INTERACTIVE CONTROL ENGINEERING
Principles and Applications

Volume 4 Override, Split-Range, and Constraint Control

CHAPTER 7

Horizontal Directional Drilling Where the Soil Chooses the Binding Limit

Pages 164–187

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How to cite this chapter. "Horizontal Directional Drilling Where the Soil Chooses the Binding Limit," in *Override, Split-Range, and Constraint Control*, John D. Hedengren, Ed., vol. 4 of *Interactive Control Engineering: Principles and Applications*. Advanced Process Solutions, LLC, 2026, ch. 7, pp. 164–187.

The page numbers in this file are those of the printed volume.

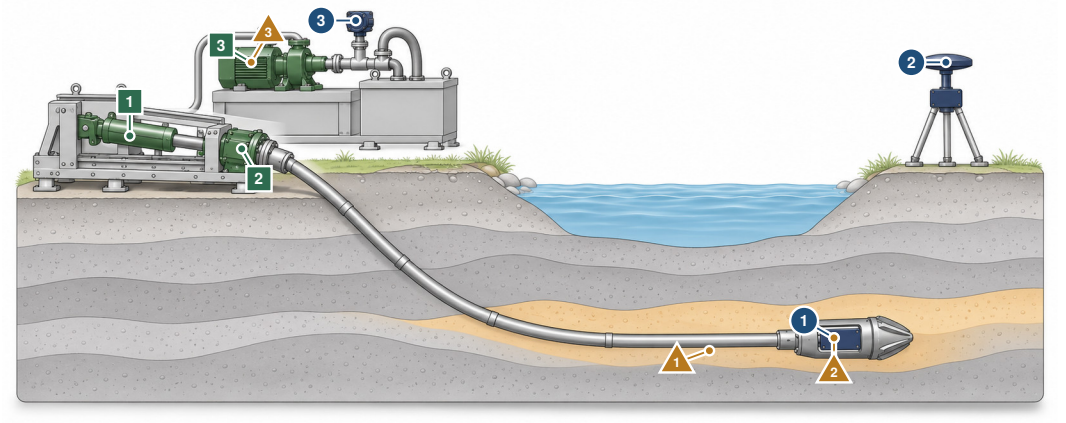
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The volume online: contents, other chapters and citation records
https://apmonitor.com/apps/books/v04-override-constraint/#horizontal-directional-drilling

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CHAPTER 7

Horizontal Directional Drilling Where the Soil Chooses the Binding Limit



The controller moves 1 carriage thrust 2 spindle speed 3 mud pump flow

The controller reads 1 beacon behind the bit: pitch, roll, mud pressure 2 walkover locate of the depth 3 mud pump pressure

What disturbs it 1 a change of soil at the bit 2 a bias in the beacon's pitch 3 a mud pump fault

The drill on the bank pushes, turns and feeds mud to a bore it cannot see, and only the beacon at the head reads the mud pressure that the ground above must hold. Illustration, not to scale.

IN PLAIN TERMS Drilling Under a River Without Breaking Out

The main idea. A drill on one bank pushes a string of steel rods under a river and steers the cutting head by turning or pushing each rod. Mud pumped down the rods carries the cut soil back out, and the drill should cut as fast as the soil allows.

The challenge. Each kind of soil sets a different limit on that speed. The mud pressure grows with every meter, and where the ground above is thin it can split the soil and burst out at the surface.

Why it matters. A safety layer that eases off the push when the pressure nears that limit keeps the mud underground.

THREE WAYS TO READ THIS CHAPTER

Explore	12 min	the first page, the fact on bore sizes (Section 7.1), the two history segments (Section 7.2), the two try-it segments and the fact on the override (Section 7.5) and the key points
Study	55 min	the whole chapter with its three pause points and the twelve exercises at its end
Practice	15 min	the first page, the results (Section 7.5), Technology in Practice (Section 7.7), Limitations (Section 7.8) and the open challenge

The control question A steered pilot bore drills through soils that each hand the drilling rate to a different limit, while the mud pressure along the bore meets the thin ground of the exit climb. How do a rate optimizer, a pressure override and an estimator on sparse locates carry a river crossing to its exit within every limit?

Learning objectives

- Compute the turn of one pushed rod and explain why steering is a duty-cycle actuator that costs rate.
- Identify the constraint that holds the rate in clay, sand and gravel, and derive the mud-ratio ceiling on the rate.
- Predict where along a bore the annular pressure first meets the ground's limit, and what a pressure override takes away.
- Estimate the depth error a pitch bias builds between locates, and explain how an estimator that learns the bias carries the depth across a river.

Prerequisites Sections 1.4.2, 1.4.3, 1.4.4, 1.4.8 and 1.6.4, and Chapter 5 for a throughput supervisor on predicted constraints.

The app https://apmonitor.com/apps/horizontal-directional-drilling/

See also Volume 9, Chapter 8 for an optimum on a constraint that moves with the conditions, Volume 5, Chapter 13 for dead reckoning between sparse fixes with a Kalman filter, and Volume 10, Chapter 2 for a rate of penetration pushed against an annular pressure window and a cuttings load.

7.1 Introduction

A utility drill steers without a rudder. In the generic 30 m driveway service simulated here, a stiff clay takes the pilot bit down at a pitch of −14 %, and every 3 m rod is either rotated, which holds the pitch within 0.3 point, or pushed without rotation with its slanted face turned to a clock position. One rod pushed at 12 o'clock turns the bore from −14.2 to −4.7 % (9.4 points), but the bit cuts at 1.19 m/min pushed against 2.43 m/min rotating and the rod takes 206 s. Steering is therefore a duty-cycle actuator sampled once per rod, and every meter it costs is a meter drilled slower.

The same drill on a 180 m river crossing meets four further problems at once. The rate is limited by the spindle torque in clay, by the mud that must carry the cuttings out of sand, by the thrust in gravel and by the bus on a shore supply, so the binding constraint migrates along one bore. Rotary drilling in the oilfield has long been run against such limits through a rate law and a measure of drilling efficiency [1, 2], and Volume 10, Chapter 2 pushes an oil well's rate of penetration against limits of the same kind. Depth is known only by integrating the beacon's pitch between walkover locates, and nobody can walk over a river. The mud pressure in the annulus grows with every meter drilled, while the pressure the ground can hold is a cavity-expansion limit that falls with the cover [3–5]. Mud that breaks through to the surface, an inadvertent return, is the failure regulators and owners watch for [5], and surface heave is the related damage mechanism that field trials have measured [6].

> ✦ DID YOU KNOW? **From a Pilot Bore to a Wide Crossing**
>
> The first pass of a crossing cuts a guided bore 73 to 114.3 mm across, which later passes ream to the size of the pipe. The industry's equipment now accommodates bores up to 1524 mm across and lengths beyond 2000 m [7].

Two common beliefs are contradicted by the simulator. The first is that the bit sets the drilling rate. In the sand of case 4 the drill set for speed cut at 8.32 m/min and averaged 126.0 m/h, but it outran its 100 L/min of mud, laid a bed of cuttings and broke out at 114.6 m. The second is that the deepest part of a crossing is where the mud pressure is most dangerous. On the river crossing as shipped, at 6080 s the annular pressure was 0.20 to 0.31 of the ground's limit under the river and 0.996 of it at 172.6 m on the exit climb, where the cover had thinned to 1.11 m, and the mud broke out there 14.5 s later.

However, each part of this plant has its own literature, and the parts rarely meet. The geotechnical literature treats the allowable mud pressure [4, 5, 8], the construction literature treats the industry and its practice [9, 10], the drilling literature treats the rate and its efficiency [1, 2], and design guidance treats the pipe that is pulled back afterward [11, 12]. This chapter assembles the steering, the guidance, the drilling rate, the cuttings and the mud-pressure window of one pilot bore on a single simulated electric drill, and measures which control layers a river crossing needs and why. The cavity-expansion limit, the specific energy, the rate law and the Kalman filter are established methods, and the chapter works with an implementation of them and the numbers measured on it: a fifteen-state model whose cuttings balance closes to 1.2×10^{-12} of the soil cut, a rate optimizer within 0.5 % of a dense grid, and a controller boundary that admits only instrument readings. Eight cases and a graded crossing each carry a completion rule.

