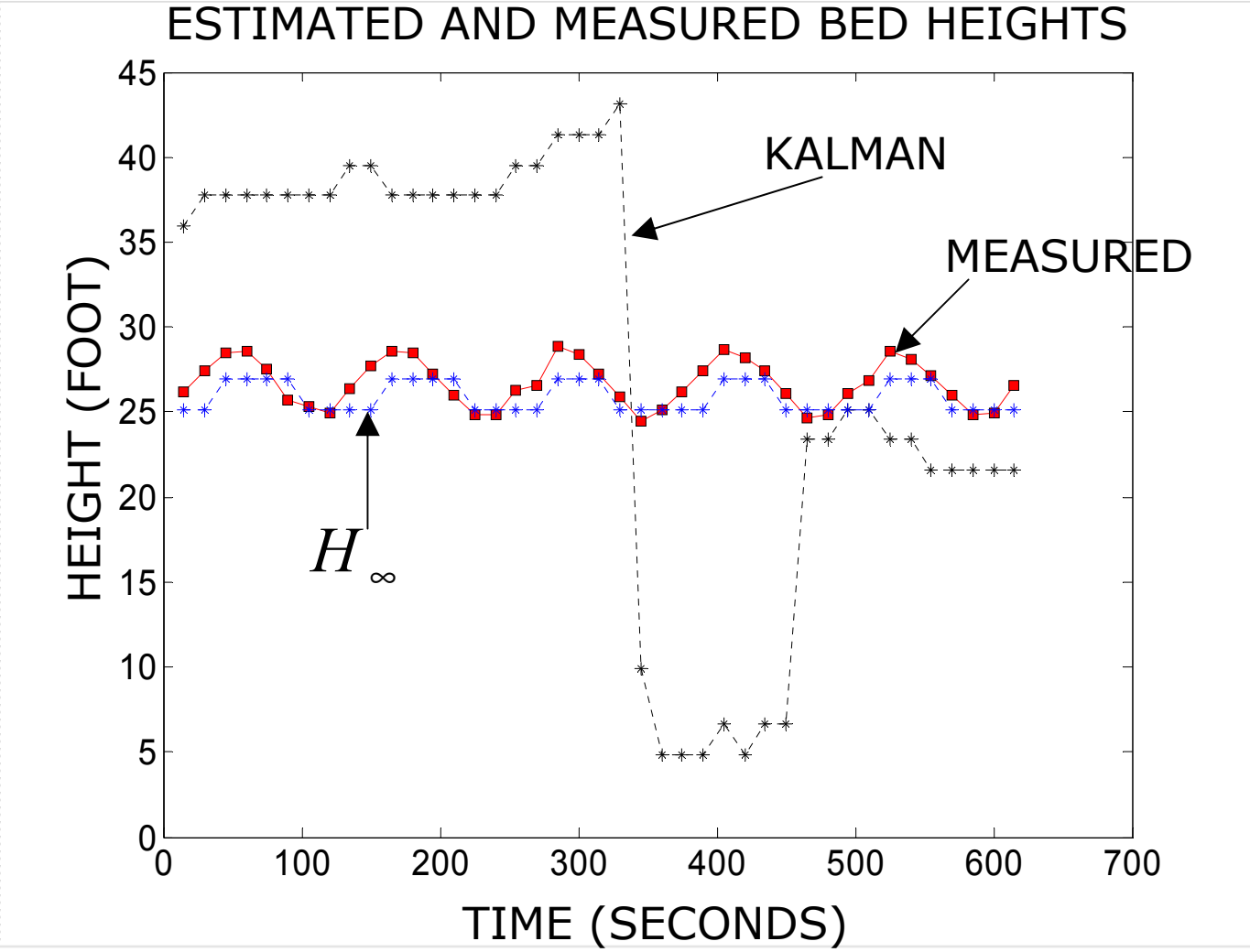
# Simulation Results (Kalman) (K32)



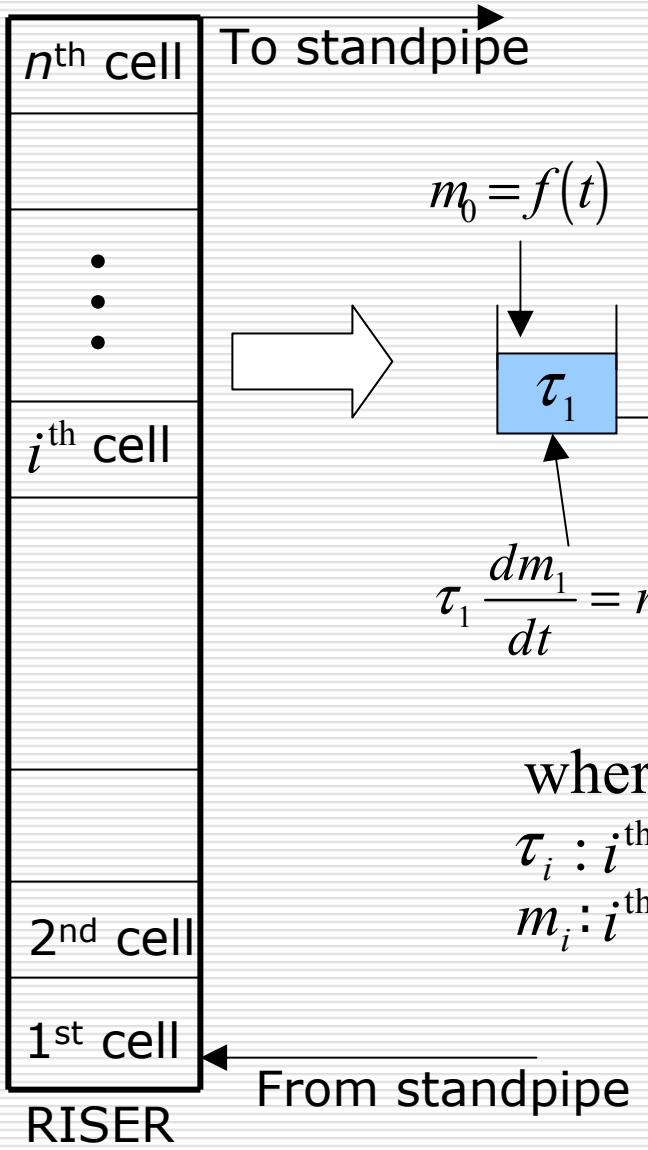
# Results (Kalman & $H_\infty$) (K35)

