Lecture

TK17 System Identification, 2015

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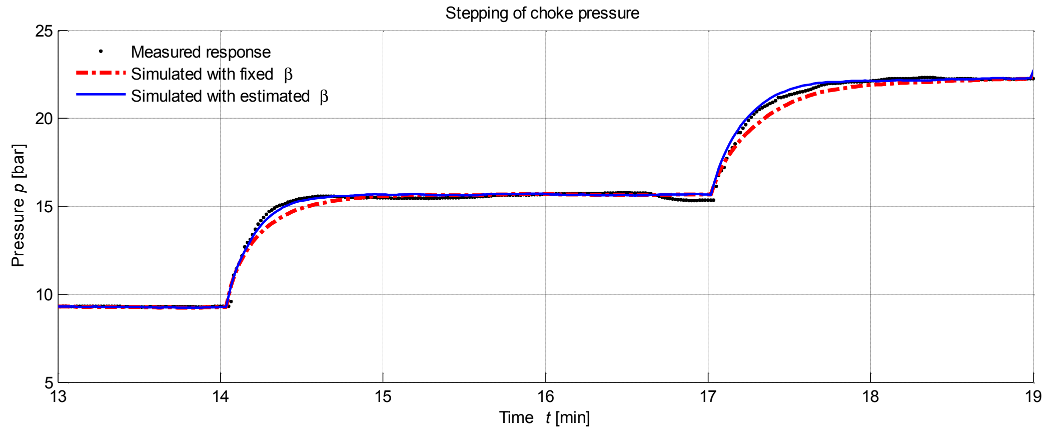
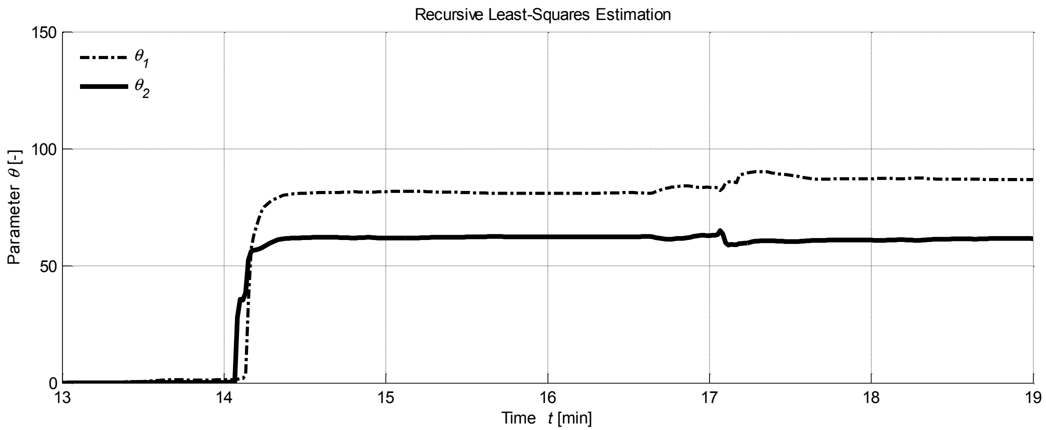
KELDA drilling controls

Overview

- The steps of system identification
  - Practical aspects
  - Illustrated on case study
- Topics
  - System description
  - Mathematical modelling
    - » Nonlinearities
    - » Parametrization
    - » Discretization
    - » Estimation
    - » Data processing



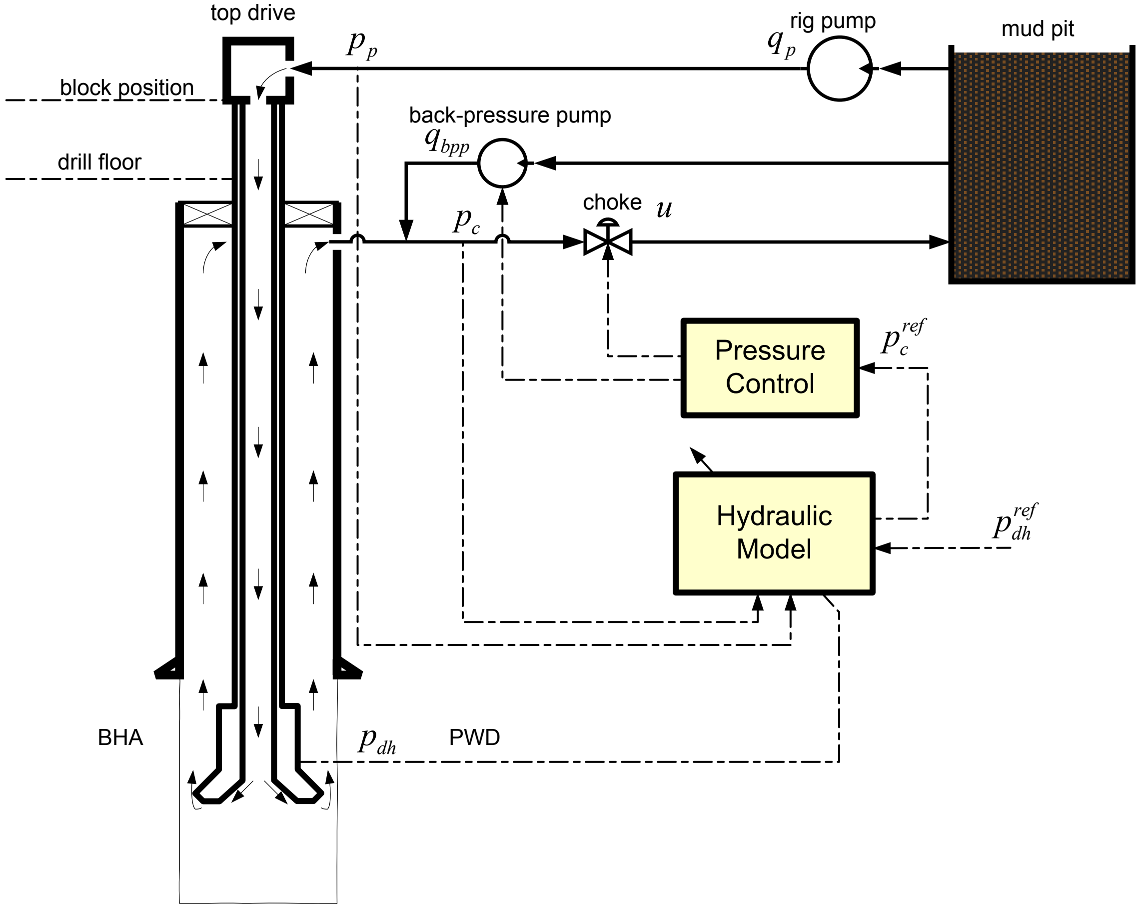


System description

- Understand your system…

Case study: Managed Pressure Drilling

- Application: Downhole pressure control during drilling operations
- Objective
  - Observer design for estimation of downhole pressure
  - Model-based control design
  - Online calibration of model (adaptation)
  - Fault-detection
- Task
  - Identify parameters of hydraulic model from real well data