Section 7.2 follows the domain. Section 7.3 sets out the model, from the path and the rate law to the mud pressure against the ground's limit and the electric bus, and Section 7.4 the rod sequencer, the guidance, the steering autopilot, the rate optimizer and the two overrides. Section 7.5 measures the cases, from one pushed rod to the graded river crossing, and Section 7.6 separates the kinds of evidence, Section 7.7 sets the loop on a real drill's hardware, Section 7.8 states the limitations, Section 7.9 concludes, and Section 7.10 holds the exercises.

7.2 Trenchless Crossings, Mud Pressure and the Pilot Bore

Horizontal directional drilling installs a product pipe in three passes, a steered pilot bore, one or more reaming passes and a pullback. How the method learned to steer and grew into an industry is told in the first history segment below. The pullback that follows the pilot has its own load estimates [12], and the design of pipelines installed by the method is the subject of an engineering society's design volume [11]. The simulator stops at the end of the pilot bore.

> ⧖ HISTORY **1960s to 2000: Learning to Steer Under a River**
>
> Early attempts at horizontal drilling in the 1960s on the West Coast of the United States had no proven way to steer the bit. A pioneer of the method learned that some tools climb toward the surface on their own and set the length of a crossing by the angle of entry and the type of bit, which gave vertical control but no horizontal steering. By 1971 downhole survey methods and drilling techniques had been brought over from oil exploration [13], and a first crossing was drilled under a river in California that year [7]. By 2000 the method was described as perhaps the fastest growing segment of trenchless construction, with 17 makers of rigs and accessories and thousands of rigs in North America, and a survey drew 49 responses from contractors in the United States and Canada [9]. Suggested practices for urban work appeared the same year [10].

The mud-pressure problem came from soil mechanics, and the second history segment below follows the cavity-expansion limit from 1972 to the step-by-step evaluation of 2008. A 2020 alignment optimization compared the drilling pressure with the allowable every 0.3 m along candidate designs and described the cavity-expansion equation known as the Delft method as the most commonly accepted formulation [14]. A newer design equation has since been proposed for sand [8]. A full-scale field experiment on four bore paths related surface heave to backream rate, cover, mud flow and reamer type [6].

The drilling rate came from the oilfield. Specific energy, the work spent per volume of rock removed, was proposed as a drilling efficiency measure in 1965 [1], and a multiple regression of drilling variables on offset-well data gave the multiplicative rate law of 1974 [2]. The simulator borrows the multiplicative form and the efficiency measure, not either paper's coefficients.

> ⧖ HISTORY **1972 to 2008: How Much Mud Pressure the Ground Holds**
>
> The expansion of a cylindrical cavity in an elastic-plastic soil was solved in general form in 1972, with the ultimate pressure set by the initial ground stress, the strength and the rigidity index, the ratio of the shear modulus to the strength [3]. Applied to a borehole, the pressure at which the plastic zone reaches an allowable radius is the largest the ground will hold. For purely cohesive ground, a 2006 analysis introduced the earth pressure at rest explicitly and found that holding the zone of shear failure to half the cover leaves a reserve of 20 to 30 % against blowout [4]. A 2008 step-by-step guide to hydrofracture evaluation called the cavity expansion model the appropriate one for most bores in soil, kept a tensile strength model for shallow rock, and paired the maximum allowable pressure with a minimum required pressure that ensures the cuttings leave the hole [5].

The electric drive is the newest element. A 2018 assessment of non-road mobile machinery found that electrification had started slowly, through hybrids of some specific machines, with component cost the main short-term barrier and electric powertrains expected to become mainstream in the long term [15]. A battery-electric drill turns the spindle, the carriage and the mud pump into three loads on one bus, which makes energy per meter a product number and power a constraint on the rate. Guidance has changed in the same direction. In conventional practice the beacon behind the bit reports its pitch and roll to a walkover locator, and a drill whose console receives the beacon's data directly (integrated guidance) still needs the locator for depth wherever the surface can be walked. The console's estimate is then a filtering problem [16], as it is for the survey vehicle of Volume 5, Chapter 13, which dead reckons between sparse acoustic fixes.

7.3 The Crossing as Modeled

The simulated drill is a generic mid-size, battery-electric, rack-and-pinion utility drill with 180 kN of thrust and pullback, a 7.5 kN m spindle on a 90 kW motor from 0 to 220 rpm, a mud pump of 380 L/min at 8 MPa, 3 m rods of 60 mm outside and 44 mm inside diameter, and a 115 mm slant-face pilot bit with the beacon housing behind it. A 150 kWh battery and a 40 kW charger feed a 120 kW inverter. Every value is a teaching value of that class and none is a maker's figure. The river crossing, shown in Figure 7.1, runs 180 m from the entry at station $x = 0$ down a -14 % tangent, through a sag bend of radius 90 m to a horizontal 8 m deep, under a river from 55 to 120 m whose bed lies 3.5 m down, and up a $+12$ % exit tangent. The ground is a soft silty clay cap 1.5 m thick on land over stiff clay, sand from 58 m, a gravel lens from 124 to 146 m and sand again, with the water table 1.5 m down. Units are meters, seconds, newtons and pascals. The console shows US field units by default, and its unit switch selects the SI units in which the exercises of this chapter are stated.

Each variable in Table 7.1 carries its role. Fifteen states are integrated. Six are the path, the drilled length s, the position (x, z, y), the pitch θ (nose-up positive) and the azimuth ψ. Four are the annulus, the soil fraction of the returns C, its product with the required mud ratio C_R, the bed B and the soil returned to the pit. Two are the battery energy E and the energy drawn, and three are the lagged spindle, pump and carriage commands.

7.3.1 The Path and How a Slant Face Steers

The bore advances along its own length at the drilling rate, as shown in Equation (7.1).

$$\frac{\mathrm{d}x}{\mathrm{d}s} = \cos\theta\cos\psi, \quad \frac{\mathrm{d}z}{\mathrm{d}s} = \sin\theta, \quad \frac{\mathrm{d}y}{\mathrm{d}s} = \cos\theta\sin\psi$$
$$\frac{\mathrm{d}\theta}{\mathrm{d}s} = \begin{cases} \kappa_s\cos\varphi & \text{pushed at } \varphi \\ -\kappa_d & \text{rotated} \end{cases} \qquad \frac{\mathrm{d}\psi}{\mathrm{d}s} = \frac{\kappa_s\sin\varphi \text{ or } \kappa_w}{\max(0.2, \cos\theta)} \tag{7.1}$$

where $\frac{\mathrm{d}s}{\mathrm{d}t} = \mathrm{ROP}$, κ_s is the soil's push curvature, κ_d its droop and κ_w its walk while rotating, and $\varphi = 0$ is 12 o'clock. A push fraction d of a rod is pushed and the rest rotated, so the rod's mean