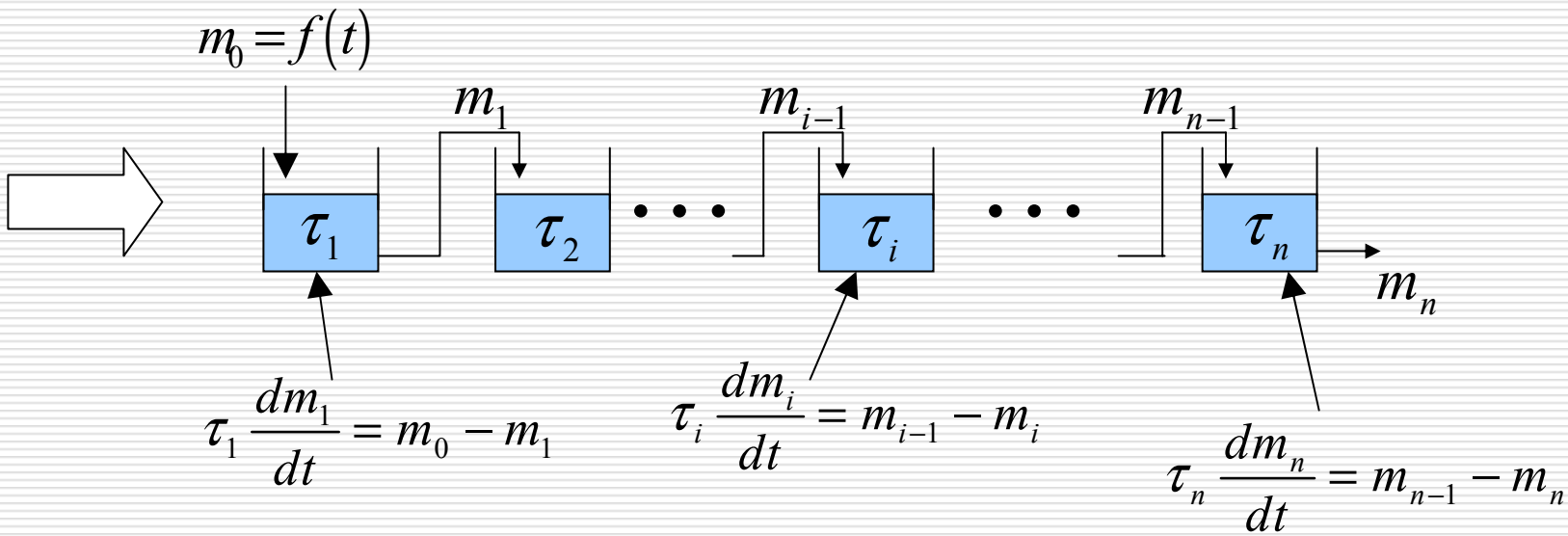


# Results (Kalman & $H_\infty$ )



# Dynamic model of riser




where

$\tau_i$ : $i^{th}$ tank time constant

$m_i$ : $i^{th}$ tank mass

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# Dynamic model of riser

$$\tau_i \frac{dm_i}{dt} = m_{i-1} - m_i$$

$$m_i = \frac{\Delta P_i A}{\tau_i g}$$

$$\tau_i \frac{d\Delta P_i}{dt} = \frac{\tau_i}{\tau_{i-1}} \Delta P_{i-1} - \Delta P_i, \quad i = 2, 3, \ldots, n$$