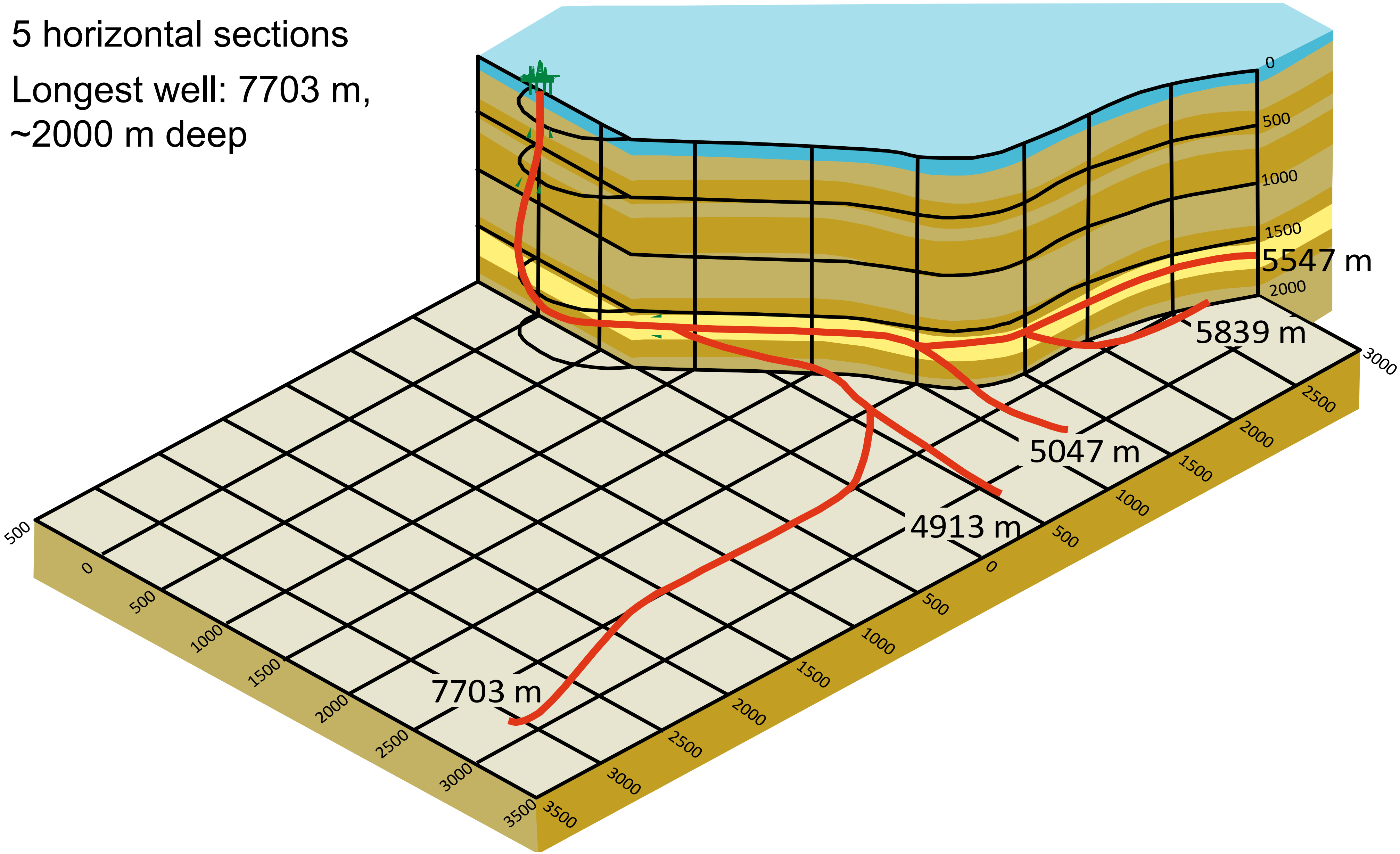


Drilling – It's big

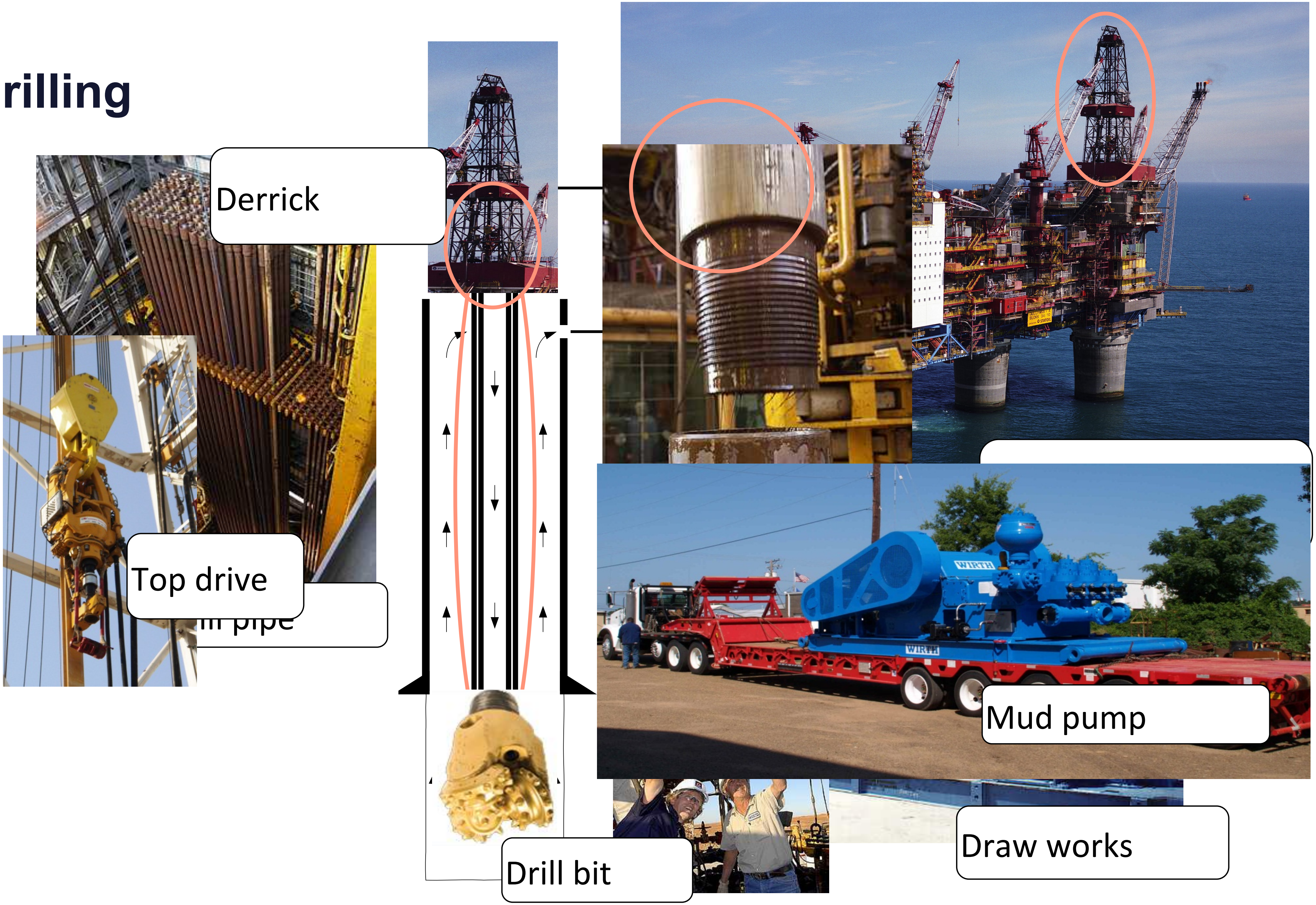
- Up to 10 km long

Example Troll

- 5 horizontal sections
- Longest well: 7703 m, ~2000 m deep



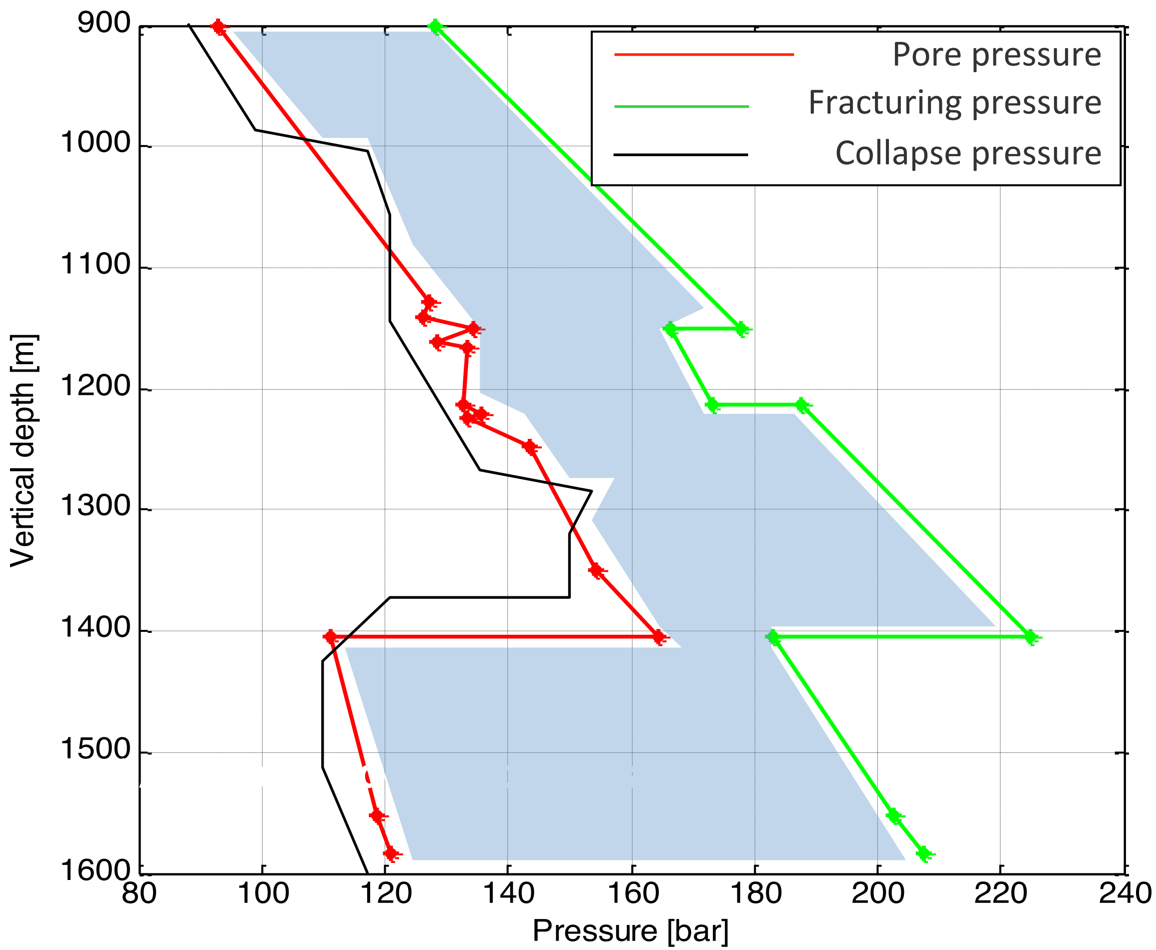
Drilling



Introduction to pressure control

- Drilling window management
  - Fracture pressure
  - Pore/Collapse pressure

- Too high pressure
  - Loss of drilling fluid
  - Damage reservoir
- Too low pressure
  - Wellbore collapse
  - Influx of formation fluid



Well control – Influx

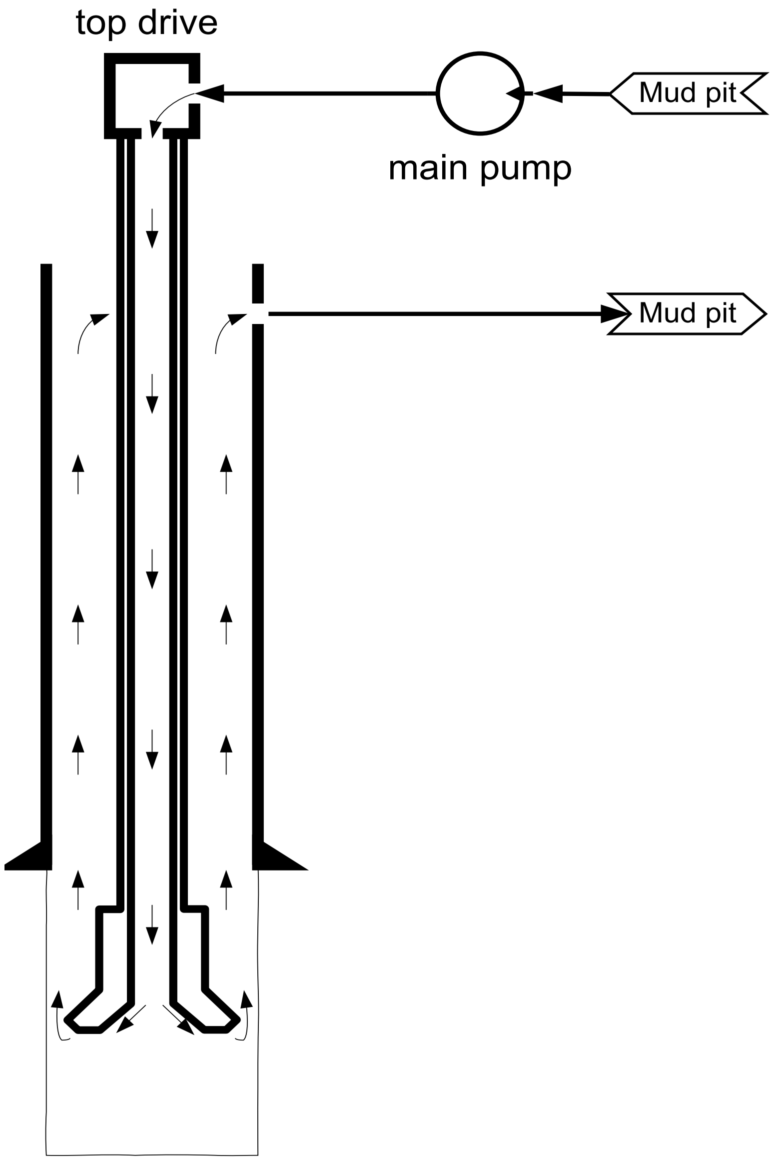
- **Kick**: unwanted influx of formation fluids into a well during a drilling operation
- **Well control**: the technique used to prevent influx of formation fluids into the wellbore involving pore and fracture pressure estimation.
  - **Primary well control**: mud with controlled density, such that the pressure in the open wellbore is kept between the pore pressure and the fracture pressure.
  - **Secondary well control**: BOP (Blow Out Preventer)
- **Blowout**: uncontrolled flow of formation fluids to surface

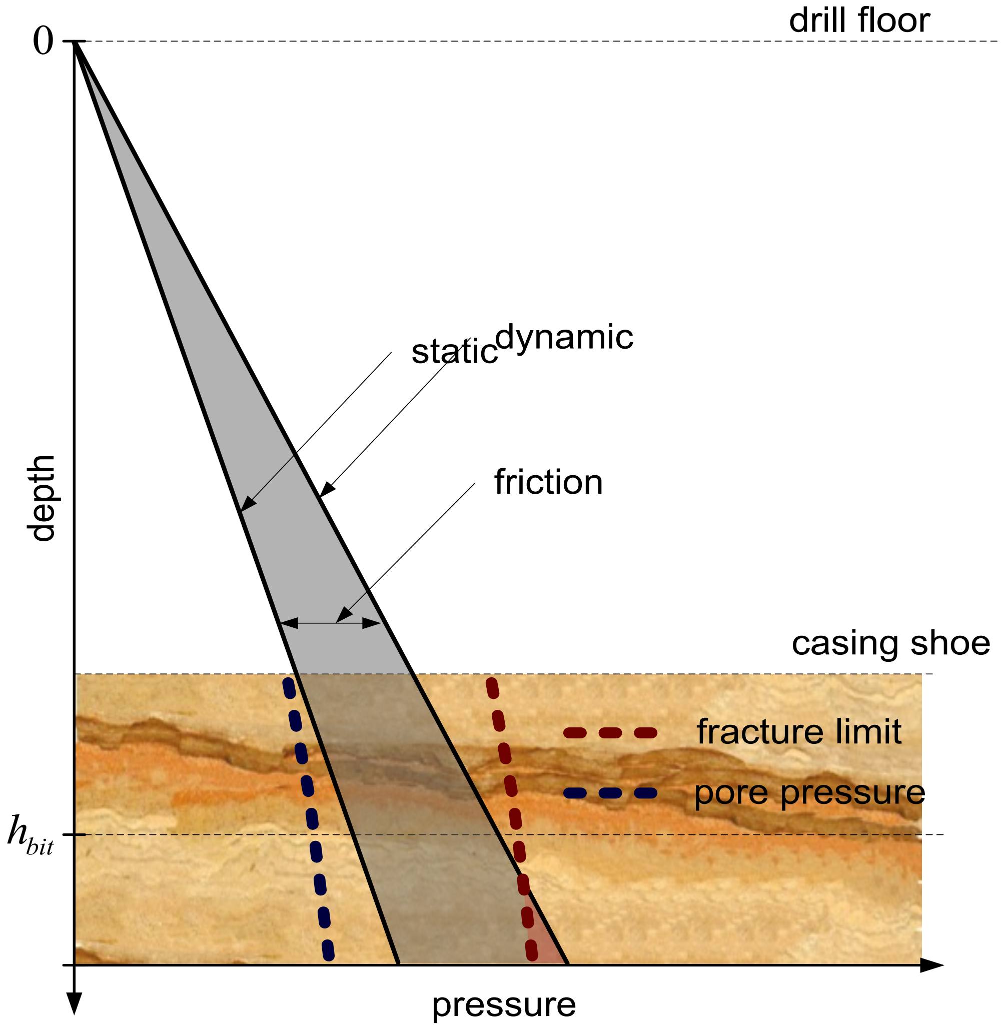

A Fountain at Bibi-Eibat in Flames, Baku

Importance of pressure control

- Safety is extremely important
  - HSE (loss of lives, spills to environment)
  - License to drill
- Economy
  - Enable drilling of targets with small margins
  - Reduce Non-Productive Time
  - Avoid sidetracks
  - Reach TD with desired ID