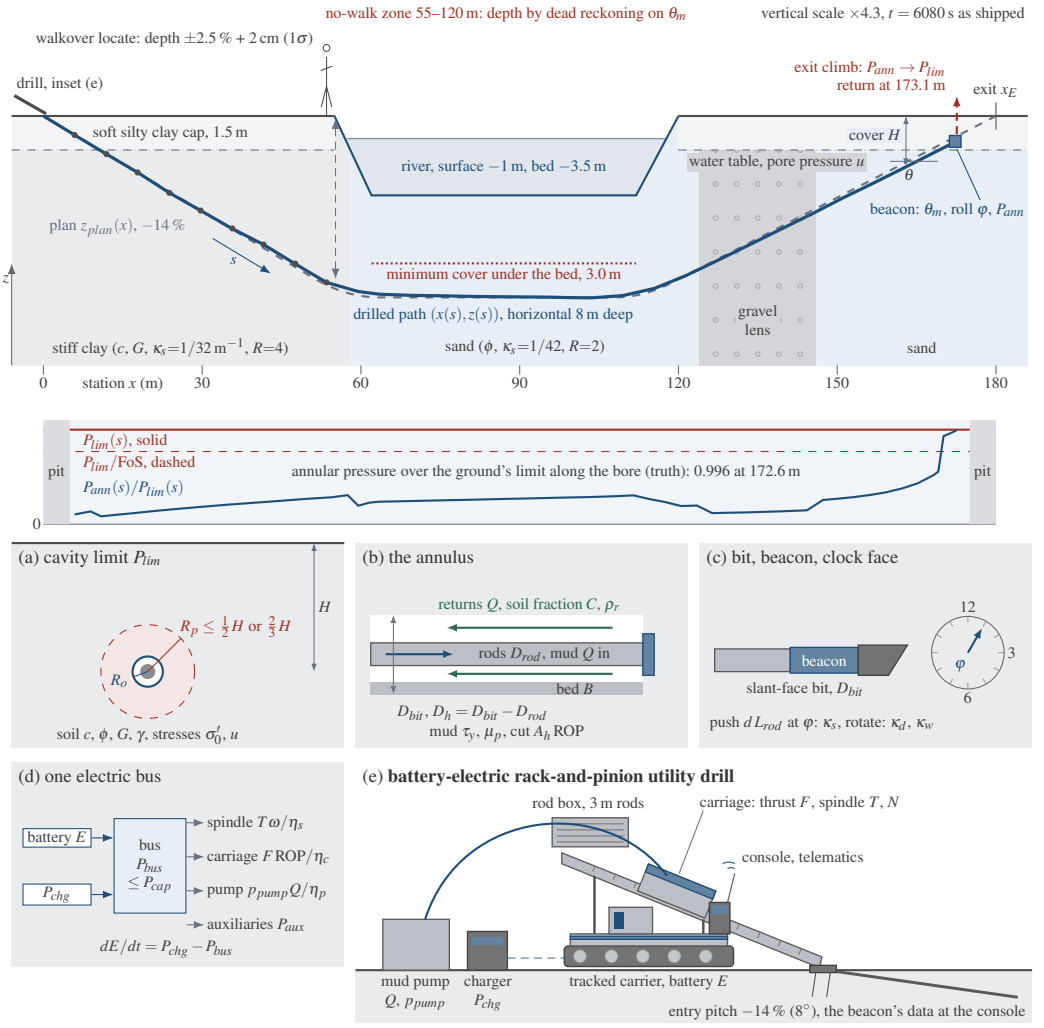


Figure 7.1 The river crossing as modeled, mirroring the simulator's Section view at $t = 6080$ s as shipped. The drill at the entry pushes rods along the drilled length s through soils of strength c, ϕ, G, γ and push curvature κ_s, on a path (x, z) of pitch θ (thick solid) against the plan z_{plan} (dashed), with locates on land (dots) and none over the river. The beacon reports θ_m, the roll φ and the annular pressure P_{ann}, and the strip under the section shows P_{ann}/P_{lim} along the bore against P_{lim} (solid) and P_{lim}/FoS (dashed), 0.996 at 172.6 m on the exit climb where the cover H is thin. Insets: (a) the cavity of radius R_o and its allowable plastic radius R_p (dashed circle), (b) the annulus with returns of soil fraction C over a bed B, (c) the bit, beacon and clock face, (d) the bus, (e) the drill at the entry, drawn at its own scale. The lateral offset y and azimuth ψ lie normal to the page. Not to scale.

curvature is about $d\kappa_s$. The console shows the pitch as $100 \tan\theta$ in percent. A rod whose curvature passes $1/R_{min}$, with a teaching bend radius of 30 m, counts as bent past its radius. At that radius a 3 m rod turns 5.73°, 10.03 points of pitch from level and 10.09 from −14 %, while the stiff clay's $\kappa_s = 1/32\,\text{m}^{-1}$ gives 9.47 points by hand from −14.2 % against the 9.40 measured in case 1, the difference being the 5 s spent turning the face before the push.

Table 7.1 Variables by Role, With Their Ranges

Variable	Role	Range or default	Unit
$z - z_{plan}$, x_{exit}	CV, path and exit	exit ±1.0	m
ROP, average rate	objective	—	m/min, m/h
P_{ann}/P_{lim}	constraint (truth)	$\leq 1/\text{FoS}$	—
T, P_{bus}, C	constraints	85 %, cap, ratio	—
d, φ	MV, push, clock face	0–100 %, 24	—
F	MV, carriage thrust	0–180 (100)	kN
N	MV, spindle speed	0–220 (100)	rpm
Q	MV, mud flow	0–380 (120)	L/min
soil, boundaries	DV, geology	clay to soft rock	—
b	DV, beacon pitch bias	±2 (0)	%
cobble, pump, power	DV, events	—	—
s, x, z, y	states, path	0–190	m
θ, ψ	states, pitch, azimuth	—	rad
C, C_R, B	states, annulus	≥ 0, $B \leq 0.6$	—
E	state, battery	0–150	kWh
θ_m, φ_m, $P_{ann,m}$	beacon, 1 Hz	0.1 %, 24, 1 kPa	—
depth, offset	walkover locate	2.5 % + 2 or 5 cm	m

7.3.2 Drilling Rate, Torque and the Drive

The rate saturates in the thrust that reaches the bit and has a best spindle speed past which the face balls in clay or washes in sand, in the multiplicative spirit of the oilfield rate laws [2], as shown in Equation (7.2).

$$\begin{aligned} \text{ROP}_{rot} &= K\left(1 - \mathrm{e}^{-F_b/F_s}\right)\left[\frac{N}{N_f}\,\mathrm{e}^{1-N/N_f}\right]^{\gamma} f_{pk} \\ \text{ROP}_{push} &= \min(K_p F_b,\ K)\, f_{pk} \\ f_{pk} &= \left[1 + (B/0.25)^2\right]^{-1} \\ F_b &= F - c_{rot}\left(\mu_r w_b L + \sum d_L \Delta s\right)\mathrm{e}^{\mu_r \Theta} \end{aligned} \tag{7.2}$$

where $\gamma = 0.6$, $L = s$ is the string length, w_b the rod's buoyed weight per meter, $\mu_r = 0.3$ its axial friction, d_L the soil's drag per meter of hole, Θ the total turn of the path so far (a capstan factor), and $c_{rot} = 0.15$ while the string rotates and 1 while it is pushed. The spindle torque and the drive's limits are given by Equation (7.3).

$$\begin{aligned} T &= T_0 + \mu F_b r_e + \sum t_L \Delta s + c_v\, \omega L + k_{pk} B L \\ \omega &= \max\left\{\omega' \leq \omega_{ref} : T(\omega') \leq T_{rated},\right. \\ &\qquad \left. T(\omega')\,\omega' \leq \min(P_{sp},\ \eta_s P_{left})\right\} \end{aligned} \tag{7.3}$$

where $\omega = 2\pi N$, r_e is two thirds of the bit radius, t_L the soil's string torque per meter, ω_{ref} the drive's ramped reference (a 2 s lag), and P_{left} the bus power left after the pump and the carriage. The motor's 90 kW meets the 7.5 kN m rating at 114.6 rpm, and a torque over the rating at standstill stalls the spindle. A cobble adds 1500 N m for 0.3 m and knocks the head 0.4 to 0.8° in pitch.

7.3.3 Cuttings, the Bed and the Mud Ratio

The annulus between the rods and the hole, of area A_{ann} and volume $V = A_{ann}\max(3, s)$, is one well-mixed volume. The bit cuts A_hROP of soil, the mud carries a soil fraction up to $C_{cap} = \eta/(1 + R_{mix})$ with $\eta = v/(v + v_{set})$ and $v = Q/A_{ann}$, and what it cannot carry settles into a bed that clean mud

erodes slowly, as shown in Equation (7.4).

$$\begin{aligned} V\frac{\mathrm{d}C}{\mathrm{d}t} &= A_h\mathrm{ROP} - C(Q + A_h\mathrm{ROP}) - V\,r_b \\ V\frac{\mathrm{d}C_R}{\mathrm{d}t} &= RA_h\mathrm{ROP} - C_R(Q + A_h\mathrm{ROP}) - V\,r_b R_{mix} \\ V\frac{\mathrm{d}B}{\mathrm{d}t} &= V\,r_b - BA_{ann}\mathrm{ROP} \\ r_b &= k_d\,g(Q)(C - C_{cap})^+ - k_e\frac{Q}{V}B\left(1 - \frac{C}{C_{cap}}\right)^+ \end{aligned} \tag{7.4}$$

where R is the required mud-to-soil volume ratio of the soil at the bit, $R_{mix} = C_R/C$ that of the soil the returns carry, $k_d = 1/30\,\mathrm{s}^{-1}$, $k_e = 0.3$, and $g(Q)$ rises from 0 at 30 L/min to 1 at 60 L/min, so the mud's gel holds what it carries while the pump stops and starts. The bed is capped at 0.6. The soil leaving at the pit is $C(Q + A_r\mathrm{ROP})$, which closes the balance.