where

$\Delta P_i =$ pressure of $i^{th}$ cell

$A =$ cross sectional area

$g =$ gravitational acceleration

with

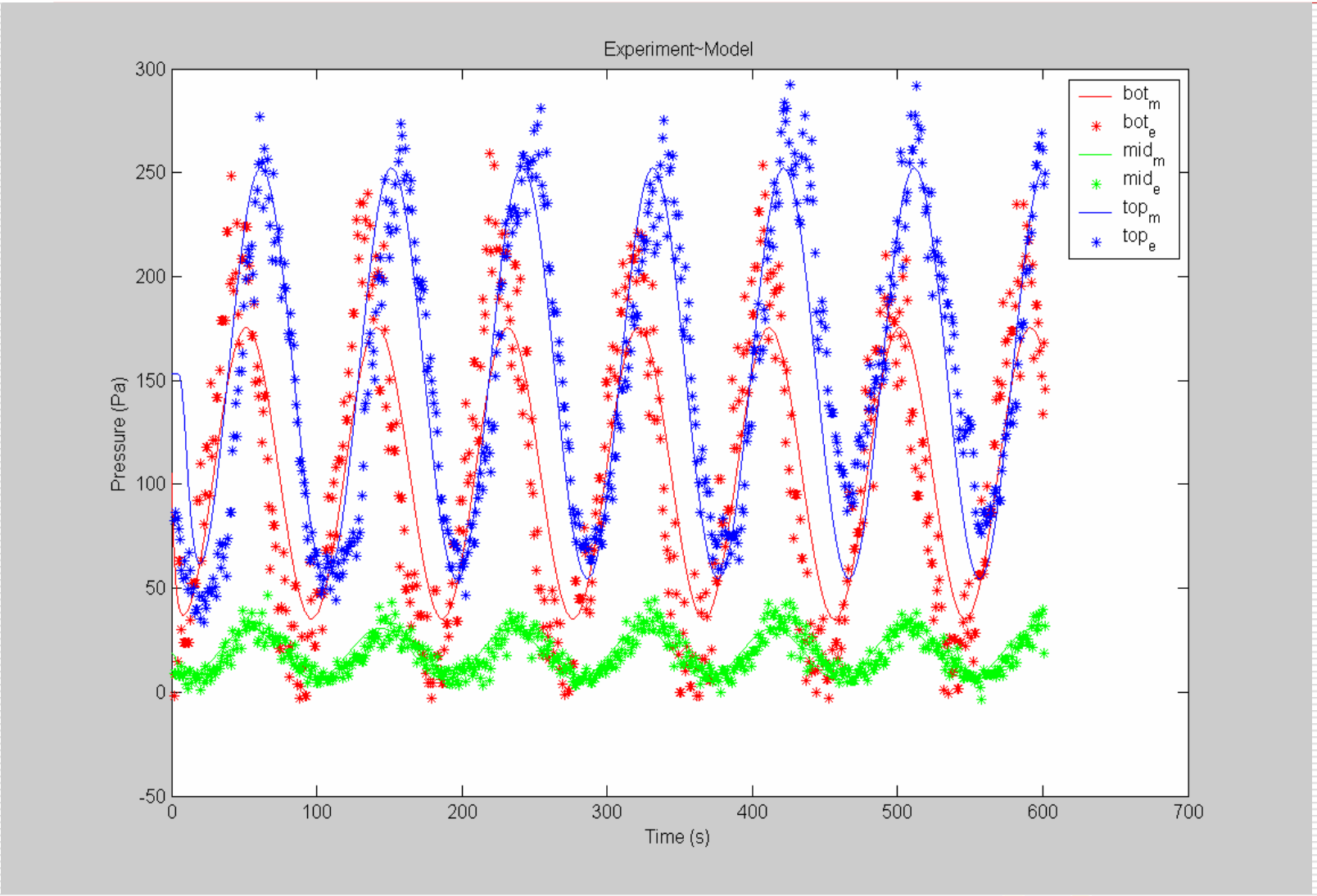
$$\tau_1 \frac{d\Delta P_1}{dt} = \frac{m_{\text{circ}} g \tau_1}{A} - \Delta P_i \ , \ \tau_i = \frac{\overline{M_i}}{\overline{m}_{\text{circ}}} = \frac{\overline{\Delta P_i} A / g}{\overline{m}_{\text{circ}}}$$

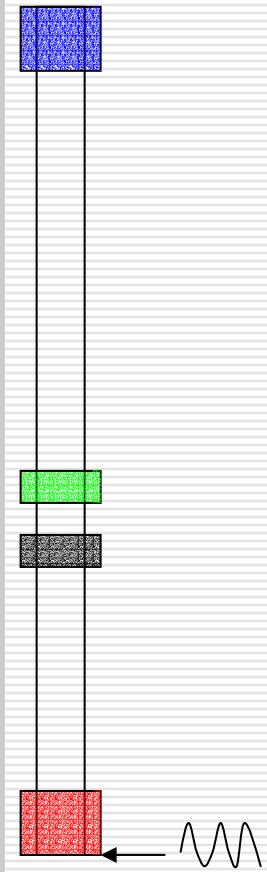
where

$\Delta P_1 =$ pressure of first cell

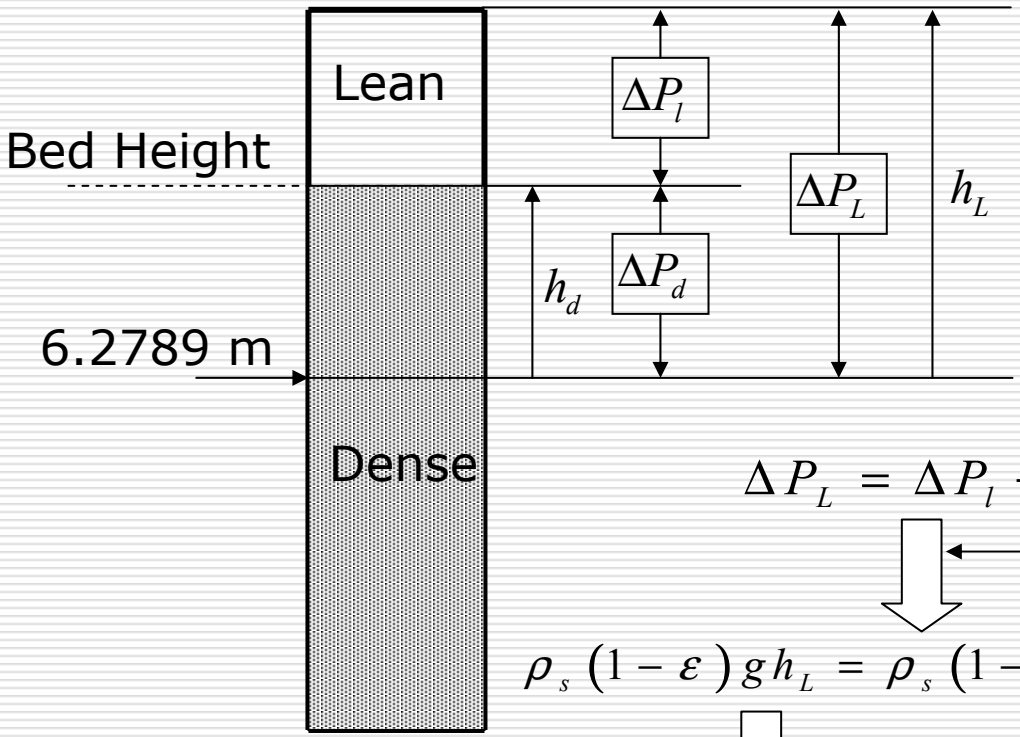
$m_{\text{circ}} =$ mass circulation rate