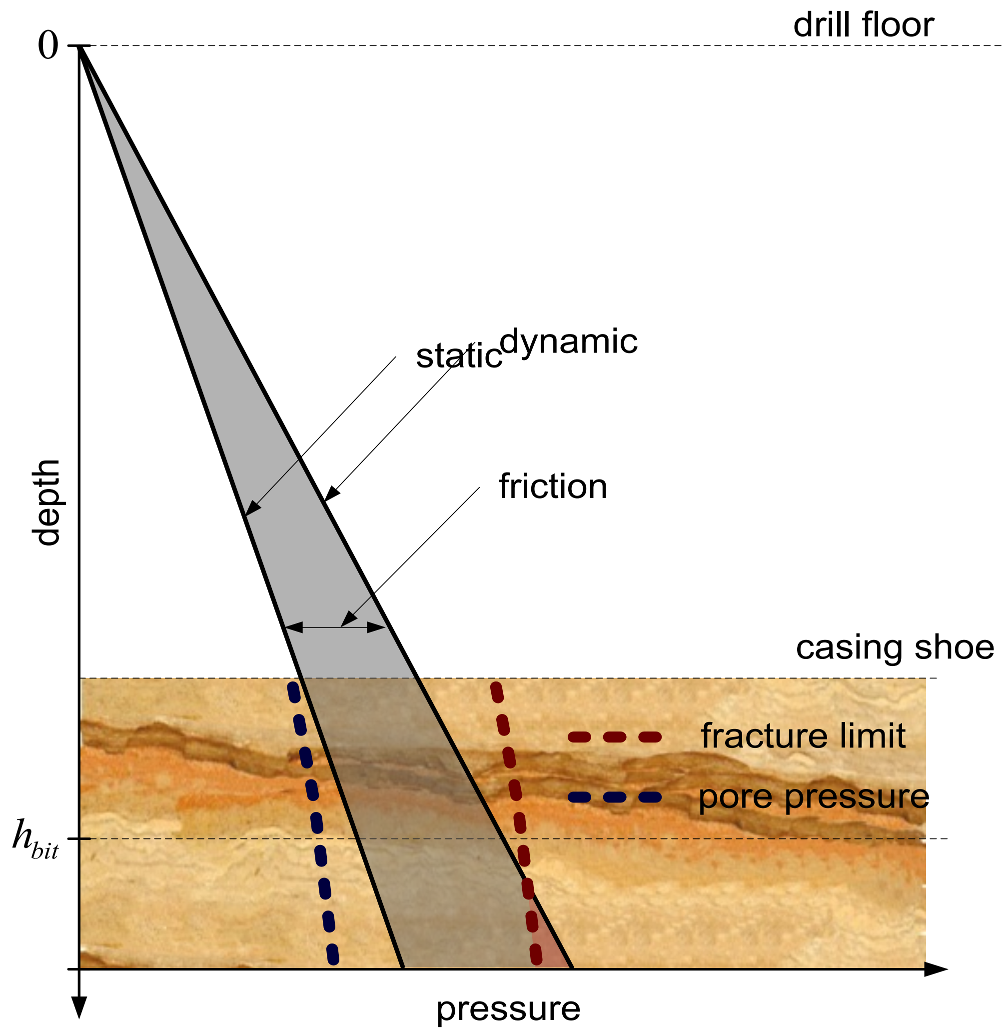
Conventional drilling



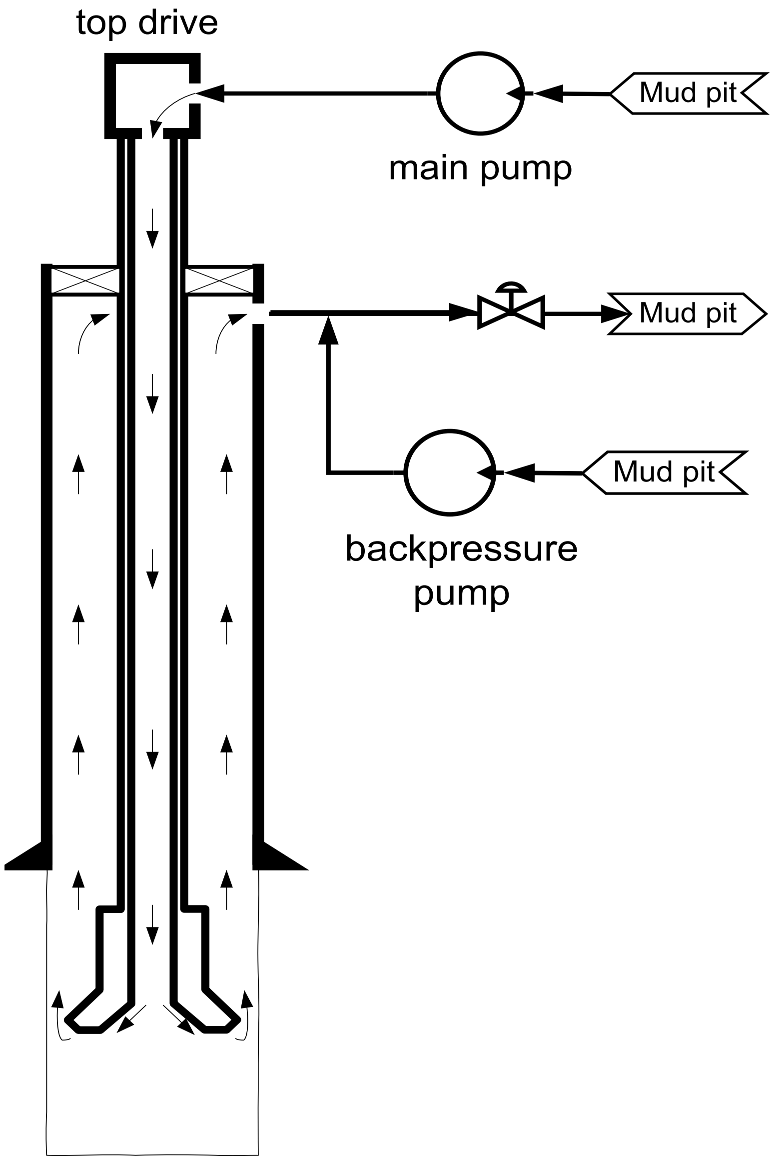


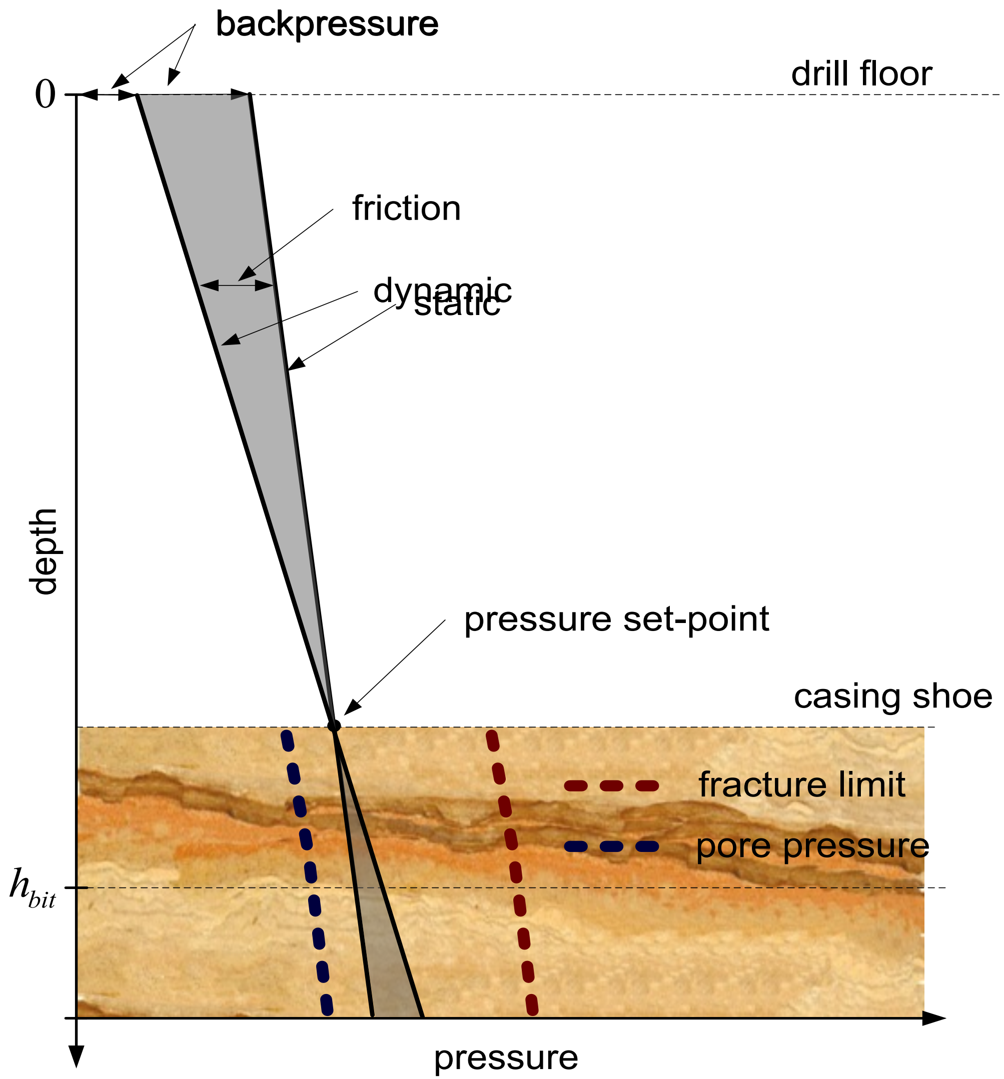
Conventional drilling

- Downhole pressure primarily controlled by density (pressure gradient)
- Frictional pressure drop (ECD) primarily controlled by circulation rate
- Other transient effects
  - Block velocity: Surge & swab
  - Drillstring rotation: Friction (ECD)
  - Heat transfer; temperature dynamics: Density (PVT)

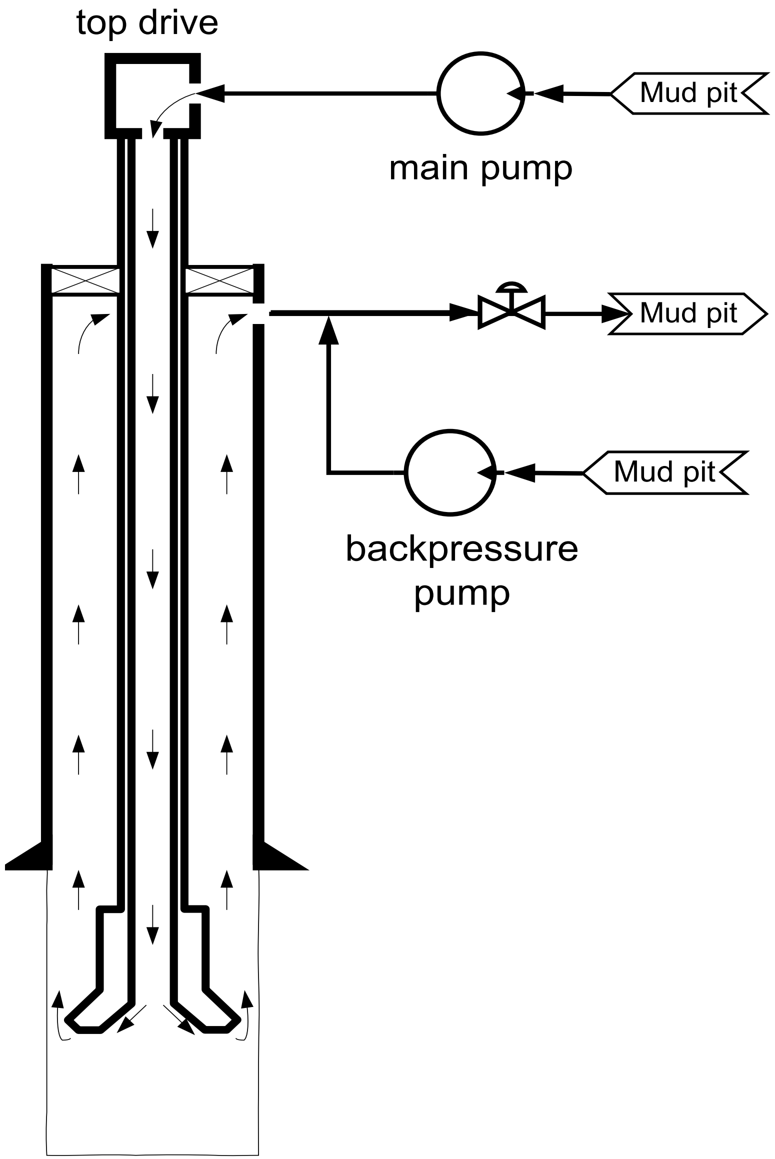


Managed pressure drilling





Managed pressure drilling



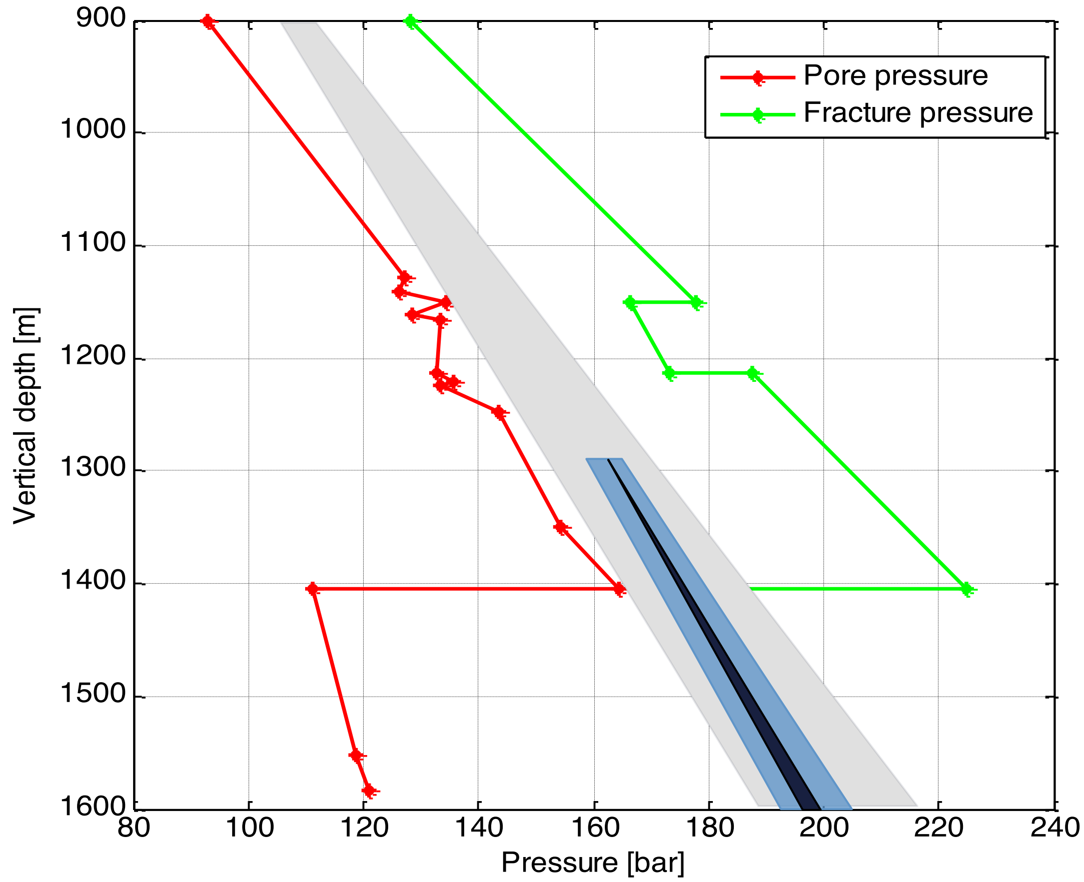
- Downhole pressure indirectly controlled by back-pressure
  - MPD choke manifold
- Enable fast compensation of well hydraulics
  - Density changes
  - Friction (ECD)
  - Surge & swab
- Hardware setup similar to well control and underbalanced drilling
  - BOP
  - Rig choke

Precision of pressure control

KELDA drilling controls

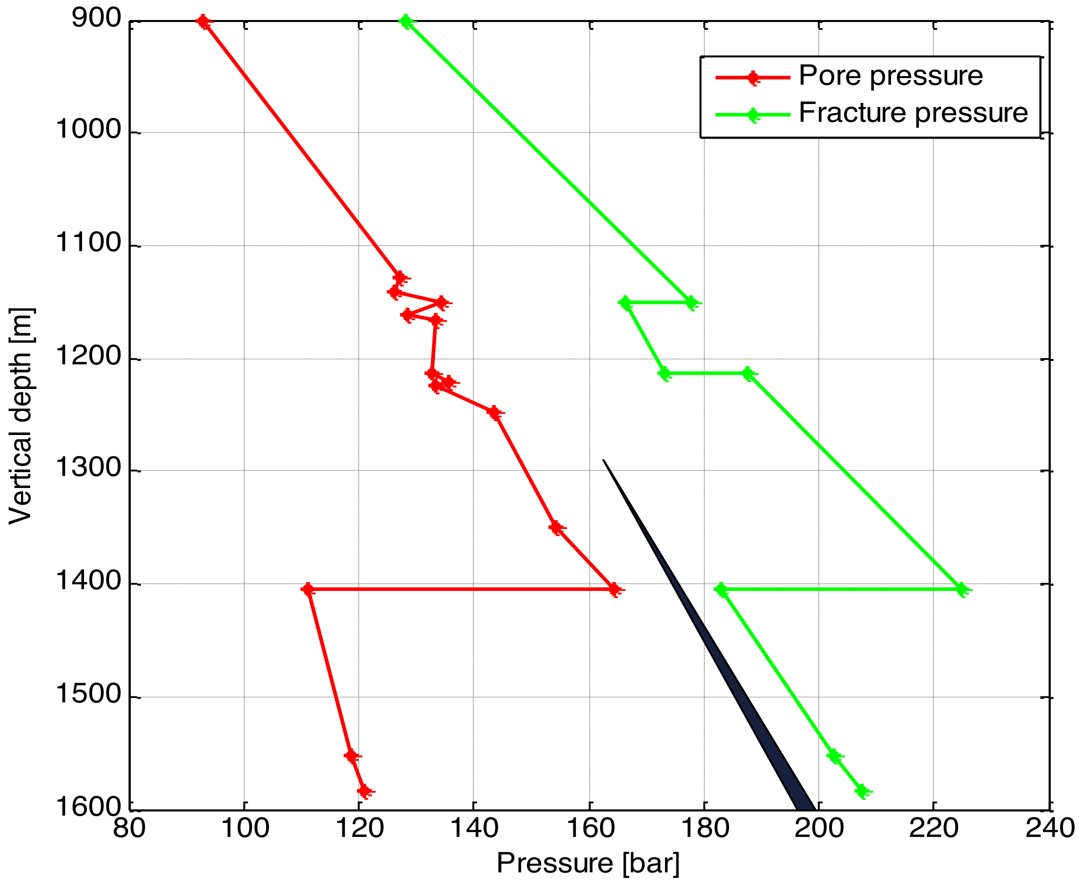
- Conventional drilling ± 20 bar (hr)
- **Manual MPD ± 10 bar (min)**
- **Automatic MPD ± 2.5 bar (sec)**