7.3.4 The Annular Pressure and the Ground's Limit

The mud pressure at a node i of the path, kept every 0.5 m of drilled length, is the weight of the returns below the entry pit plus the friction of the annulus between the node and the pit, as shown in Equation (7.5).

$$\begin{aligned} P_i &= \rho_r g\,(z_{pit} - z_i) + G_f\,s_i, \qquad \rho_r = \rho_m + C(\rho_s - \rho_m) \\ G_f &= \left[\frac{6\tau_y}{D_h} + \frac{48\mu_p v}{D_h^2}\right]\frac{1 + a_s C}{(1 - B)^3} \end{aligned} \tag{7.5}$$

where $D_h = D_{bit} - D_{rod} = 55\,\mathrm{mm}$, $\tau_y = 4\,\mathrm{Pa}$, $\mu_p = 12\,\mathrm{mPa\,s}$ and $a_s = 2$. The bracket is the laminar Bingham slot form of drilling hydraulics, and at 115 L/min its yield term gives 436 of the 485 Pa/m, so less flow barely lowers the friction. The bed's cubic factor is a teaching closure that makes a pack-off felt. Because every node carries the friction of all the annulus behind it, the pressure grows with the bore's length. The ground's limit at each node is the Delft cavity-expansion pressure [3, 14], as shown in Equation (7.6).

$$\begin{aligned} P_{lim} &= u + (p'_f + c\cot\phi)\,X^{-\sin\phi/(1+\sin\phi)} - c\cot\phi \\ X &= \left(\frac{R_o}{R_p}\right)^2 + \frac{\sigma'_0\sin\phi + c\cos\phi}{G}, \quad R_p = r_p H \\ p'_f &= \sigma'_0(1 + \sin\phi) + c\cos\phi \\ P_{lim}\big|_{\phi\to 0} &= \sigma_0 + c_u\left[1 + \ln\frac{1}{(R_o/R_p)^2 + c_u/G}\right] \end{aligned} \tag{7.6}$$

where $R_o = 57.5\,\mathrm{mm}$ is the hole's radius, H the cover, σ_0 the total vertical stress (the river's water included), u the pore pressure from the local water table and $\sigma'_0 = \sigma_0 - u$. The allowable plastic radius $r_p H$ is half the cover in cohesive ground, the fraction the cohesive analysis supports [4], and two thirds in granular ground, both teaching values. The far field is taken as isotropic ($K_0 = 1$). An inadvertent return occurs when $P_i > P_{lim,i}$ at any node outside the 5 m pits at each end. It is latched, and the vent fixes the pressure of the nodes beyond it from then on. A return under the river stops the crossing.

7.3.5 The Electric Bus and the Rod Cycle

The three drives draw from one bus, the pump first, then the carriage, and the spindle gets the rest, a fixed priority in the sense of Section 1.4.8, as shown in Equation (7.7).

$$\begin{aligned} P_{bus} &= \frac{T\,\omega}{\eta_s} + \frac{F\,\mathrm{ROP}}{\eta_c} + \frac{p_{pump} Q}{\eta_p} + P_{aux} \le P_{cap} \\ P_{cap} &= \min(P_{inv},\; P_{chg} + P_{batt}), \qquad \frac{\mathrm{d}E}{\mathrm{d}t} = P_{chg} - P_{bus} \\ p_{pump} &= f_{in}(Q, L) + k_n Q^2 + P_{bit} \le 8\,\mathrm{MPa} \end{aligned} \tag{7.7}$$

where $\eta_s = 0.90$, $\eta_c = 0.85$, $\eta_p = 0.80$, $P_{aux} = 3\,\mathrm{kW}$, $P_{batt} = 100\,\mathrm{kW}$ and f_{in} is the turbulent loss inside the rods. The bit's jets alone pass 170 L/min at 8 MPa and 168.1 L/min with 180 m of rods, so the pump's 380 L/min rating is never usable with this bit. Without the battery the cap is the charger's 40 kW, and the battery is the depleting stock of Section 1.4.9. The rod cycle is the forced periodic stop. When 3 m of a rod is in, thrust and rotation stop (4 s), the rod is changed with the pump off (42 s), and the pump restarts (4 s), so every rod costs 50 s, and turning the face before a push costs another 5 s.

7.3.6 The Instruments

The drill measures its own drilled length exactly, the thrust, the spindle speed, the torque with 1 % colored noise, the flow, the pump pressure and the bus. The beacon reports once a second the pitch rounded to 0.1 % with a declared bias b and 0.05 % of colored noise, the roll in 24 clock positions, and the annular pressure at the head rounded to 1 kPa with 2 kPa of noise, and an interference event holds its last readings for 60 s. A walkover locate is sampled when a rod change starts wherever the surface can be walked and reported 25 s later, depth with a standard deviation of 2.5 % of the depth plus 2 cm and the lateral offset with 2.5 % plus 5 cm. None is taken over a road or a river, and past one only when far-side locates are switched on. The beacon gives no azimuth. True quantities are logged with a `truth_` prefix and drawn dashed, and a source test confirms that no controller file reads one.

7.3.7 Soils, Parameters and Numerics

Table 7.2 gives the five soils and Table 7.3 the drill and mud. Each soil was calibrated so that it hands the rate to its intended limit, and every value is a teaching value whose real counterpart comes from the site investigation. The plant is integrated by a fourth-order Runge-Kutta step of 0.5 s with everything that changes discretely (the soil at the bit, the path's sums, the pump's pressure ceiling) frozen over the step, and each step is cut exactly at the end of a push and of a rod's stroke. Control decisions are made each second, and a row is logged every two seconds (Section 1.6.1).

7.3.8 Assumptions

The annulus is one well-mixed volume with one bed, so a real pack-off, which is local and can be sudden, is spread over the whole hole. The friction is the laminar Bingham slot form with a fixed yield point, and the bed's cubic factor overstates what a narrowed slot does to a yield-dominated friction, which would scale as $(1 - B)^{-1}$. Each soil steers at one curvature and drills by one law, boundaries are sharp, and a slant face's deflection does not depend on its angle, the thrust or the jets. The cavity limit assumes an isotropic far field, one homogeneous soil at each node and a circular plastic zone, so layering, a free face near the exit and fractures, which all lower a real limit, are absent. No mud is lost into permeable ground. The rod's 8.5 kg/m is lighter than a plain 60/44 mm steel tube's 10.3 kg/m, which changes the string's axial friction at 180 m from 3.90 to 4.71 kN, under 0.5 % of the rating. The bus has fixed efficiencies and no battery ageing or charger losses. The safety numbers (the factor of safety 1.3, the allowable plastic radius, the 3.0 m minimum cover under the river, the 90 % torque limit, the 30 m bend radius) are teaching values. The real ones come from

Table 7.2 The Five Soils (Teaching Values)

	cap	clay	sand	gravel	rock	unit
K	3.0	3.0	11.0	5.5	1.2	m/min
F_s	45	60	35	150	160	kN
N_f	120	110	160	120	150	rpm
K_p	1.4	1.2	2.6	0.8	0.03	m/min per 100 kN
μ	0.85	1.10	0.35	0.65	0.90	—
t_L, d_L	12, 70	16, 80	7, 90	11, 250	9, 40	N m/m, N/m
$1/\kappa_s$	22	32	42	70	2000	m
$1/\kappa_d$	1400	2000	1500	—	—	m
$1/\kappa_w$	—	—	20000	2500	—	m
R	3.5	4.0[a]	2.0[a]	2.5[a]	1.5	—
v_{set}	0.012	0.010	0.045	0.090	0.060	m/s
c	30	60	0	0	400	kPa
ϕ	0	0	33	38	30	°
G	4.5	9	15	40	300	MPa
γ	18.5	19.5	19.5	20.5	22.5	kN/m^3
r_p	1/2	1/2	2/3	2/3	2/3	of cover

[a] Adjustable in the Model dialog.