# Simulation of riser model(K32)



# 2-region model



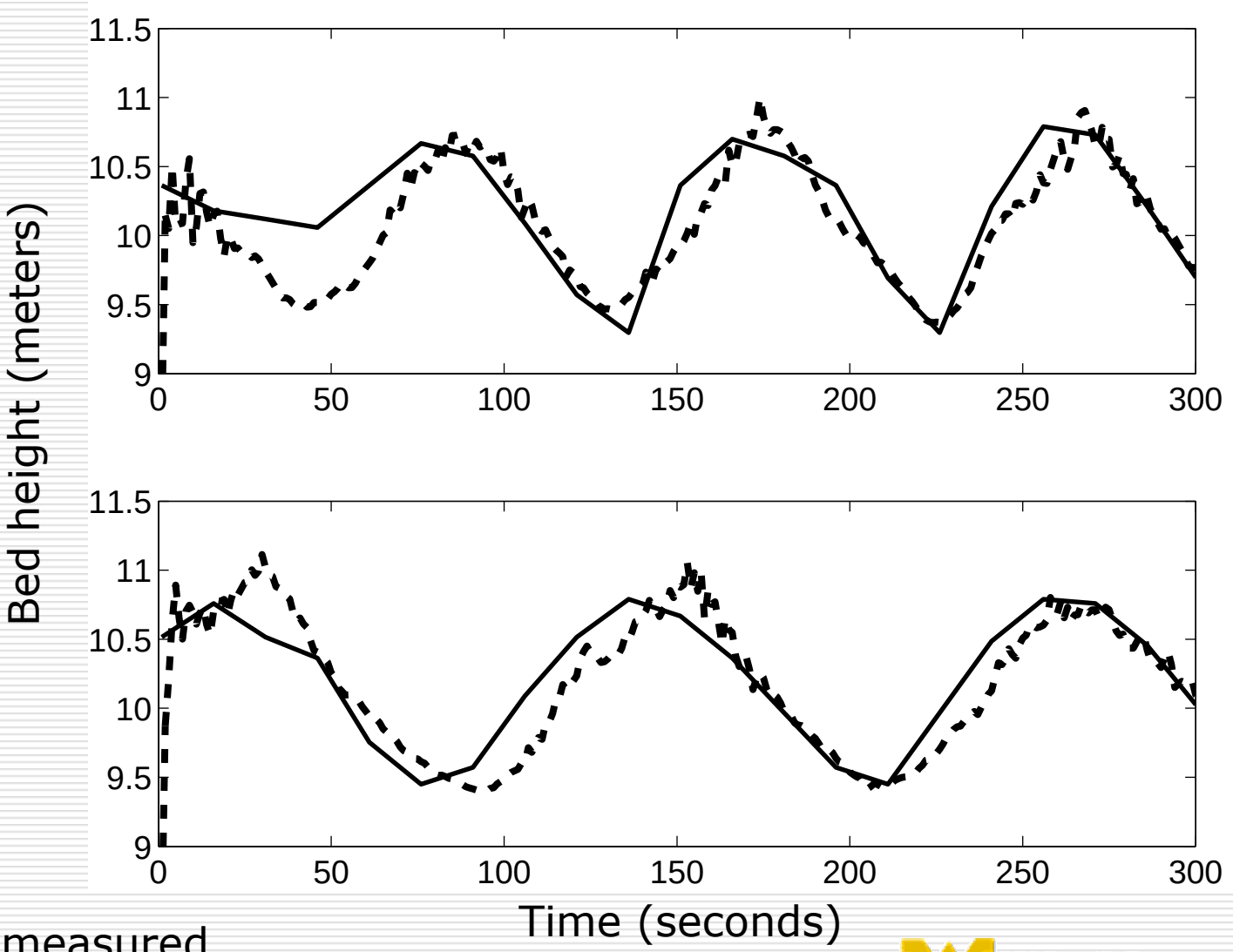

$$\Delta P = \rho_s (1-\varepsilon) g h$$

$$\Delta P_L = \Delta P_l + \Delta P_d$$

$$\rho_s (1-\varepsilon) g h_L = \rho_s (1-\varepsilon_l) g (h_L - h_d) + \rho_s (1-\varepsilon_d) g h_d$$

$$h_{bed} = 6.2789 + h_d = 6.2789 + \frac{(\varepsilon_l - \varepsilon) h_L}{\varepsilon_l - \varepsilon_d}$$

# 2-Region Model Results




Line - measured
Dashed - estimated

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# System identification method

- Solid Circulation Rate Estimate
  - System model build

$$x(k+1) = Ax(k) + Bu(k)$$

$$y(k) = Cx(k)$$

  - A,B,C matrices can be obtained from the system identification toolbox under MATLAB environment.
  - Transfer system model without fictitious states

$$y(k+1) = CAC^{-1}y(k) + CBu(k)$$

# System identification method

- Define H convert y to z contained only pressure variable

$$y(k+1) = \bar{A}y(k) + \bar{B}u(k)$$

$$z(k) = Hy(k)$$

- The estimator dynamic is suggested as, $\hat{y}(k+1) = \bar{A}\hat{y}(k) + \bar{B}u(k) + K_k\left(p(k) - \hat{z}(k)\right)$