- MPD enables fast and precise control of well hydraulics



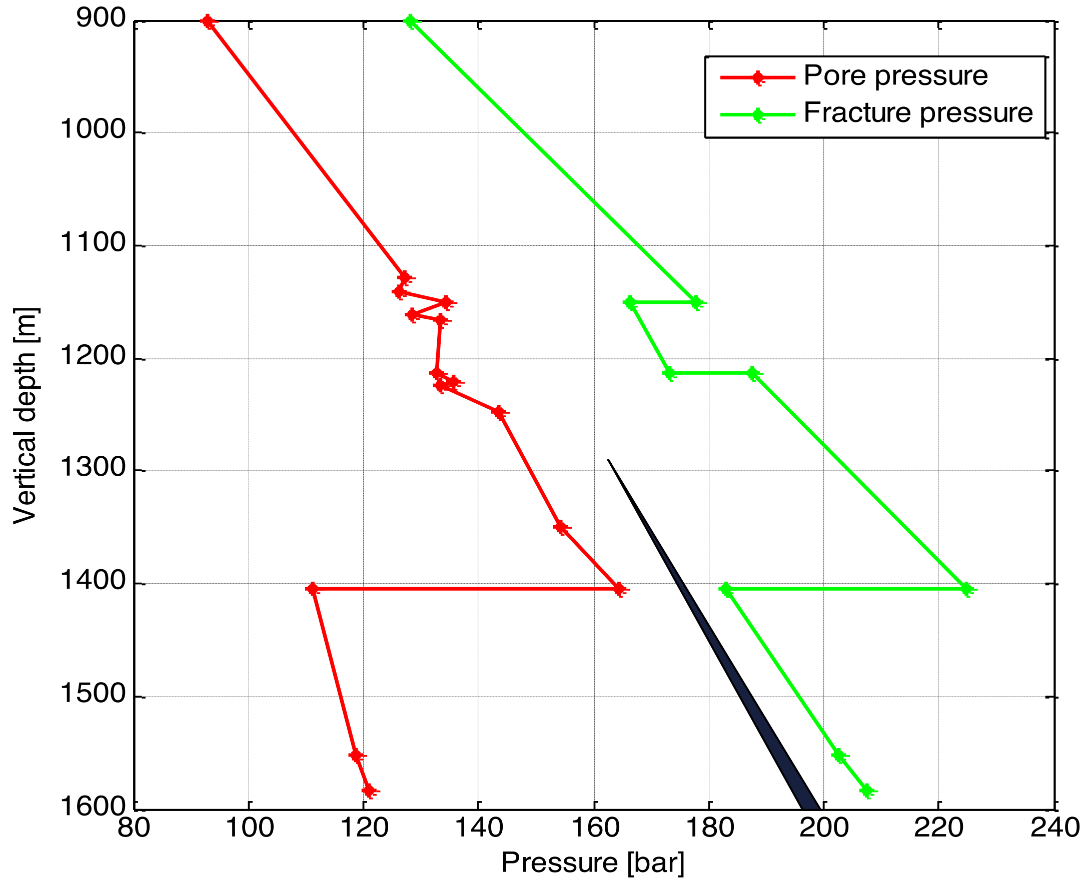
Main business drivers for MPD

- Enable drilling of reservoirs with tight pressure margins
  - Fast and precise control of well hydraulics
- MPD technology increasingly important; enabling drilling of difficult reservoirs
  - Maturing fields, longer wells, depletion, complex geology, etc.



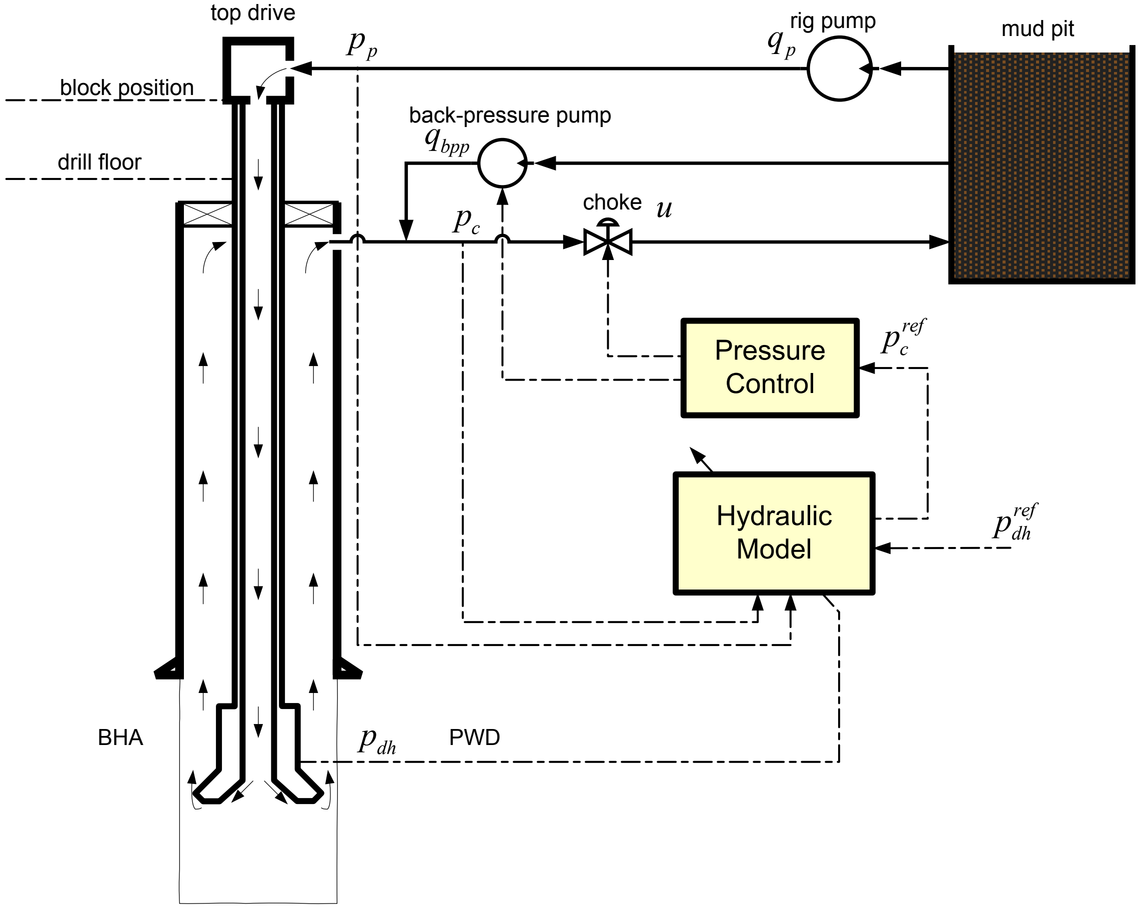
Existing solutions for automatic MPD

- Fast and precise control of well hydraulics, but…
  - High-end solution
  - High complexity of operation
  - Dedicated MPD expertise required offshore to operate and calibrate system
- Still requires significant manual interaction!
- Untapped potential of MPD technology
  - ➔ Automation technology



Mathematical modeling

- System characteristics
  - Steady state
  - Transients
- Physical: 1st principle models
  - Balance equations (mass, momentum, energy, etc.)
  - Fluid dynamics, state equation, flow characteristics, elasticity, etc…
- Empirical models
  - Dynamics: Lag models, Step response, etc.
  - Nonlinearities: Function approximation



Objective of modeling

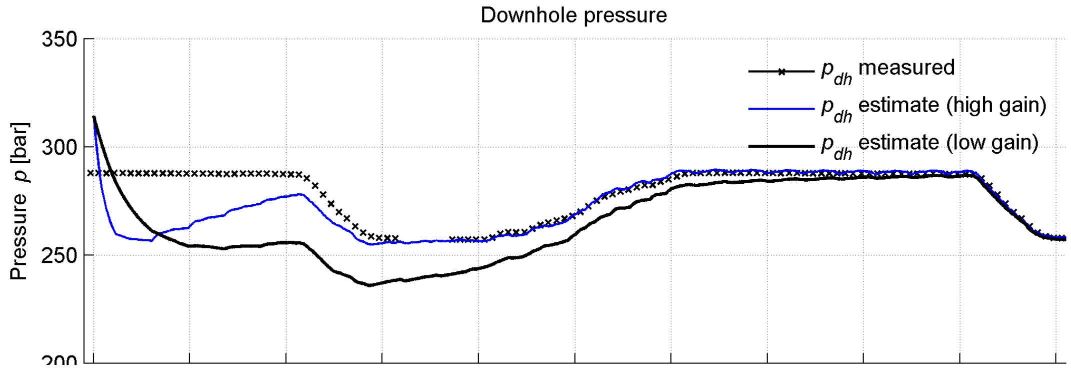
- What are you using it for?
  - High fidelity simulation model
    - Qualitative analysis
    - Performance analysis
  - Model-based design
    - Control system design
    - Observer design
- Trade-off: accuracy vs simplicity

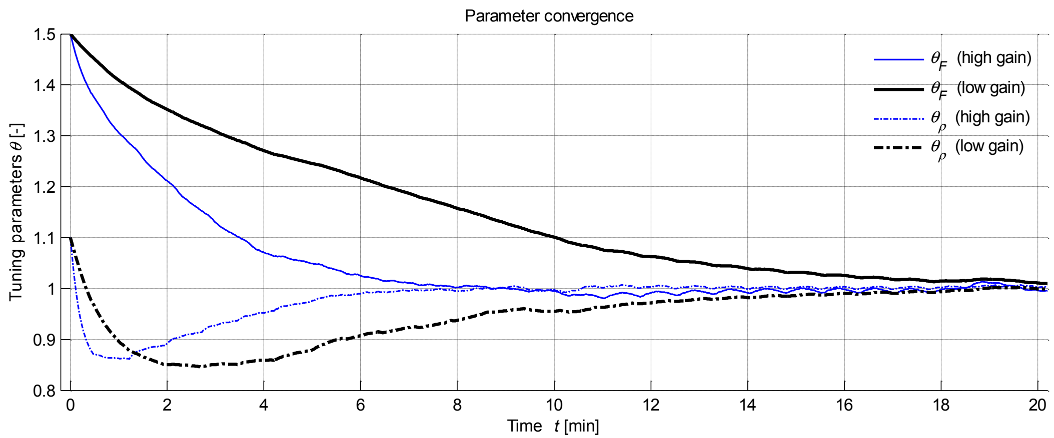
"Make things as simple as possible, but not simpler",

Albert Einstein

Fit-for-purpose modeling

- Basis for advanced control design
  - Control system
  - Estimators and observers
  - Fault-detection
- Ensure accuracy of downhole pressure
- Enable model calibration (adaptation)
- Ensure robustness of algorithms
- Remove unneccessary complexity
  - Neglect fast dynamics
  - Neglect slow dynamics
  - Lump parameters





Advanced distributed model

- Hydraulic model:

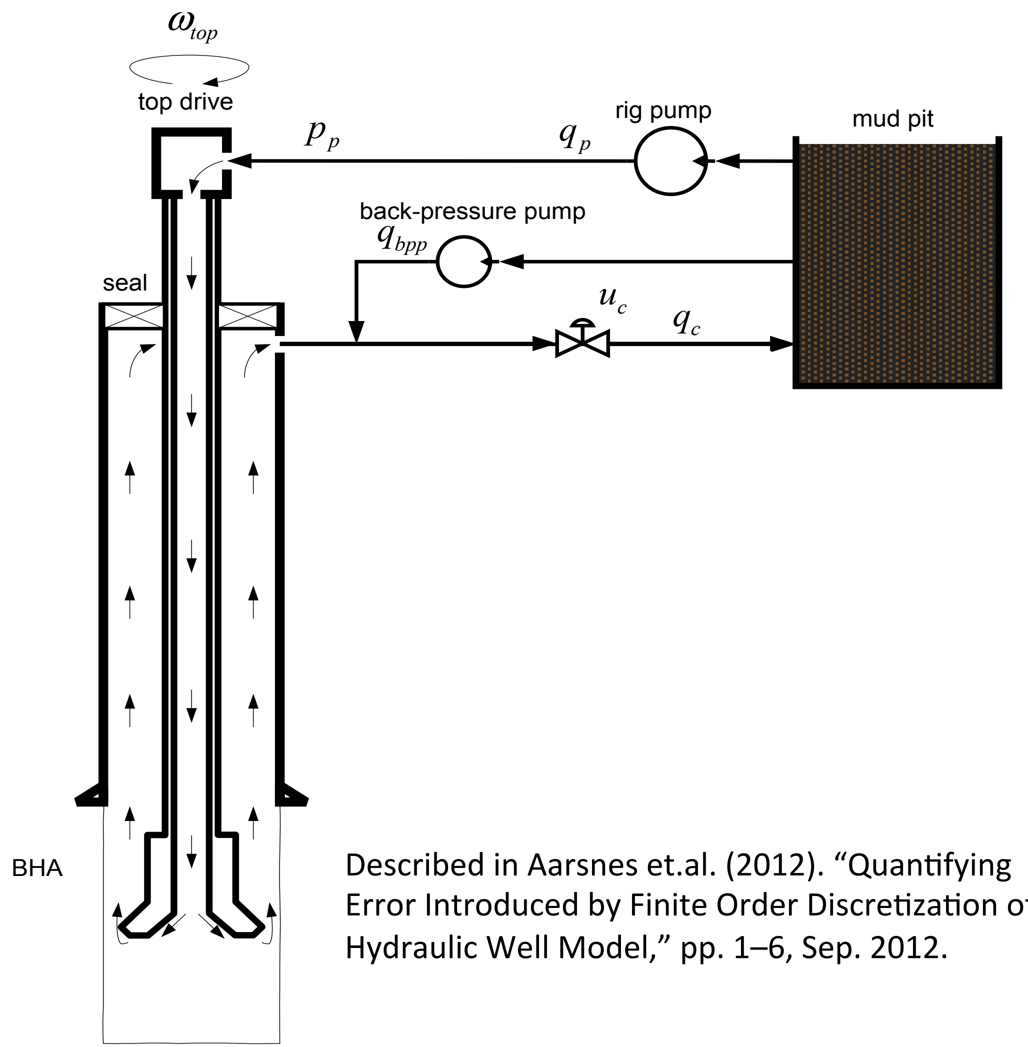
$$\frac{\partial p}{\partial t} = -\frac{\beta}{A}\frac{\partial q}{\partial x}$$
$$\frac{\partial q}{\partial t} = -\frac{A}{\rho}\frac{\partial p}{\partial x} - \frac{F}{\rho} + Agcos\left(\alpha\left(x\right)\right)$$

- Flow in: q_p, q_{bpp}, flow out: q_c
- Choke flow model:

$$q_c = K_c\sqrt{p_c - p_0}\cdot G(u_c)$$

u_c – choke opening (control input)

$K_c, G(u_c)$ – choke characteristics



Described in Aarsnes et.al. (2012). “Quantifying Error Introduced by Finite Order Discretization of a Hydraulic Well Model,” pp. 1–6, Sep. 2012.