Table 7.3 Drill, Mud, Guidance and Controller Parameters. A = Adjustable in the Model Dialog, T = Teaching Value, D = Derived

Symbol	Meaning	Value	Unit	Status
F_{max}	thrust rating	180	kN	T
T_{rated}, P_{sp}	spindle torque, motor	7.5, 90	kN m, kW	T
N_{max}	spindle speed range	220	rpm	T
Q_{rated}, p_{max}	pump	380, 8	L/min, MPa	T
k_n	bit jets, $\Delta p = k_n Q^2$	1×10^{12}	Pa s^2/m^6	T
L_{rod}, D_{rod}, d_{rod}	rod length, diameters	3.0, 60, 44	m, mm	T
w_{rod}	rod mass per meter	8.5	kg/m	T
R_{min}	rod bend radius	30	m	A
D_{bit}, r_e	bit, torque arm	115, 38.3	mm	T, D
T_0, c_v, k_{pk}	torque terms	150, 0.3, 30	SI	T
μ_r, c_{rot}	string friction, rotation cut	0.3, 0.15	—	T
τ_N, τ_Q, τ_F	drive lags	2, 1.5, 1	s	T
E_{max}, P_{chg}	battery, charger	150, 40	kWh, kW	T, A
P_{inv}, P_{batt}	inverter, battery power	120, 100	kW	A, T
η_s, η_c, η_p	drive efficiencies	0.90, 0.85, 0.80	—	T
t_{rod}	rod change, stop to restart	50	s	A
ρ_m, ρ_s	mud, soil density	1050, 2000	kg/m^3	T
τ_y, μ_p	yield point, plastic viscosity	4, 0.012	Pa, Pa s	A, T
a_s, B_{max}	solids factor, bed cap	2, 0.6	—	T
k_d, k_e	settling, erosion	1/30, 0.3	s^{-1}, —	T
FoS	factor of safety on P_{lim}	1.3	—	A
pits	returns expected	5	m	T
σ_{loc}	locate depth accuracy	2.5 % + 0.02	m	A
t_{loc}	locate report delay	25	s	T
q_z, q_b	depth, bias filter noise	1×10^{-4}, 1×10^{-10}	per m	T
q_y, q_ψ	lateral, azimuth filter noise	1×10^{-4}, 2×10^{-6}	per m	T
L_a	autopilot look-ahead	9	m	A
T_{opt}	optimizer period	10	s	A
T_{cap}	optimizer torque ceiling	85	%	A
m	mud-ratio margin	10	%	T
r_{ov}, F_{rel}	override target, release	0.97, 20	—, kN	T
limits	torque, cover, exit, time	90 %, 3, 1, 2.75	m, h	T

the crossing's design report and permit, the hydrofracture evaluation [5], the drill maker's operating limits and the rod maker's specification, and a simulated pass is not a design or a permit.

7.4 Sequencer, Guidance, Autopilot and Optimizer as Coded

Every layer runs each $\Delta t_c = 1\,\mathrm{s}$ from the measurement packet, the declared geotechnical log and the bore plan. The log has the same soils and boundaries as the ground unless a case moves a true boundary earlier.

7.4.1 The Rod Sequencer and the Guidance

The sequencer reads only the drilled length and steps through drill, stop, change and start. At each start it takes the next rod's push fraction d and clock face φ from the operator or the autopilot. The console's position is dead reckoned from the measured pitch for every meter drilled, and three guidance modes differ in how a locate enters, as shown in Equation (7.8).

$$\begin{aligned} \hat{z}^{+} &= \hat{z} + \Delta s\,\sin(\theta_m - \hat{b}) \\ \hat{\psi}^{+} &= \hat{\psi} + \frac{\kappa_{log}\,\Delta s_{push}\,\sin\varphi}{\max(0.2, \cos\theta_m)} \\ \begin{bmatrix} \hat{z} \\ \hat{b} \end{bmatrix}^{+} &= \begin{bmatrix} \hat{z} \\ \hat{b} \end{bmatrix} + \mathbf{K}\,(z_{loc} - \hat{z}), \qquad \mathbf{K} = \frac{\mathbf{P}\mathbf{h}^{\top}}{\mathbf{h}\mathbf{P}\mathbf{h}^{\top} + \sigma_{loc}^{2}} \end{aligned} \tag{7.8}$$

where $\mathbf{h} = [1\ 0]$ and the covariance grows with $\partial\hat{z}^{+}/\partial\hat{b} = -\Delta s\cos\theta_m$ and the process noise of Table 7.3. Dead reckoning ignores the locates and keeps $\hat{b} = 0$. The walkover practice (Locate reset) replaces $\hat{z}$ and $\hat{y}$ at each locate. The estimator is two two-state Kalman filters [16], one on depth and pitch bias and one on lateral offset and azimuth, started with a pitch-bias standard deviation of 1 %. A constant pitch bias b in percent grows a depth error of $b\cos^{3}\theta$ per meter, 1.000 cm/m level and 0.973 cm/m at -14 %, so a learned bias carries the depth across a reach nobody can walk.

7.4.2 The Steering Autopilot

At each rod start the autopilot aims at the plan a look-ahead L_a ahead of the console's head, in the manner of pure-pursuit path tracking, as shown in Equation (7.9).

$$\begin{aligned} \alpha_v &= \operatorname{atan}\frac{z_{plan}(\hat{x} + L_a) - \hat{z}}{L_a} - \hat{\theta}, \quad \alpha_h = \operatorname{atan}\frac{-\hat{y}}{L_a} - \hat{\psi} \\ \mathbf{t} &= \left(\frac{2\sin\alpha_v}{L_a} + \kappa_d,\ \frac{2\sin\alpha_h}{L_a} - \kappa_w\right), \quad \varphi = \operatorname{atan2}(t_h, t_v) \\ d &= \min\left(\frac{|\mathbf{t}|}{\kappa_s},\ \frac{0.9}{R_{min}\,\kappa_s},\ 1\right) \end{aligned} \tag{7.9}$$

where the clock face is rounded to 24 positions, a push fraction under 8 % becomes a rotated rod, and the soil's curvatures come from the log. Where the soil gives no authority ($\kappa_s < 1/500\,\mathrm{m}^{-1}$) the autopilot rotates and reports that it is short of steering authority instead of pushing a rod that would only drill slower.

7.4.3 The Soil Read and the Rate Optimizer

With the bit rotating and cutting, the measured specific energy [1] is compared with each soil's model at the same thrust and speed, as shown in Equation (7.10).

$$\begin{aligned} \mathrm{MSE} &= \frac{F_b}{A_h} + \frac{2\pi N T}{A_h\,\mathrm{ROP}} \\ \mathrm{score}_j &= \left\langle \left| \ln\frac{\mathrm{MSE}}{\mathrm{MSE}_j} \right| \right\rangle_{15\,\mathrm{s}} + 0.25\,[j \neq j_{log}] \end{aligned} \tag{7.10}$$

where the candidates are the soils the log shows within 12 m of the head and the reading changes only on an improvement of 0.15. Every $T_{opt} = 10\,\mathrm{s}$ the optimizer then solves the problem of Equation (7.11)

for the soil it reads.

$$\begin{aligned} &\max_{F,N,Q} \ \mathrm{ROP}(F,N) \\ &\text{s.t. } T + T_b \le 0.85 \min(T_{rated},\ P_{sp}/\omega) \\ &\quad P_{bus} \le 0.97 P_{cap}, \quad F \le F_{max} \\ &\quad \frac{A_h \mathrm{ROP}}{Q + A_h \mathrm{ROP}} \le (1-m)\frac{\eta(Q)}{1+R}, \quad p_{pump} \le 8\,\mathrm{MPa} \\ &\quad \rho_r g (z_{pit} - \hat{z}_i) + \kappa_f G_f(Q, C_b)\, s_i \le \frac{P_{lim,i}}{\mathrm{FoS}} \ \ \forall i \end{aligned} \tag{7.11}$$

where the nodes i are every point of the console's path outside the pits and twelve points every 0.5 m up to 6 m ahead on the plan, C_b is the larger of the steady returns and a cuttings observer's estimate (the plant's balance driven by the measured rate and flow), and the load ahead relaxes from the observer's value toward the steady one over the time the bit takes to get there. The friction factor κ_f and the torque offset T_b are learned by the framework's shared bias updater from the beacon's annular pressure and the measured torque, and the bit's torque is taken at the stickiest soil the log shows over the next rod. The search is a $19 \times 15 \times 8$ grid over thrust, speed and flow followed by a pattern search that halves its steps seven times, and among points within 0.3 % of the best rate it keeps the one with the least bus power. When the best point is held by the pressure at less than 97 % of the full flow, the optimizer drills at the full flow instead, or circulates there if no rate is legal, because less flow lowers the yield-dominated friction only slightly and leaves the cuttings in the hole. The binding constraint is the one with the highest use at the chosen point, at least 0.97, the active constraint of Section 1.4.2. The torque ceiling of 85 %, the factor 0.97 on the bus, the margin m on the mud ratio and the factor of safety on the pressure are back-offs in the sense of that section, each paid in rate.