$$\hat{z}(k) = H\hat{y}(k)$$

where

$\hat{y}(k) =$ estimator state variables

$p(k) =$ pressure measurements

$\hat{z}(k) =$ estimated pressures

$K_k =$ Kalman gain matrix

# System identification method

- Update Kalman gain, $K_k$

$$M_k(-) = AM_{k-1}(+)A^T + Q$$

$$K_k = M_k(-)C^T\left\{CM_k(-)C^T + R\right\}^{-1}$$

$$M_k(+) = \left\{I_N - K_k C\right\}M_k(-)$$

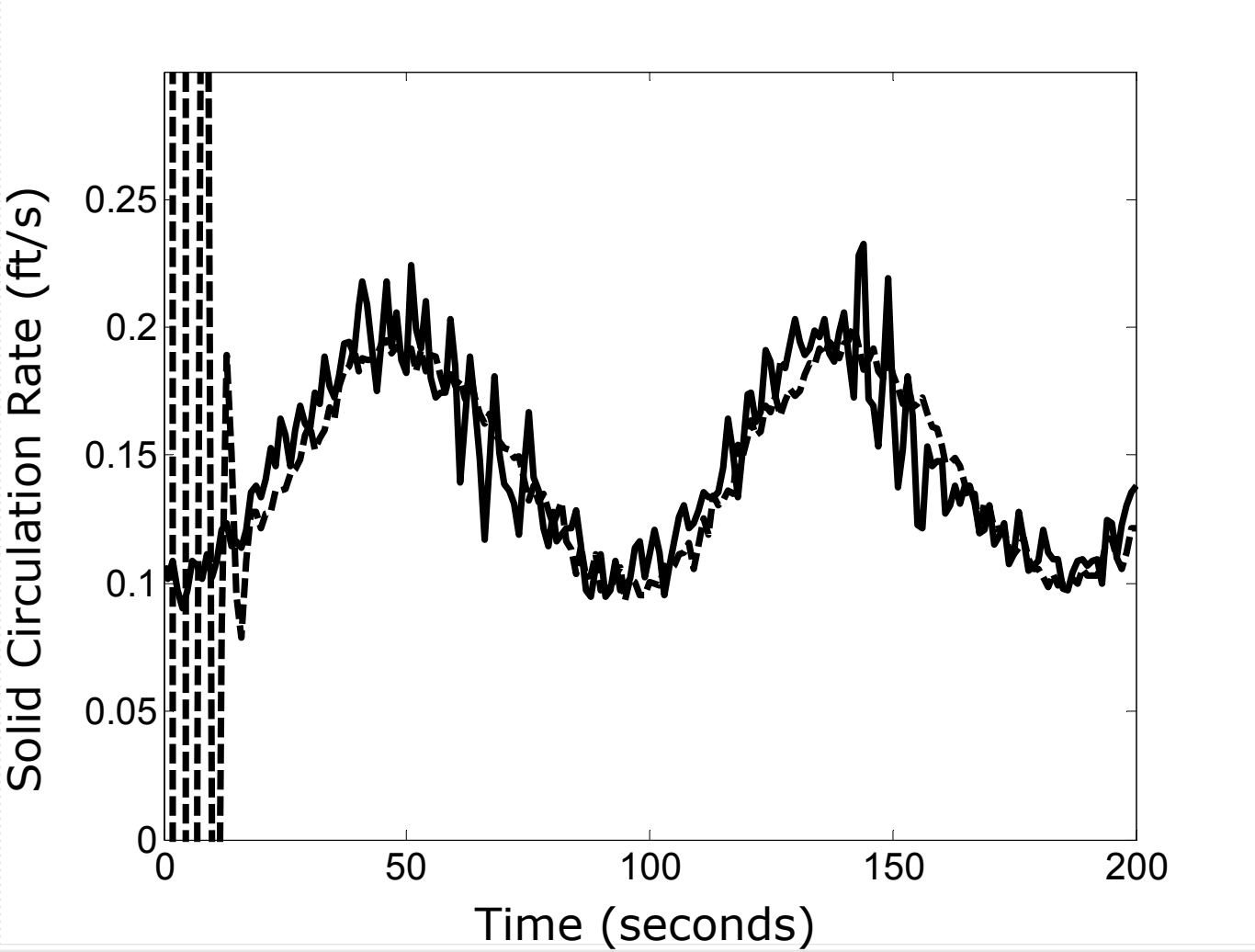
where

$$M_k = \text{Error covariance matrix}$$

$$K_k = \text{Kalman gain matrix}$$

$$I_N = N \times N \text{ identity matrix}$$

# System identification method




Line - measured
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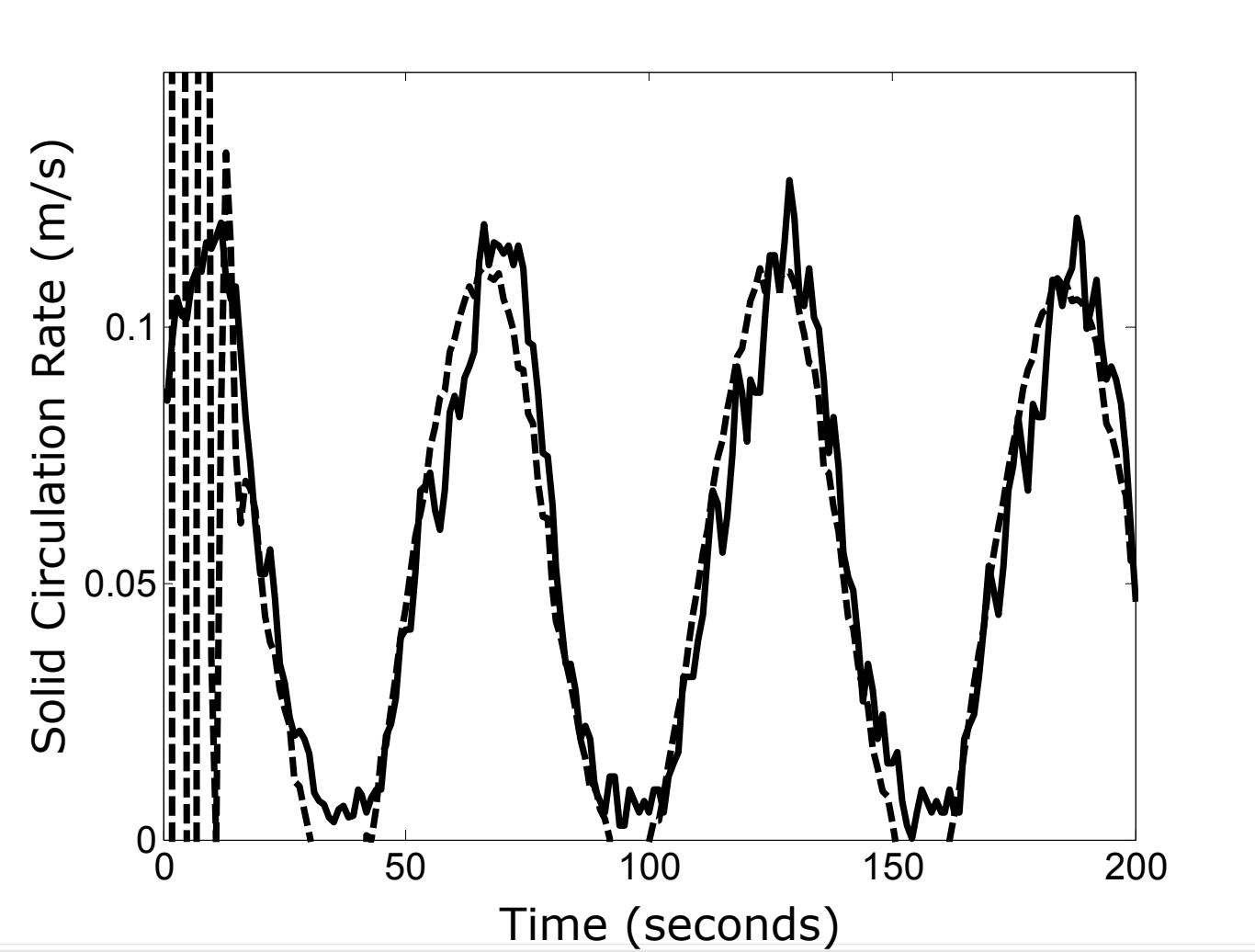
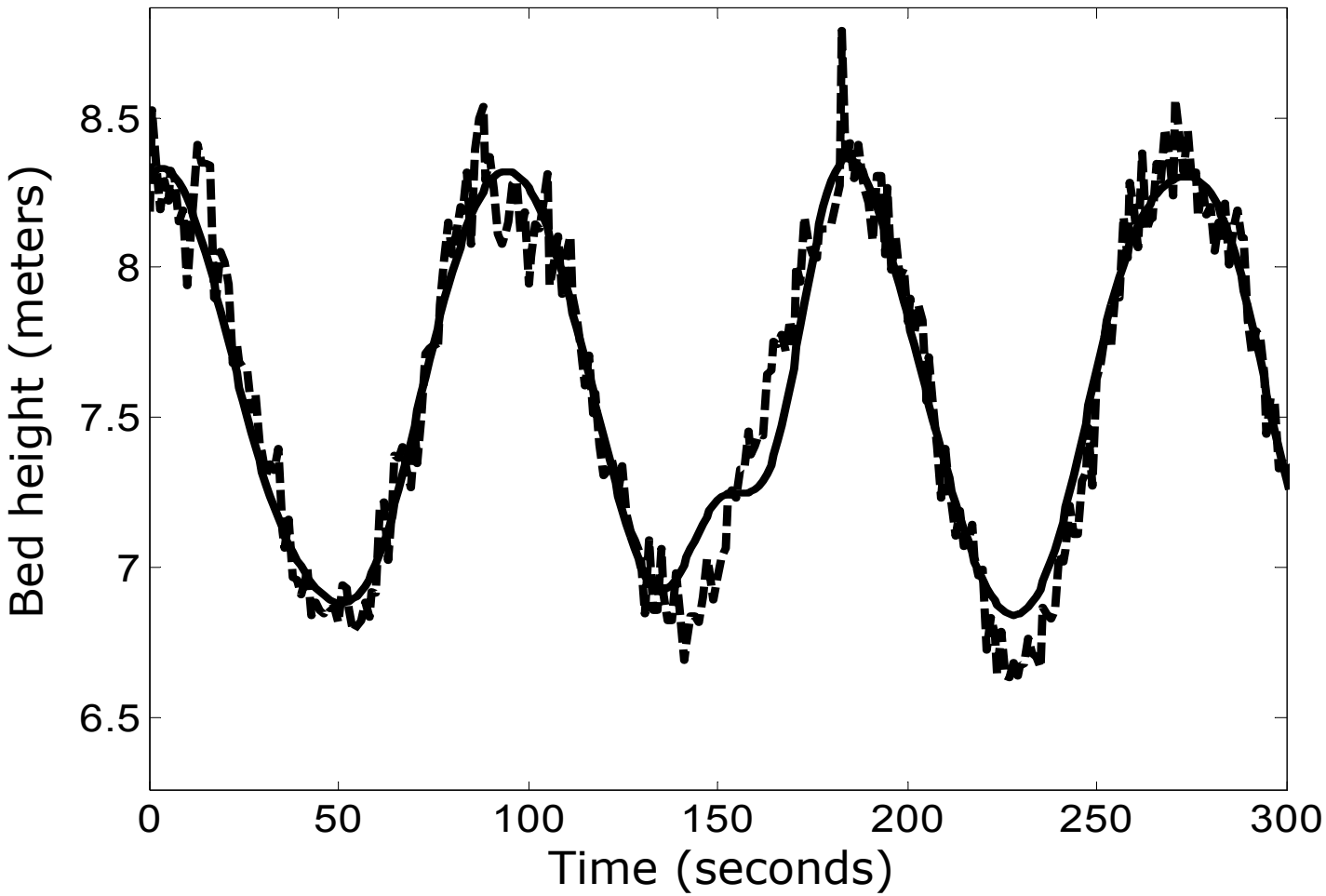
# System identification method