Simplified model

- Pressure and flow dynamics

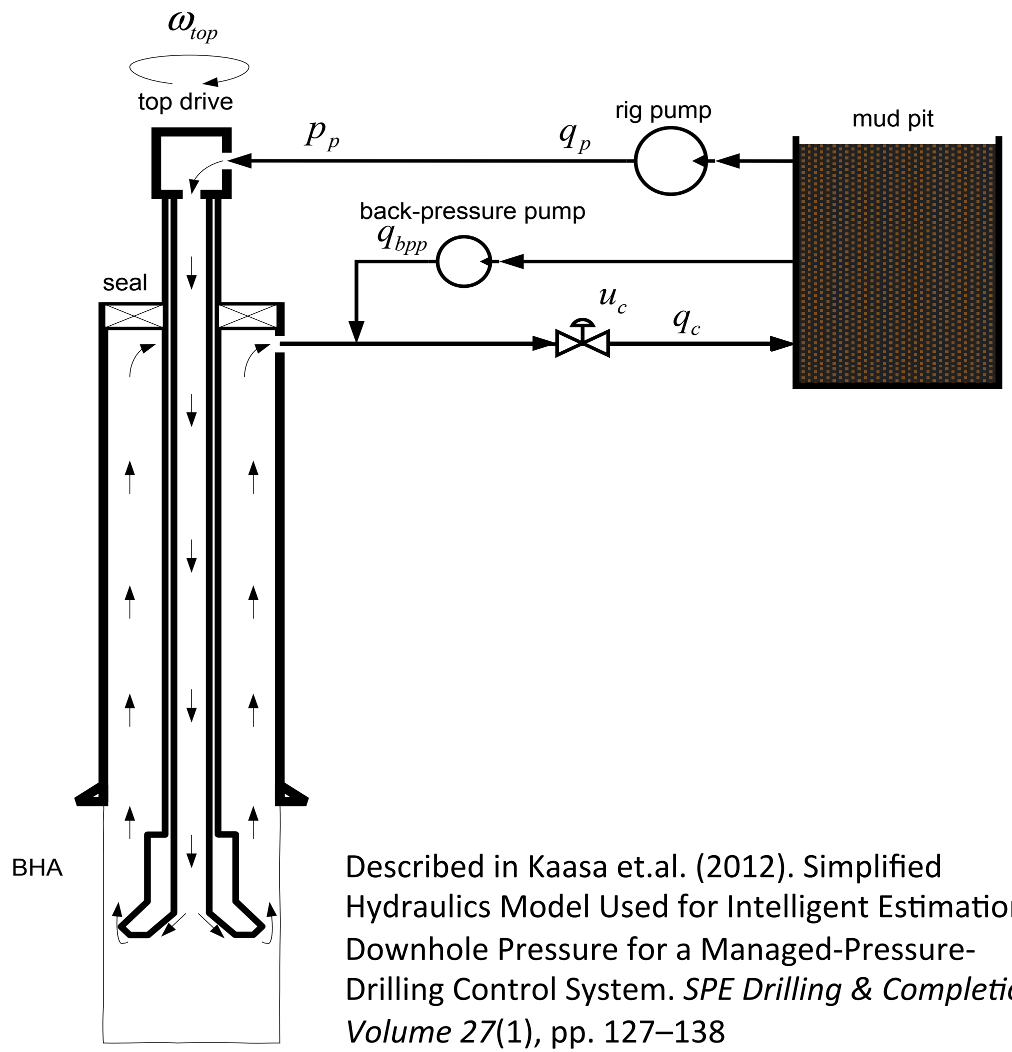
$$\frac{V_d}{\beta_d}\frac{dp_p}{dt} = q_p - q$$

$$\frac{V_a}{\beta_a}\frac{dp_c}{dt} = -\frac{dV_a}{dt} + q + q_{bpp} - q_c\left(p_c, u\right)$$

$$M\frac{dq}{dt} = p_p - p_c - F(q) - (\rho_d - \rho_a)gh$$

- Downhole pressure

$$p_{dh} = p_c + \rho_a g h\left(x\right) + F_a\,(x, q)$$

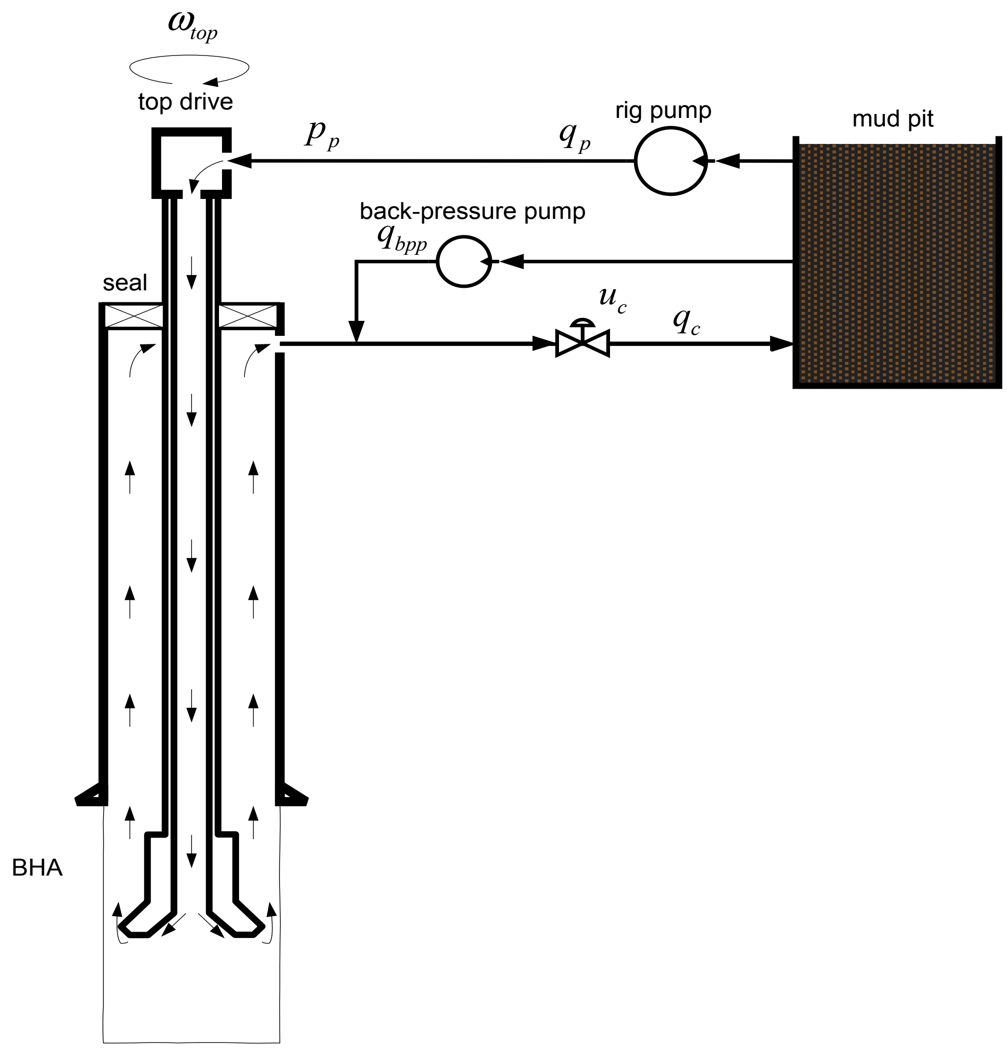


Described in Kaasa et.al. (2012). Simplified Hydraulics Model Used for Intelligent Estimation of Downhole Pressure for a Managed-Pressure-Drilling Control System. *SPE Drilling & Completion, Volume 27*(1), pp. 127–138

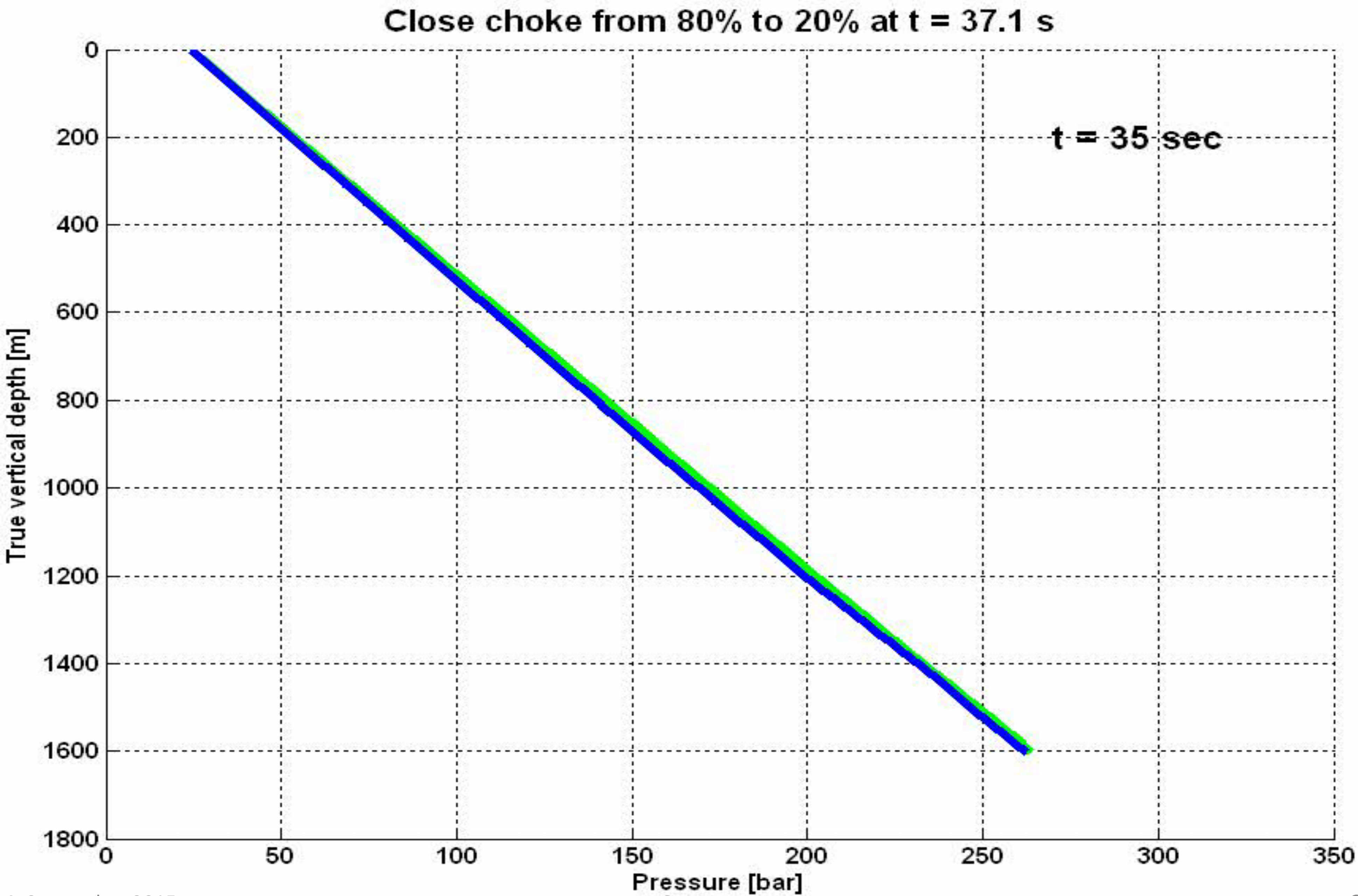
Advanced versus simplified model

- Common for both
  - Basic assumptions
  - Steady-state characteristics
- Advanced model
  - Distributed flow and pressure variables along the flow path
- Simplified model
  - Averaged flow and pressure variables