7.4.4 Overrides, the Soft Start and the Three Models

Two min-select overrides act on the thrust with external reset, each an integrator on the request actually in force [17] (Sections 1.4.3 and 1.4.4), as shown in Equation (7.12). Chapter 11 builds the limits on its advance the same way.

$$\begin{aligned} \dot{F}_{ov} &= -0.25 F_{max} \frac{\hat{r} - 0.97}{0.03} \\ \hat{r} &= \max_i \frac{\rho_r g (z_{pit} - \hat{z}_i) + \hat{G} s_i}{P_{lim,i}/\mathrm{FoS}} \\ \dot{F}_{tq} &= -0.5 F_{max} \frac{T_m/T_c - 1}{0.02} \quad (\times 0.2 \text{ recovering}) \\ F_{cmd} &= \min(F_{req},\ F_{ov},\ F_{tq},\ F_{max}) \end{aligned} \tag{7.12}$$

where $\hat{G}$ is the gradient the measured head pressure implies over the drilled length, T_c is the torque ceiling at the present speed, and each limit snaps back to the request once it is clear. The pressure override takes thrust off and keeps the mud flowing. In Auto the thrust command climbs at 40 kN/s whenever rotation or a push starts, and after a push the spindle waits until the measured thrust has fallen under 20 kN, so a bit still loaded with the push's thrust never starts against the torque rating. The plant model is Section 7.3. The controller's model is the declared soil table, the log and the plan, which does not know the soil at the bit, the bed or the friction and torque offsets except through what it learns. No model predictive controller was built, so the app does not offer the option of Section 1.6.3. The rate problem is solved again every 10 s on a steady evaluator, and the time of a crossing is set by the rod changes and the pressure window.

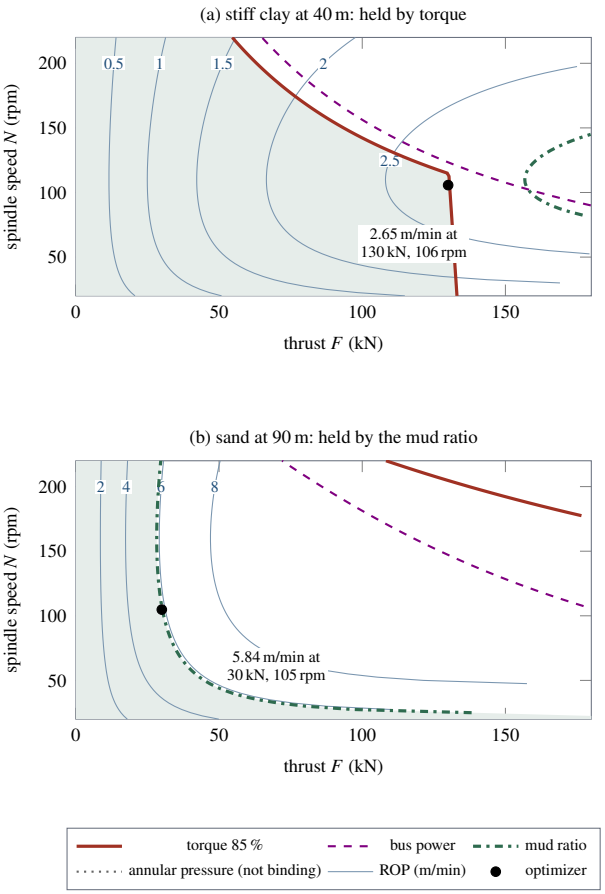


Figure 7.2 The optimizer's rate map on the river crossing with the suggested settings, from the app's own evaluator at the optimizer's flow (137 L/min in the clay, 167 L/min in the sand). Shaded points are legal, thin lines are contours of the rate, the dot is the optimizer's point, and the limits are the torque ceiling (very thick solid), the bus power (dashed) and the mud ratio (very thick dash-dotted). In the stiff clay at 40 m the torque ceiling holds the best point, and in the sand at 90 m the mud ratio does, an edge that is itself a contour of the rate.

7.5 What the Nine Runs Show

The cases appear in Table 7.4. All figures in this section come from the engine of Section 1.6.1 stepped without a browser at the default seed and the app's 0.5 s step. A setting that a sentence changes was entered before the run began, and loading a case first, choosing it from the list after another case, or pressing Reset gives the same run.

7.5.1 Steering by the Rod and Finding the Head

Rotated, the first two rods of case 1 held the pitch within 0.3 point and the rod after the push within 0.2. Left rotating throughout, the bore stayed at −14 % and was 2.96 m under the plan at 25 m, while left on Push it surfaced at 14.3 m after four rod changes. In case 2 the look-ahead is the steering loop's gain, as listed in Table 7.5. Aiming 9 m ahead, the autopilot reached the exit 0.15 m from the target in 0.80 h, never more than 0.18 m off the plan, with 14 of 20 rods pushed. Aiming 3 m ahead it held within 0.11 m but pushed 17 of 19 rods, took 1.04 h and came out 0.90 m off, and at 25 m it cut the bends, 0.59 m off the plan and 1.79 m off at the exit.

Table 7.4 The Cases, as Shipped. The App Lists Case 9 as the Challenge

#	Site and settings	Teaching point
1	30 m driveway, stiff clay, Manual, rotating	rotate to go, push to steer
2	60 m lawn, clay, Manual, then the autopilot in Auto	following a plan
3	66 m road, no walking 21–45 m, 1 % pitch bias, Locate reset	dead reckoning, the estimator
4	120 m of sand from 34 m, 100 kN, 120 rpm, 100 L/min	the mud-ratio edge
5	150 m, clay, sand from 52, gravel from 104 m, clay settings	the binding limit moves
6	160 m from 100 m, loaded annulus, 120 kN, 120 rpm, 100 L/min	pressure override
7	90 m of clay, battery out, 40 kW	the shared bus
8	70 m, cobbles, soft rock from 17 m under the sag bend	infeasible steering
9	180 m river, clay's 125 kN, 110 rpm, 115 L/min, Locate reset, no far-side locates, 0.3 % bias	the whole problem

Table 7.5 Measured Results on the Cases. Average Rate Includes Every Rod Change

Case	Setting	Rate (m/h)	Other
2	look-ahead 9 m	75.3	exit 0.15 m, off plan 0.18 m
	look-ahead 3 m	57.1	exit 0.90 m, off plan 0.11 m
	look-ahead 25 m	76.5	exit 1.79 m, off plan 0.59 m
3	Locate reset (shipped)	74.8	depth error 0.246 m, exit 0.49 m
	estimator	75.7	depth error 0.141 m, exit 0.37 m
	dead reckoning	77.8	0.494 m at 50 m, exit 5.39 m
4	set for speed (shipped)	126.0	return at 114.6 m
	optimizer	108.4	worst ratio 0.71
	20 kN, 60 rpm	55.2	worst ratio 0.67
5	clay settings (shipped)	87.6	worst ratio 0.84
	optimizer	93.8	worst ratio 0.73
6	shipped	105.9	return at 149.8 m
	pressure override	44.2	worst 0.77, acting 54.6 min
	optimizer, override Off	76.6	worst 0.76
	optimizer and override	66.6	worst 0.74
	150 L/min	111.3	return at 154.8 m
7	shipped, 40 kW	68.5	37 rpm, 0.348 kWh/m
	optimizer	72.6	101 L/min, 0.312 kWh/m
	battery On	76.3	96 rpm, 0.505 kWh/m
8	shipped	48.7	1.50 m off plan at 39.2 m

Pause. Try Exercise 7.1 before reading on.