Line - measured
Dashed - estimated

# Calculating Bed Height




Line - measured
Dashed - calculated

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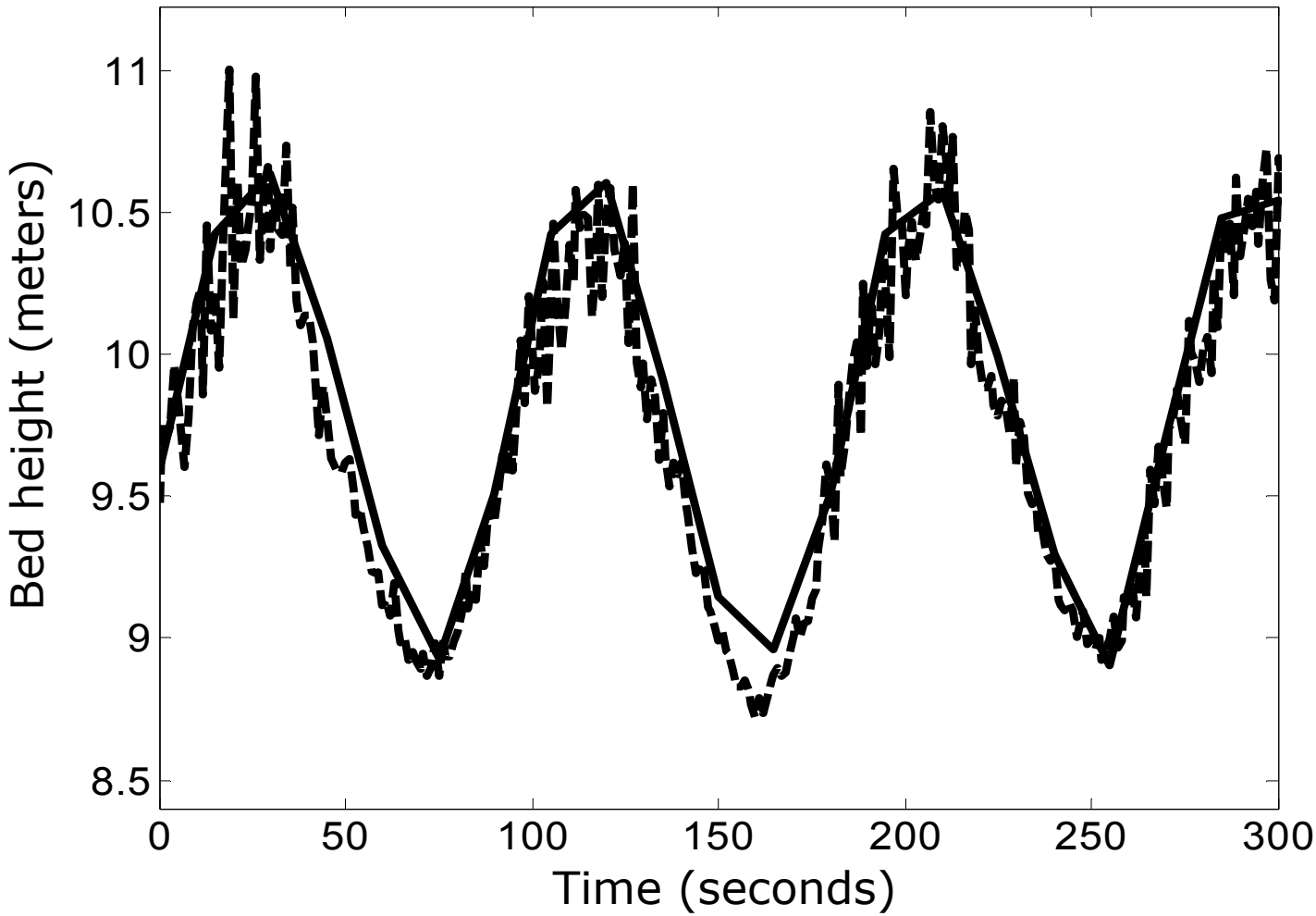
# Calculating Bed Height (cont'd)




Line - measured
Dashed - calculated

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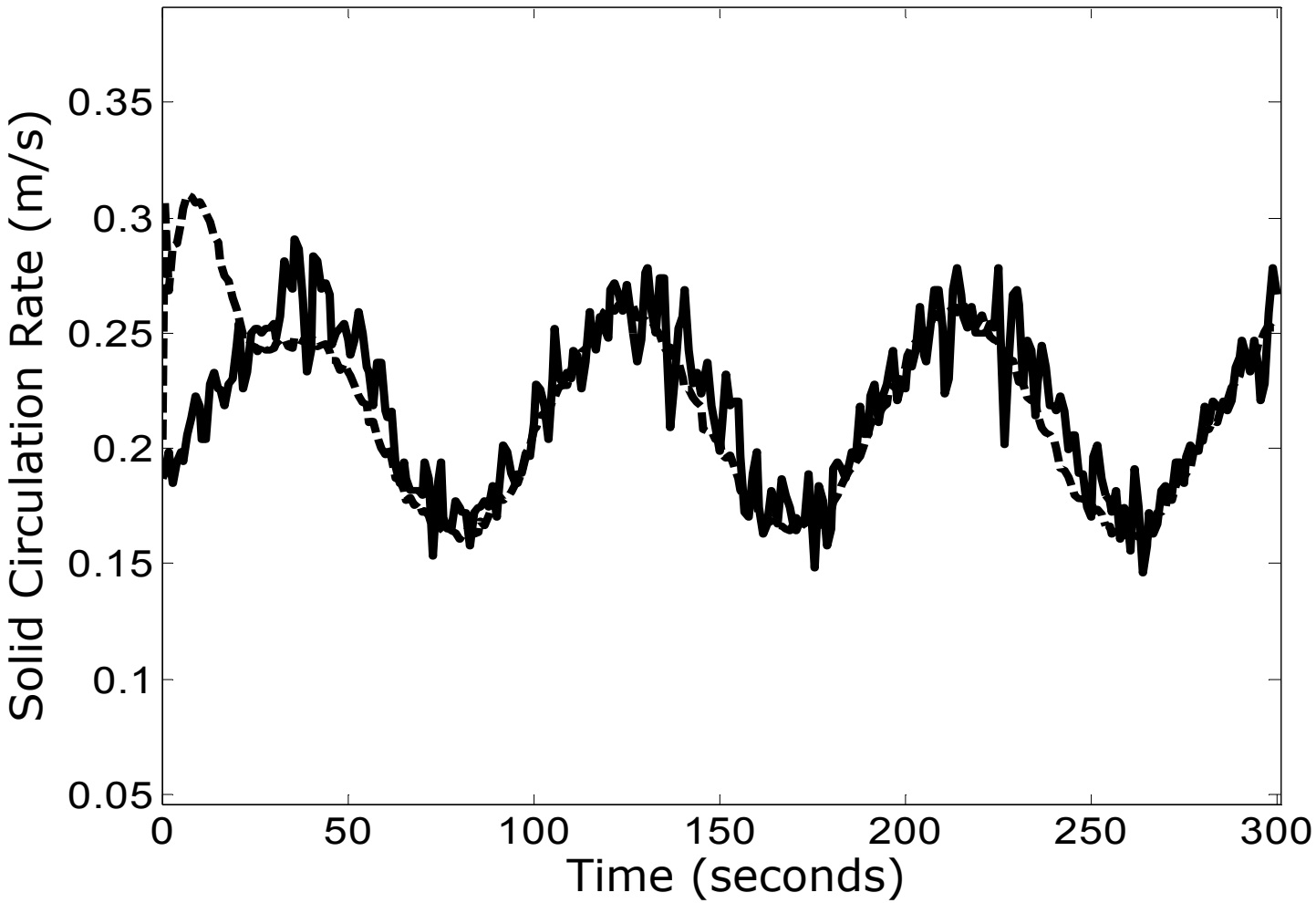
# Solid Circulation Rate Estimate, (High Rate)