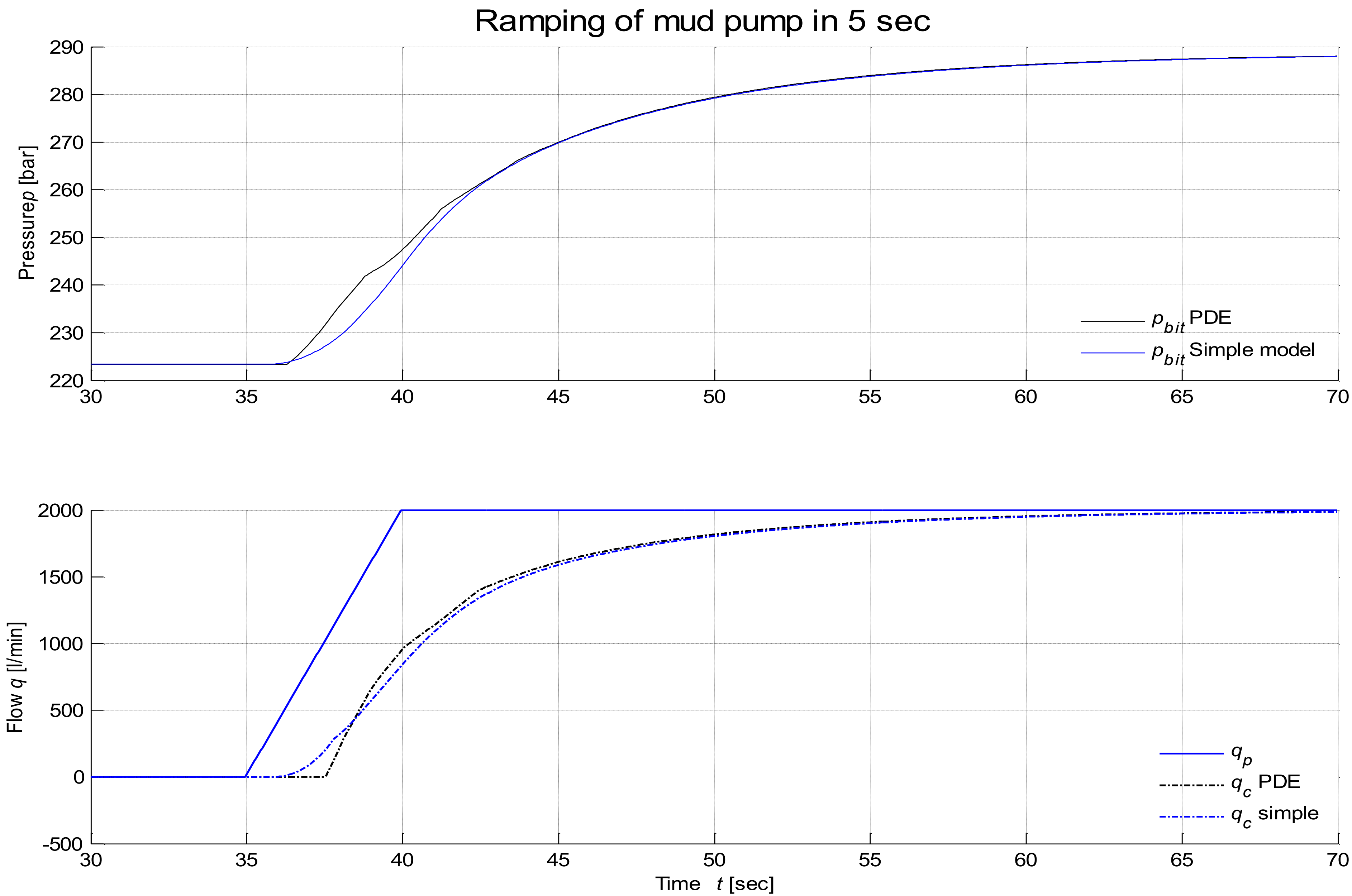
- So what are the differences…



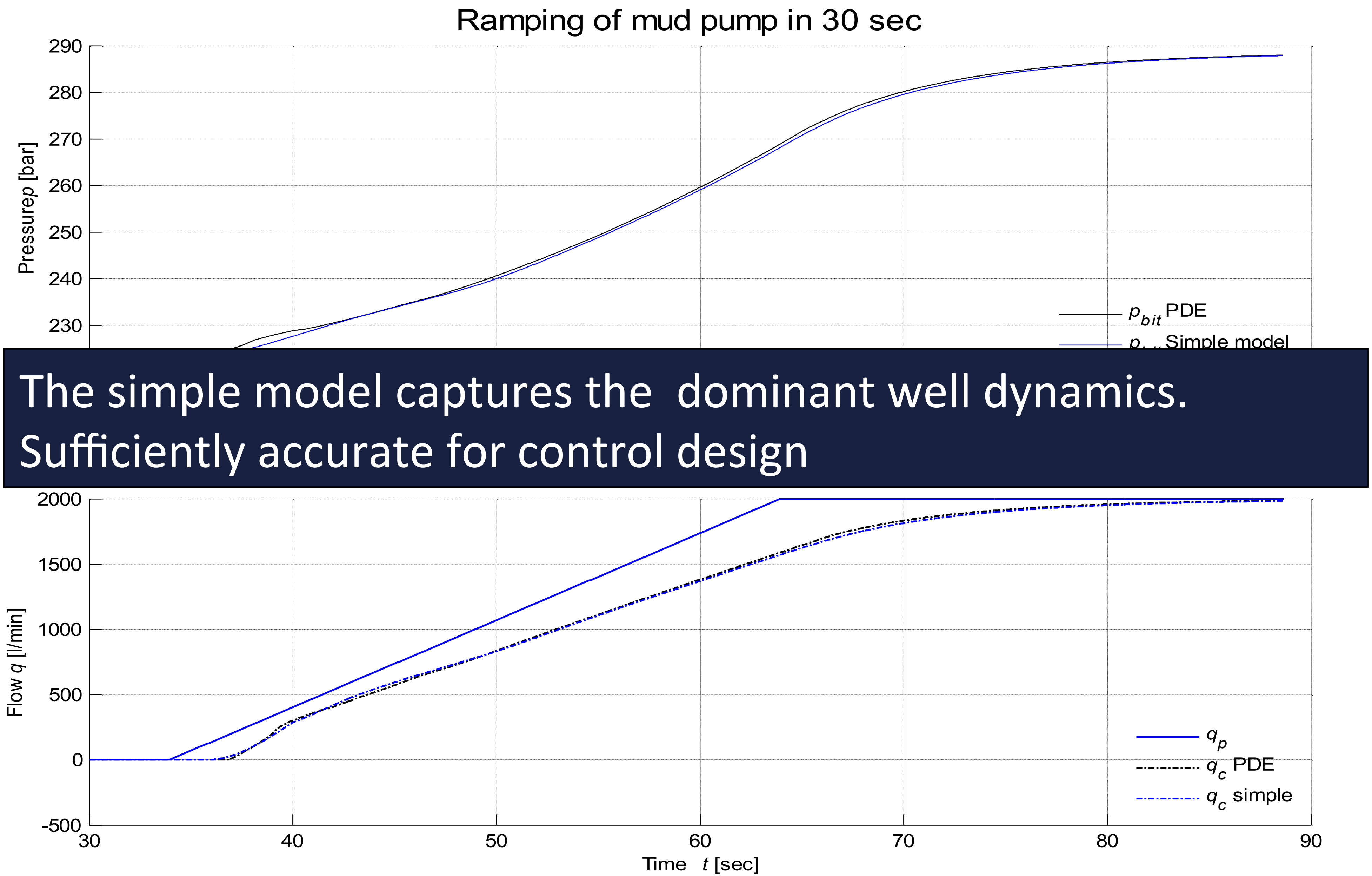
Propagation of pressure wave



Extremely fast ramp-up of rig pump



Normal ramp-up of rig pump



The simple model captures the dominant well dynamics.
Sufficiently accurate for control design

Simple ODE model

- Pressure and flow dynamics

$$\frac{V_d}{\beta_d}\frac{dp_p}{dt} = q_p - q$$

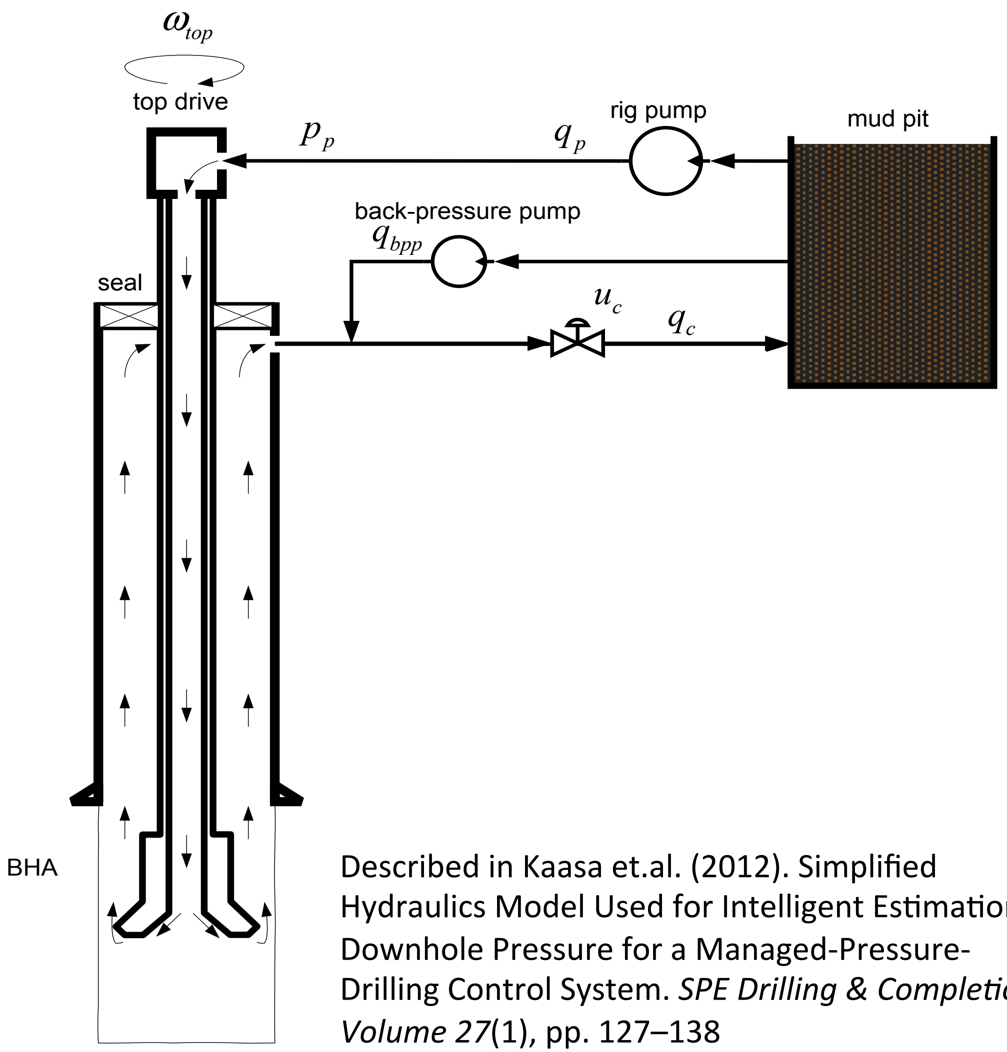
$$\frac{V_a}{\beta_a}\frac{dp_c}{dt} = -\frac{dV_a}{dt} + q + q_{bpp} - q_c\left(p_c, u\right)$$

$$M\frac{dq}{dt} = p_p - p_c - F(q) - \rho_d g h_d - \rho_a g h_a$$

- Downhole pressure

$$p_{dh} = p_c + \rho_a g h_a\left(x\right) + F_a\ (x,q)$$

- Simple model for controller and observer design
- Few parameters and low order
- *Suitable for most operations*



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Unknown constants

- Dynamics

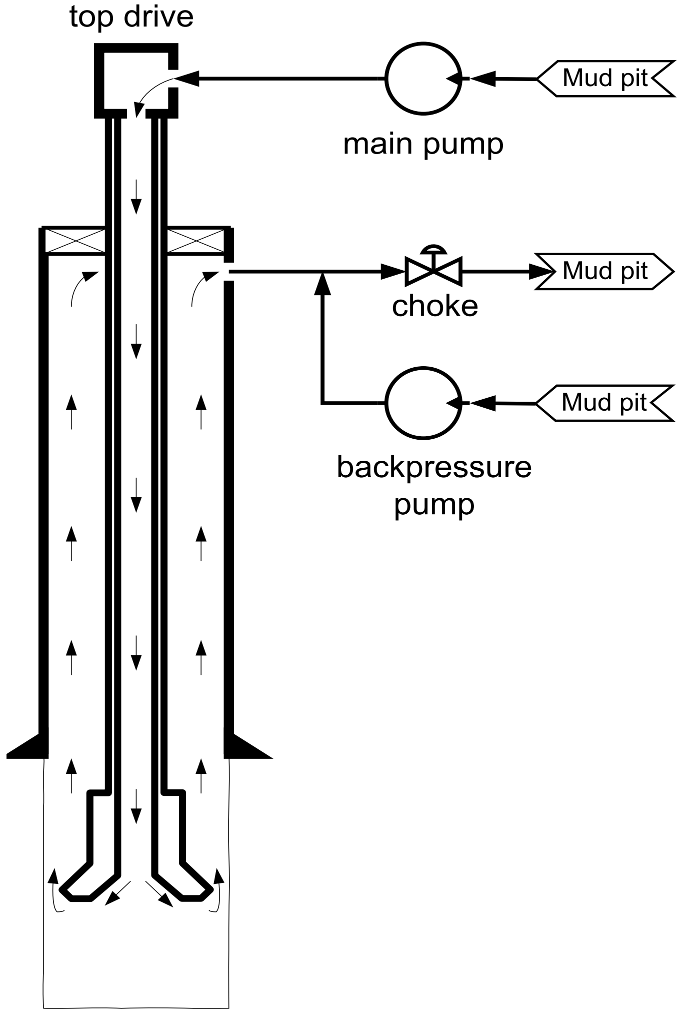
$$\frac{V_d}{\beta_d}\frac{dp_p}{dt} = q_p - q$$

$$\frac{V_a}{\beta_a}\frac{dp_c}{dt} = -\frac{dV_a}{dt} + q + q_{bpp} - q_c\left(p_c, u_c\right)$$

$$M\frac{dq}{dt} = p_p - p_c - f_d\left(q\right) - f_a\left(q\right) + \rho_d g h_d - \rho_a g h_a$$

- Output

$$p_{dh} = p_c + f_a\left(q\right) + \rho_a g h_a$$



Unknown nonlinearities

- Dynamics

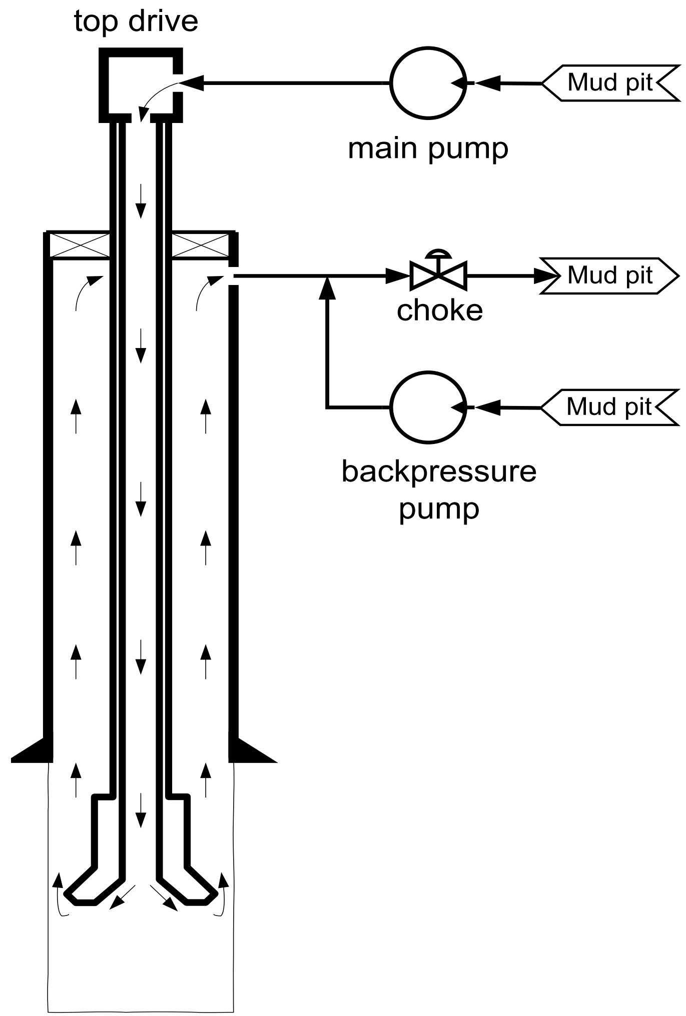
$$\frac{V_d}{\beta_d}\frac{dp_p}{dt} = q_p - q$$

$$\frac{V_a}{\beta_a}\frac{dp_c}{dt} = -\frac{dV_a}{dt} + q + q_{bpp} - q_c\left(p_c, u_c\right)$$

$$M_\Sigma \frac{dq}{dt} = p_p - p_c - f_d\left(q\right) - f_a\left(q\right) + \rho_d g h_d - \rho_a g h_a$$