Under the road of case 3 the last locate before the road came at 20.8 m and the first after it at 47.8 m, 27.0 m of drilling later. With Locate reset the console was 0.246 m off the truth just before that locate, which brought it to 0.010 m. The estimator learned a bias of 0.90 % from the locates before the road and was never more than 0.141 m off, and dead reckoning alone drifted 0.494 m by 50 m and exited 5.39 m from the target. On seeds 1 and 2 the worst errors were 0.367 and 0.405 m with Locate reset against 0.064 and 0.074 m with the estimator, so the estimator's advantage is real but its size depends on the noise of the locates that taught it.

7.5.2 The Rate and the Limit That Holds It

In the sand of case 4 the drill set for speed cut at 8.32 m/min on the level run at 100 L/min, built a bed to 0.110 of the annulus and broke out at 114.6 m, just short of the exit pit. The optimizer opened the flow to the jets' limit of 168 L/min, slowed the bit to 5.36 m/min on the mud-ratio edge, and averaged 108.4 m/h with no return. It was held by the mud for 948 s of its drilling and by the pressure for 377 s on the climb to the shallow exit. Because the mud constraint bounds the returns' soil fraction, it bounds the rate itself, ROP $\le Qc/[A_h(1-c)]$ with $c=(1-m)\eta/(1+R)$, which at 167 L/min in sand is 5.86 m/min whatever the thrust or speed, as shown in Figure 7.2b. The shipped bit cut 55 % faster than the optimizer's on the level run and averaged only 16 % more, because the 50 s rod change dominates a fast rod.

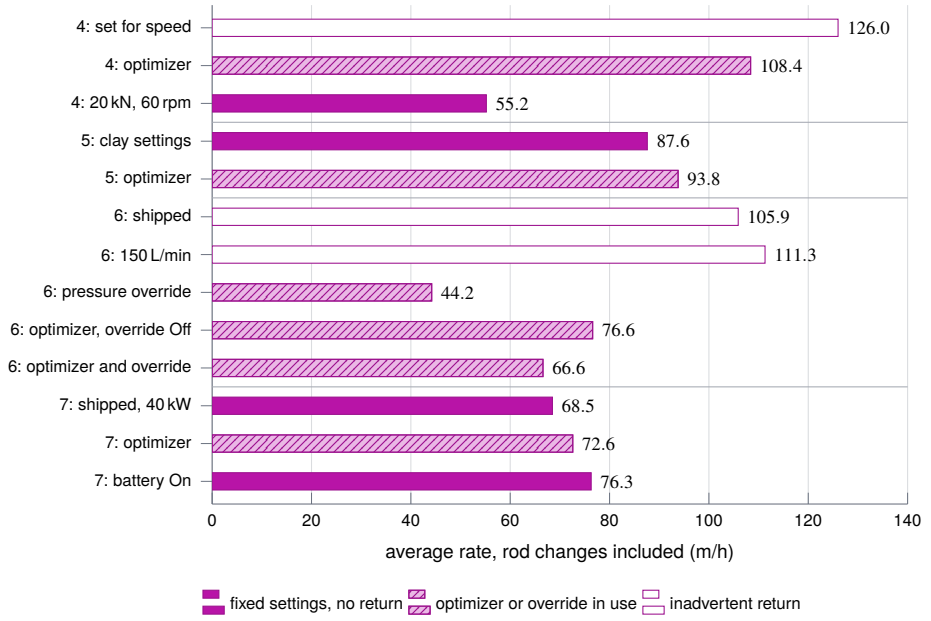


Figure 7.3 Average rates of cases 4 to 7 from Table 7.5, grouped by case (thin rules). White bars broke out, hatched bars ran with the rate optimizer or the pressure override. Notice that the fastest bar of cases 4 and 6 is a run that broke out, and that the override alone is the slowest way through case 6.

Pause. Try Exercise 7.2 before reading on.

In case 5 the limit moved with the soil, as the optimum of the data hall in Volume 9, Chapter 8 moves with the weather. With the optimizer the clay ran at 2.55 m/min held by the torque for 99 % of its drilling, the sand at 5.53 m/min held by the mud ratio for 97 %, and the gravel at 3.17 m/min held by the thrust for 64 %. The fixed clay settings drove the sand at 8.66 m/min, past its mud, and the gravel at 2.58 m/min, short of its thrust, and averaged 87.6 m/h against 93.8 m/h with a worst pressure ratio of 0.84 against 0.73. On the river crossing the same search, checked against a dense $61 \times 51 \times 24$ grid, found 2.65 m/min in the clay at 40 m held by torque and 5.84 m/min in the sand at 90 m held by the mud, as shown in Figure 7.2.

> **TRY IT IN THE APP** **5 · The Soils Change, and So Does the Limit**
>
> Load the scenario, set Rate optimizer to On, press Reset and Run on the Map view. Watch the Drilling rate card name the limit that holds the optimizer. It reads torque in the clay, the mud ratio in the sand and thrust in the gravel, as the outlines on the map change with the soil.

On the 40 kW shore supply of case 7 the bus held the spindle at about 37 rpm for 96 % of the rotating time, and the bore averaged 68.5 m/h. The optimizer cut the flow from 120 to 101 L/min, which the clay's mud ratio still allowed, raised the thrust from 97 to 114 kN, turned at 35 rpm and made 72.6 m/h, held by the bus for 1730 s and the mud for 899 s. With the battery the same fixed settings made 76.3 m/h at 96 rpm and 75.1 kW, at 0.505 kWh/m against 0.312 kWh/m for the optimizer on shore power. Figure 7.3 sets the rates of cases 4 to 7 side by side.

7.5.3 The Pressure Window and the Override

The annular pressure of the river crossing grows along the bore while the limit follows the cover, as shown in Figure 7.4. At 6080 s as shipped, with a bed of 0.074 and returns of soil fraction 0.244

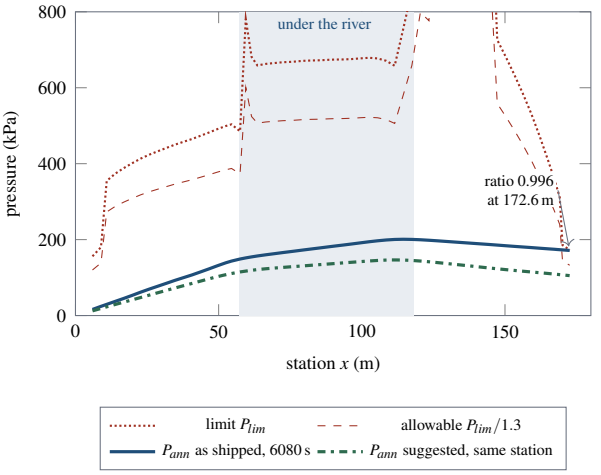


Figure 7.4 Annular pressure along the river crossing against the Delft limit (dotted) and the allowable (dashed), with the head at 172.6 m. As shipped (6080 s, very thick solid) the loaded annulus reaches 0.996 of the limit in the soft cap of the exit climb, and the mud breaks out at 173.1 m. With the suggested settings (very thick dash-dotted) the worst ratio at the same station is 0.639.

at 115 L/min, the friction gradient was 908 Pa/m and the pressure 183 kPa at 90 m against a limit of 674 kPa under the river. On the climb the limit fell from 511 kPa at 160 m in the sand to 185 kPa at 170 m in the soft cap, and the pressure there was 173 kPa. With the suggested settings at the same station the gradient was 545 Pa/m, the returns 0.054 and the bed empty, and the worst ratio 0.639.

Pause. Try Exercise 7.3 before reading on.

Case 6 isolates the exit climb. Set to keep going, the loaded annulus broke out at 149.8 m under 1.16 m of cover, and more flow alone (150 L/min) still broke out at 154.8 m. The pressure override held the thrust back for 54.6 min, let the flowing mud clean the hole, and finished with a worst ratio of 0.77 at 44.2 m/h. The optimizer alone also stayed clear (worst 0.76, 76.6 m/h) because its search keeps a predicted pressure under the allowable, and with both the rate fell to 66.6 m/h. Seven perturbations the optimizer cannot predict (a pump fault at 900, 1500 or 5400 s, soil boundaries 10 m earlier than the log, and a 60 s optimizer period, on case 6 and the crossing) never made the optimizer alone break out (worst 0.73 to 0.79), so the override is taught as the backstop for a wrong prediction or a drill run without the optimizer. With its fixed settings and no override, case 6 also broke out on seeds 1 and 2, at 150.3 and 147.4 m.