Line - measured
Dashed - estimated

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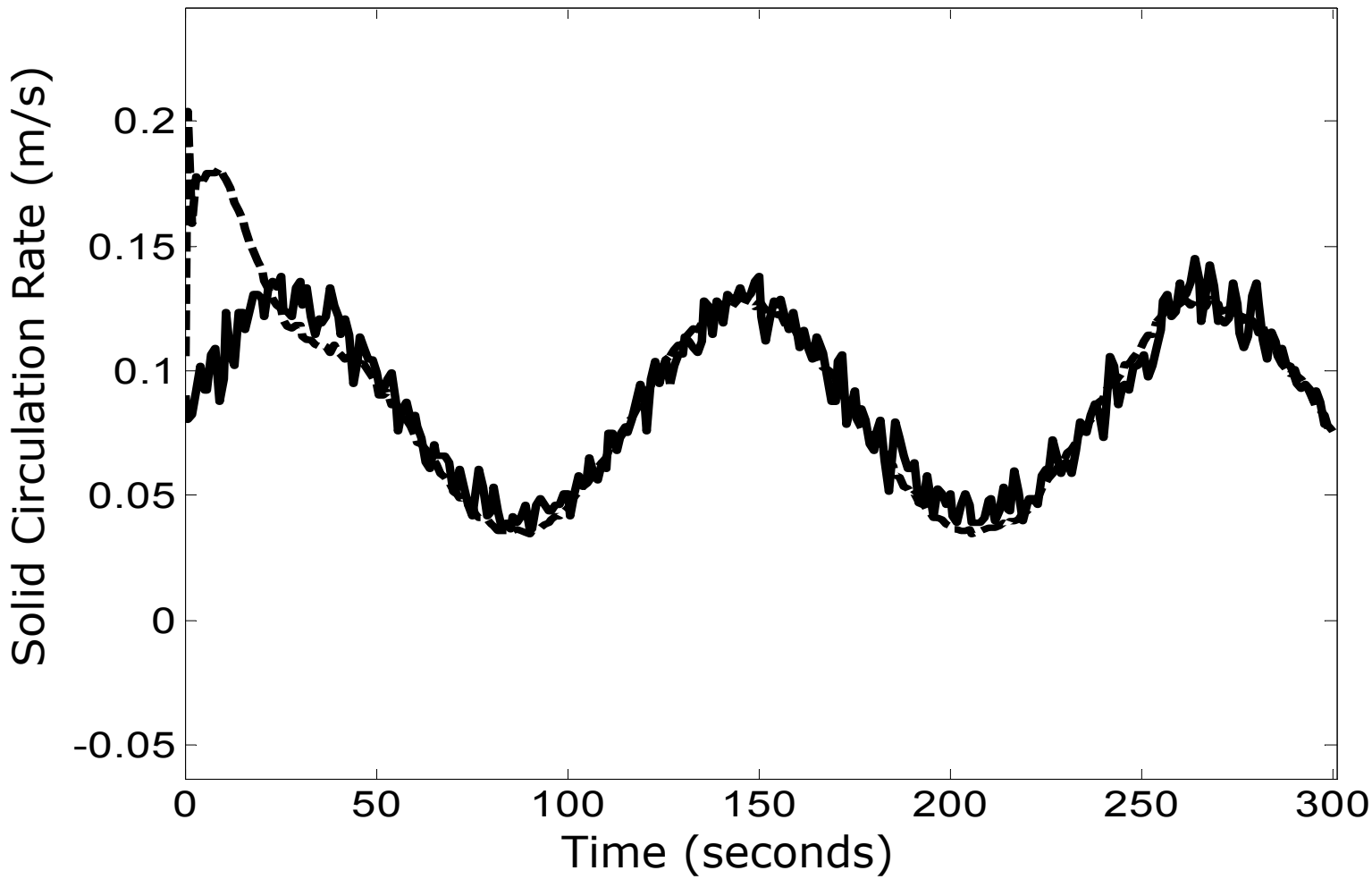
# Solid Circulation Rate Estimate, (low Rate)




Line - measured
Dashed - estimated

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# Conclusions

- The CFB at NETL is explained.
- The bed height is successfully calculated.
- System Identification is used for estimating the solid circulation.
- Experimental results are presented.
- Results show these methods are effective and successful.