- Output

$$p_{dh} = p_c + f_a\left(q\right) + \rho_a g h_a$$

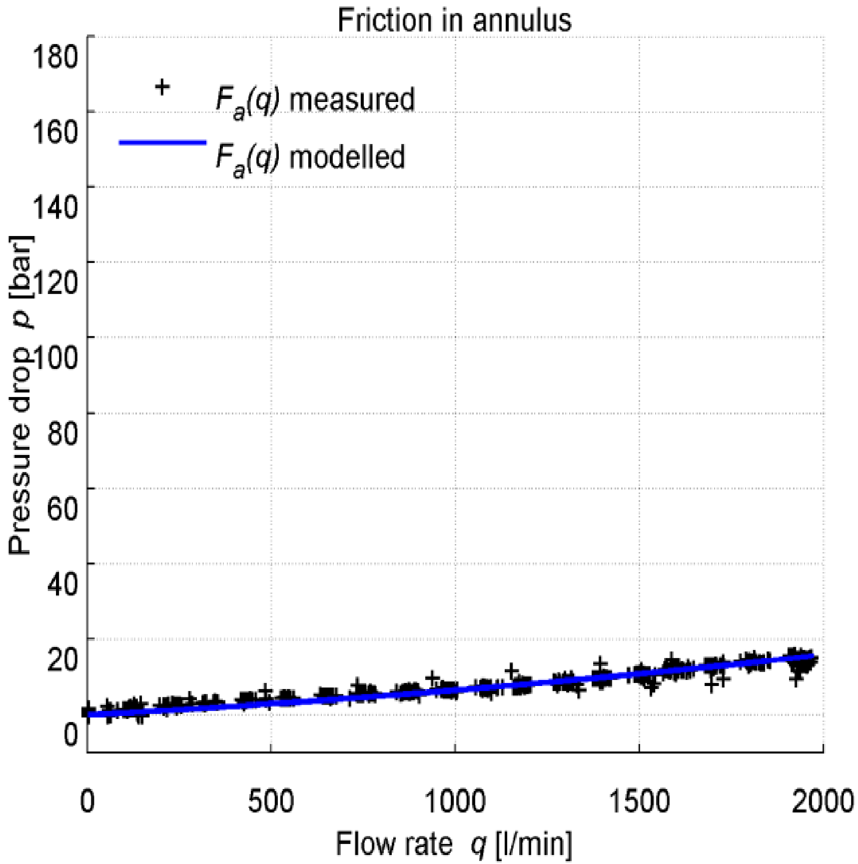


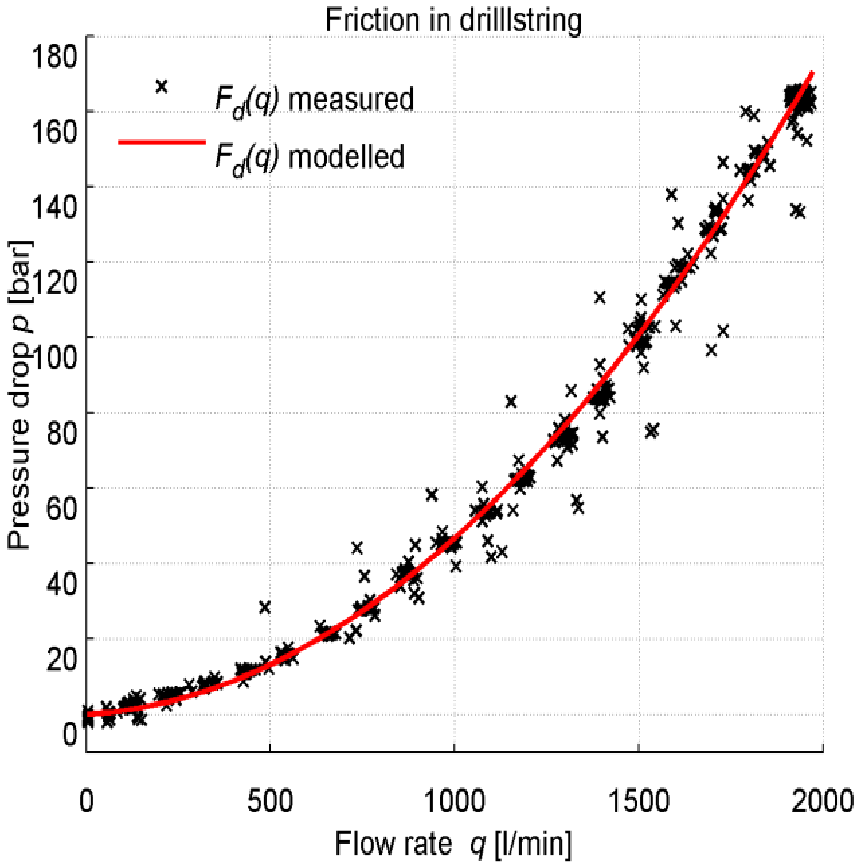
Friction characteristics

- Frictional pressure drop as function of flow

$$f_a(q) = C_a q + D_a q^2$$

$$f_d(q) = C_d q + D_d q^2$$





Unknown nonlinearities

- Dynamics

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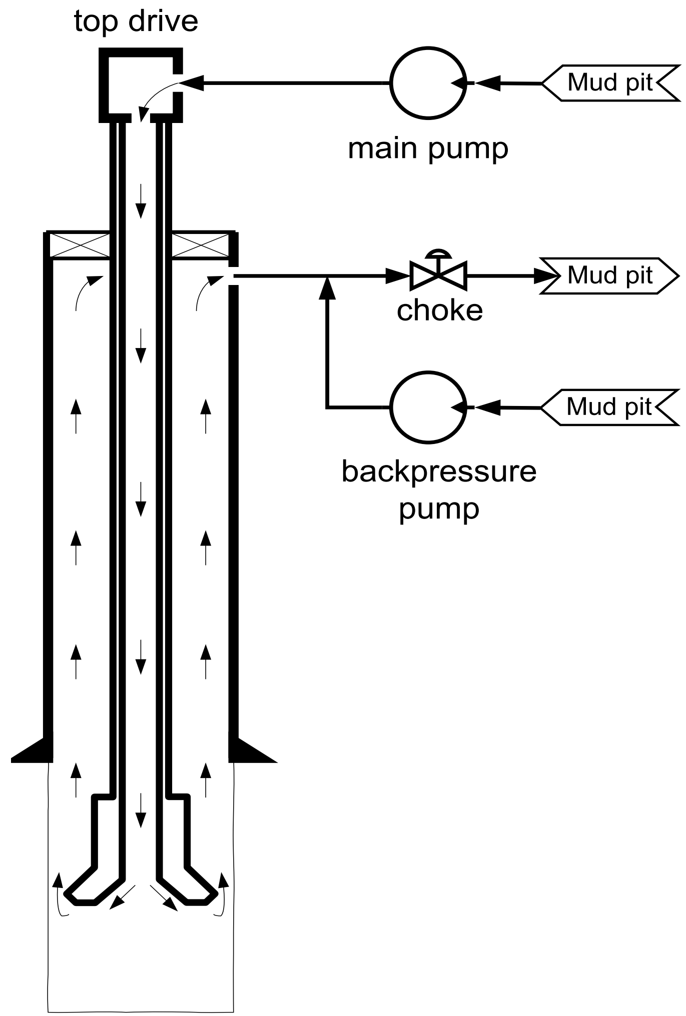
$$M_\Sigma \frac{dq}{dt} = p_p - p_c - f_d\left(q\right) - f_a\left(q\right) + \rho_d g h_d - \rho_a g h_a$$

- Output

$$p_{dh} = p_c + f_a\left(q\right) - \rho_a g h_a$$



Choke characteristics

- Flow rate through choke

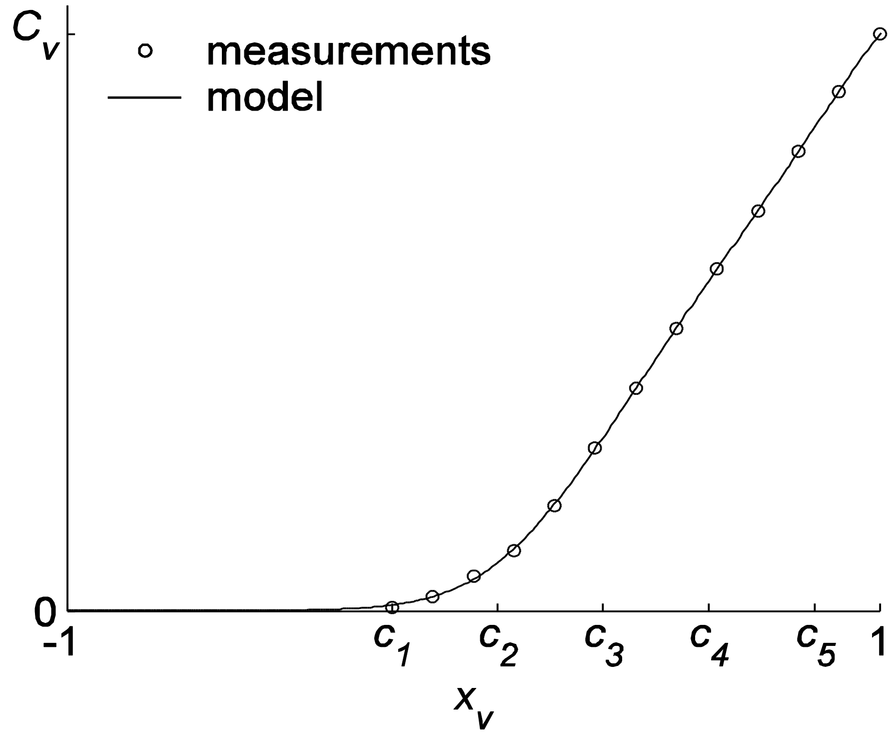
$$q_c\left(p_c,u_c\right)=\sqrt{\left(p_c-p_0\right)}g_c\left(u_c\right)$$

- Input nonlinearity

$$g_c\left(u_c\right)=\phi\left(u_c\right)^T\theta_c$$

  – Saturation, dead zone, etc.

- Actuator dynamics
  – Negligible fast
  – Back lash, hysteresis, …



θ_μ = [0.00 0.01 0.29 0.59 0.80 1.22]^T

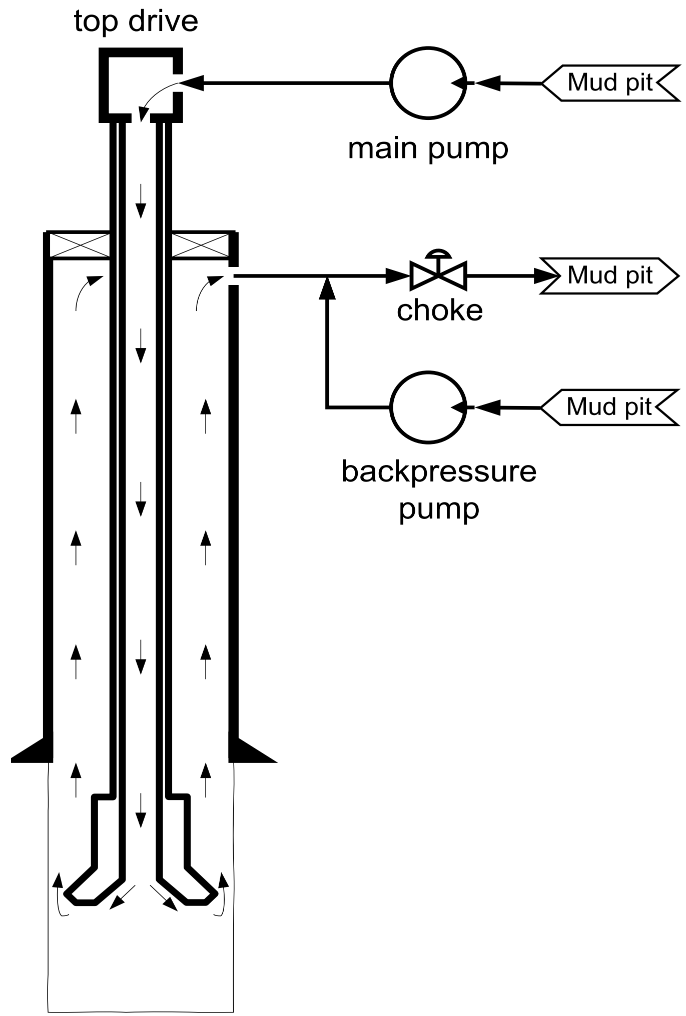
Simplifications

- Dynamics

$$\frac{V_d}{\beta_d}\frac{dp_p}{dt} = q_p - q$$

$$\frac{V_a}{\beta_a}\frac{dp_c}{dt} = -\cancelto{0}{\frac{dV_a}{dt}} + q + \cancelto{0}{q_{bpp}} - q_c\left(p_c, u_c\right)$$

$$M\frac{dq}{dt} = p_p - p_c - f_d\left(q\right) - f_a\left(q\right) + \rho_d g h_d - \rho_a g h_a$$



Hydraulic model - Summary

- Dynamics

$$C_d \frac{dp_p}{dt} = q_p - q$$

$$C_a \frac{dp_c}{dt} = q + q_{bpp} - q_c\left(p_c, u_c\right)$$

$$M \frac{dq}{dt} = p_p - p_c - f\left(q\right) + G$$

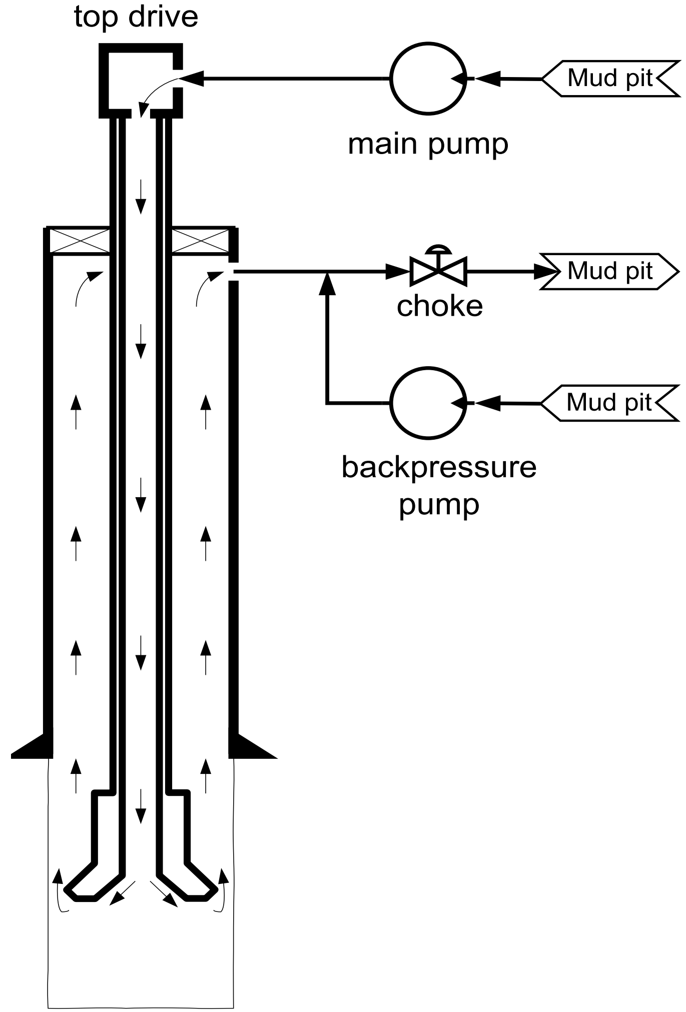
- Constants

$$G = \rho_d g h_d - \rho_a g h_a$$

- Nonlinearities

$$q_c\left(p_c, u_c\right) = \sqrt{\left(p_c - p_0\right)} g_c\left(u_c\right)$$

$$f\left(q\right) = \left(C_d + C_a\right)q + \left(D_d + D_a\right)q^2$$



Parametrization of nonlinearities

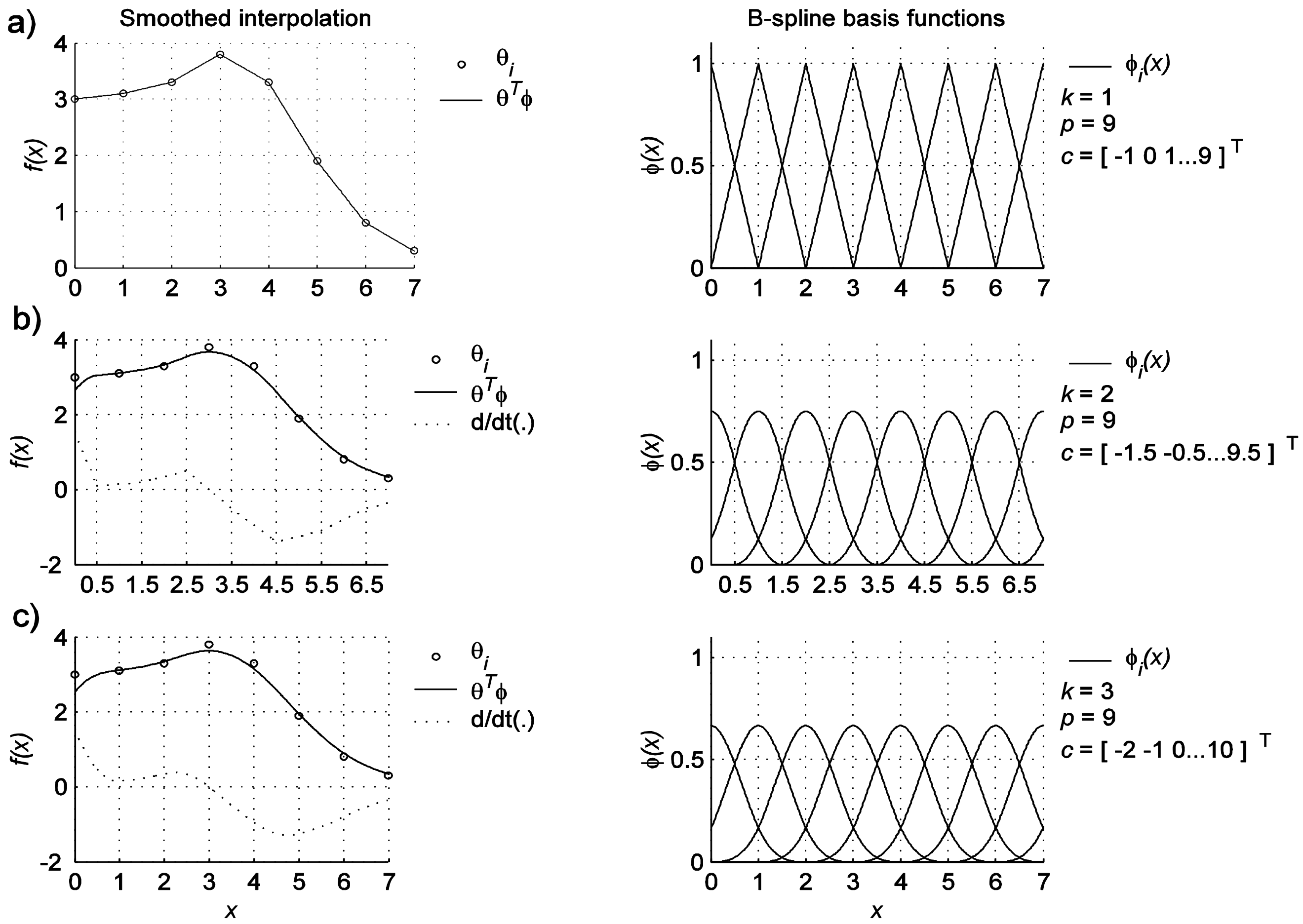
- Parameter-affine form

$$\boxed{y=\phi(x)^T\,\theta}$$

- Basis functions

$$\boxed{\phi(x)=\left[\phi_1(x),\phi_2(x),\cdots,\phi_p(x)\right]^T}$$

  - Example: $f(q)=a+bq+cq^2$
- Global vs local support
- Universal approximators
  - Interpolation: Linear splines
  - Smooth interpolation: quadratic, cubic splines, etc.



Problem formulation for estimation

- Parameter-affine model

$$\boxed{y = \phi(u)^T \theta}$$

- Measurements

$$\begin{aligned} &t_1 : y_1, u_1 \\ &t_2 : y_2, u_2 \\ &\vdots \\ &t_N : y_N, u_N \end{aligned}$$

- Example $y = a + bq + cq^2$

$$y = \phi(u)^T \theta$$

$$\Downarrow$$

$$\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_N \end{bmatrix} = \begin{bmatrix} \phi(u_1)^T \\ \phi(u_2)^T \\ \vdots \\ \phi(u_N)^T \end{bmatrix} \theta$$

$$\Downarrow$$

$$Y(y_1, y_2, \cdots y_N) = \Psi(u_1, u_2, \cdots, u_N)\theta$$

Discretization

- Dynamics in continuous-time form

$$\boxed{\frac{dx}{dt} = f\left(x,t\right)}$$

- Hydraulic model

$$\frac{V_d}{\beta_d}\frac{dp_p}{dt} = q_p - q$$

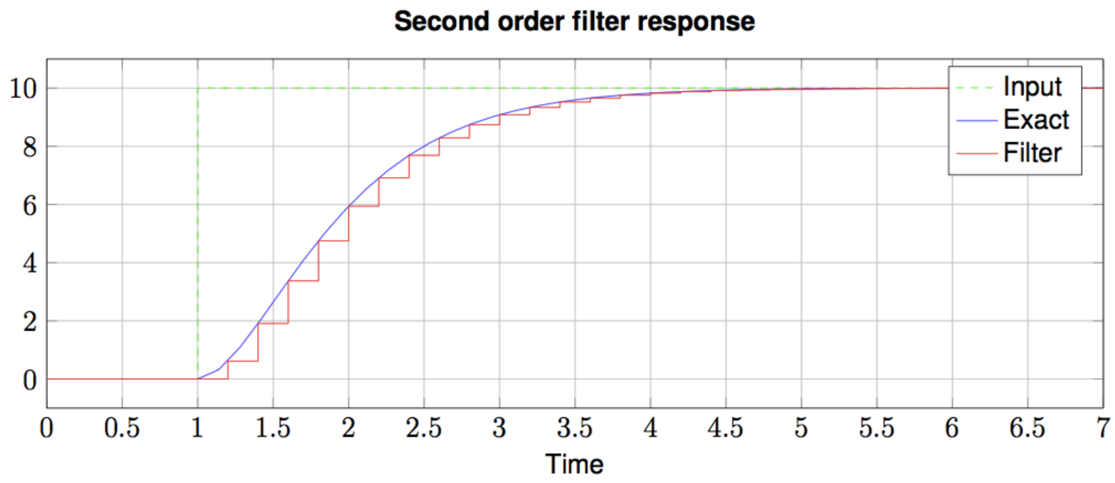
$$\frac{V_a}{\beta_a}\frac{dp_c}{dt} = q + q_{bpp} - q_c\left(p_c,u_c\right)$$

$$M\frac{dq}{dt} = p_p - p_c - f\left(q\right) + \Delta G$$

- Approximate derivative
  - Euler: $\boxed{x_{k+1} = x_k + \Delta t f\left(x_k,t_k\right)}$

- Solve analytically/numerically

$$\boxed{x_{k+1} = x_k + \int_{t_k}^{t_{k+1}} f\left(x\left(\tau\right),\tau\right)d\tau}$$



Estimation - Where to start?

- Dynamics

$$\frac{V_d}{\beta_d}\frac{dp_p}{dt} = q_p - q$$

$$\frac{V_a}{\beta_a}\frac{dp_c}{dt} = q + q_{bpp} - \sqrt{(p_c - p_0)}\,g_c(u_c)$$

$$M\frac{dq}{dt} = p_p - p_c - f(q) + \Delta G$$

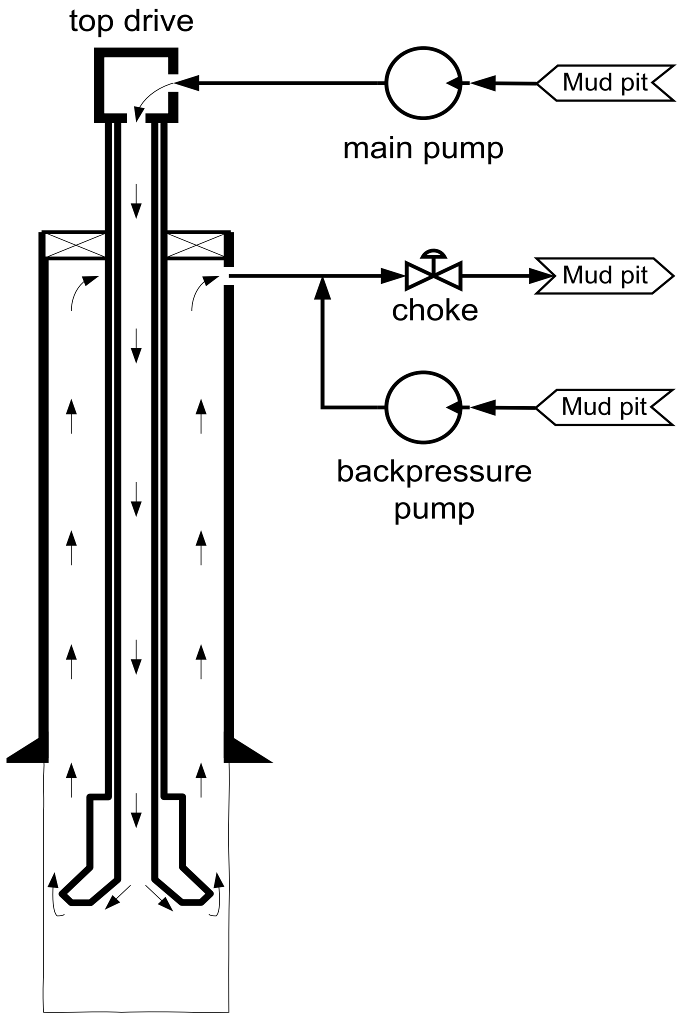
$$g_c(u_c) = \phi(u_c)^T \theta_c$$

- Output

$$p_{dh} = p_c + f_a(q) + \rho_a g h$$

$$f_d(q) = C_d q + D_d q^2$$

$$f_a(q) = C_a q + D_a q^2$$



Estimation - Divide & Conquer

- Isolate subsystems
  - Steady-state analysis
  - Measure directly

- Example: Actuator with nonlinear input

$$\boxed{\begin{aligned}&\tau \frac{dx}{dt} = -x + g(u,\theta)\\ &y = x\end{aligned}}$$

- Identify / design experiments to perform

Estimate parameters of the hydraulic model

- Dynamics

$$\frac{V_d}{\beta_d}\frac{dp_p}{dt} = q_p - q$$

$$\frac{V_a}{\beta_a}\frac{dp_c}{dt} = q - \sqrt{(p_c - p_0)}\, g_c(u_c)$$

$$M\frac{dq}{dt} = p_p - p_c - f(q) + \Delta G$$

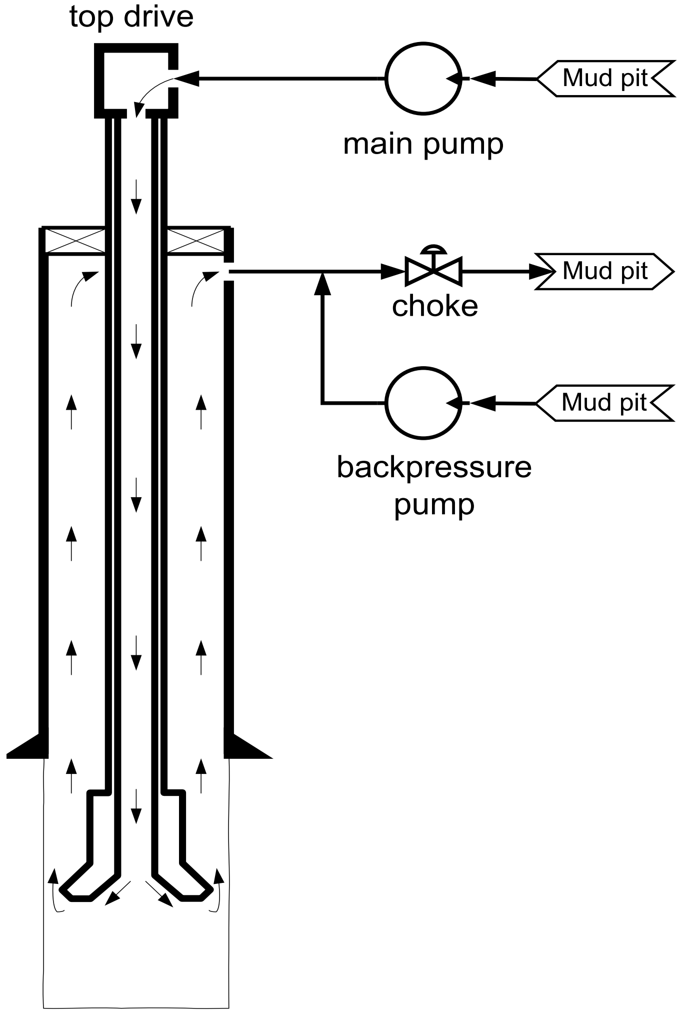
$$g_c(u_c) = \phi(u_c)^T \theta_c$$

- Output

$$p_{dh} = p_c + f_a(q) - \rho_a g h$$

$$f_d(q) = C_d q + D_d q^2$$

$$f_a(q) = C_a q + D_a q^2$$



Pre-processing of data

- Model errors
  - Unmodelled dynamics
  - Approximations
  - Sensor errors
- Sensor errors
  - Outliers
  - Offset
- Accuracy
  - Repeatability
  - Resolution
  - Range
  - Linearity

Summary - Task description

- Task
  - Offline estimation of parameters of hydraulic model from real well data
- What you will get to work with?
  - Model structure and given parameters
  - Description of model and values of given parameters
  - Real measurements from drilling operations in simple text (ascii) or Matlab (mat) format
  - Reference material (papers)
- You will need to:
  - Select and pre-process which data to use for estimation of the different parameters

- Estimate parameters of static nonlinearities
  - Nonlinear input characteristic $g_c(u_c)$

$$q_c(p_c,u_c) = \sqrt{(p_c - p_0)}g_c(u_c)$$

  - Frictional pressure drop as function of rate

$$f_d(q) = C_d q + D_d q^2$$

$$f_a(q) = C_a q + D_a q^2$$

- Estimate parameters of dominating dynamics

$$\frac{V_d}{\beta_d}\frac{dp_p}{dt} = q_p - q$$

$$\frac{V_a}{\beta_a}\frac{dp_c}{dt} = q + q_{bpp} - q_c(p_c,u_c)$$

$$M\frac{dq}{dt} = p_p - p_c - f(q) - \Delta G$$

TK17 System Identification, 2015

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KELDA drilling controls

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