TRY IT IN THE APP 6 · Shallow Cover at the Exit: The Pressure Override

Run the scenario on the Section view with Pressure override Off and watch the strip under the section: the mud breaks out at 149.8 m on the exit climb. Set Pressure override to On, press Reset and run again. The override holds the thrust back for 54.6 min and the bore exits with no return at 44.2 m/h.

7.5.4 Soft Rock and an Honest Refusal

Case 8 places the plan's sag bend in soft rock, whose push curvature is $1/2000\,\mathrm{m}^{-1}$. A sweep of push fractions from 0 to 100 % at full thrust turned a rod by at most 0.15 point against the 6 points per rod the plan's 50 m bend needs, so no setting follows the plan. Run as shipped, the bit met four cobbles, entered the rock at 19.0 m, and the autopilot reported it was short of steering authority from 20.8 m and rotated on. The true path left the plan by 1.50 m at 39.2 m, where the crew stops. The remedy is a plan drawn for the ground or rock tooling, not a tuning.

Table 7.6 The River Crossing on the Default Seed

Configuration	Time (h)	Exit (m)	Ret.	T_{max} (%)	Cover (m)	Verdict
shipped	1.83	2.54	1	91.1	4.32	fails
suggested	2.13	0.60	0	85.8	4.38	passes
suggested, override Off	1.98	0.45	0	85.8	4.38	passes
suggested, no far-side locates	2.18	1.70	0	85.8	4.38	fails
suggested, Locate reset	2.23	0.54	0	85.9	4.34	passes
shipped, estimator and far side	1.89	0.56	1	89.1	4.49	fails
shipped, optimizer and override	2.38	2.67	0	85.9	4.34	fails

DID YOU KNOW? The Safety Layer Alone Is the Slowest Way Through

From the simulator: on case 6 the pressure override alone averaged 44.2 m/h, while the optimizer alone, whose search keeps its predicted pressure under the allowable, averaged 76.6 m/h with a worst ratio of 0.76 against 0.77 (Table 7.5). Both ran without a return.

7.5.5 The River Crossing

The challenge asks for the exit within 1.0 m of the target, at least 3.0 m of cover under the bed, no inadvertent return, torque at most 90 %, no rod bent past its radius and the bore in at most 2.75 h, judged when the head breaks the surface. Table 7.6 lists the configurations. As shipped the bore took 1.83 h and missed three targets. The clay settings outran the mud in the sand and left a bed whose pressure broke out on the exit climb at 173.1 m (6094.5 s), the torque reached 91.1 % where the bit climbed from the sand into the soft cap at 169.4 m with the clay's 125 kN, and with no locate after the river the 0.3 % pitch bias put the exit 2.54 m off. That last figure follows from the bias, since $0.003 \times 125\,\text{m} = 0.375\,\text{m}$ of depth at a 12 % exit tangent moves the surfacing point about 3.1 m. The suggested settings came out 0.60 m from the target in 2.13 h with 4.38 m of cover and no return, and without the override they also pass in 1.98 h. Each half of the suggestion is necessary. Guidance alone broke out at 174.5 m, and the rate layers alone exited 2.67 m off. Over ten seeds the shipped settings failed every time (exit 1.96 to 5.30 m off, a return on 7, torque over 90 % on 9), and the suggested settings passed every time (exit 0.12 to 0.75 m, 2.13 to 2.54 h, worst ratio 0.72 to 0.77). The return as it happens is shown in Figure 7.5.

The suggested crossing is plausible for the drill's class. The bus peaked at 119.7 kW (spindle 83.2 kW, pump 27.9 kW), the pump at 8.00 MPa, the annulus at 177 kPa at the bit, the torque at 6.43 kN m and the flow at 168 L/min. Sixty rods each cost 50.0 s to change, the bit cut 46 % of the time, and the bus drew 89.6 kWh for 181.6 m, 0.494 kWh/m, while the battery fell only from 85 to 81.9 %.

7.6 Code Checks, Correlations and the Limits of the Evidence

Code verification is the application's suite of 38 checks. The cuttings balance over a disturbed run (rate, flow, pump stops, a bed laid and eroded) closes to $6.1 \times 10^{-12}\,\text{m}^3$ of $5.186\,\text{m}^3$ cut, a stopped drill has every derivative exactly zero, the drilled length equals 3 m per rod at every change, and a full push over 3 m gives each soil's declared radius to 0.00 %. The optimizer reaches 100.2, 99.7 and 99.5 % of the dense grid's best at its three test points, inside the declared 0.3 % tie-break and 0.5 % search tolerance. The bus never exceeds its cap at any step of any case (closest approach 6.8 W under it). Halving the step to 0.25 s on a replayed rod program moves case 2's exit by 1.1 cm and its time by 0.18 %. In closed loop the per-rod and per-10 s decisions can flip with the step, so every verdict and ranking holds while numbers move. The suggested crossing took 2.13 and 2.27 h at 0.5 and 0.25 s, and case 4's optimizer 108.4 and 99.5 m/h. Playback at 60 and 600× logs the same row, and a crossing costs 629 to 829 ms of headless computing per simulated hour, so the suggested 2.13 h plays in 12.8 s at the top speed.

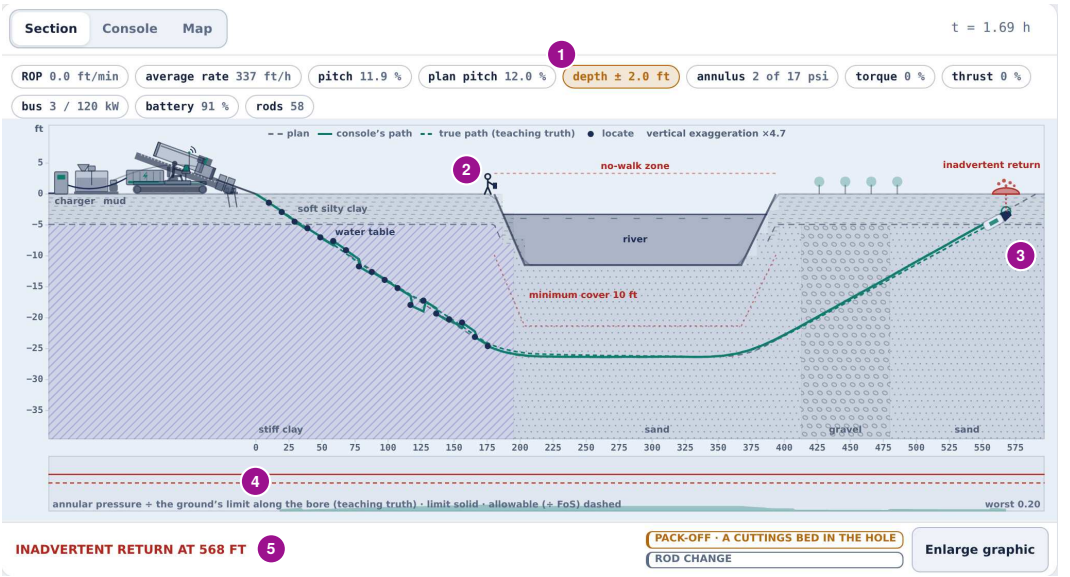


Figure 7.5 The river crossing as shipped at $t = 6100$ s on the Section view, 5.5 s after the inadvertent return, cropped to the view, with the run clock of the app's header moved into the strip beside the view tabs. (1) The readings: the beacon's pitch of 11.9 % against the plan's 12.0, the console's depth dead reckoned with ±2.0 ft (one standard deviation) after no locate past the river, an average rate of 337 ft/h (102.7 m/h) at 1.69 h, and 58 rods in the ground. (2) The no-walk zone over the river, where no locate is taken. (3) The plume over the vent at 173.1 m (568 ft) on the exit climb, with the head 1.06 m under the surface, a value from the run's log that the view does not print. (4) The strip of annular pressure over the ground's limit, the vented annulus at 0.20. (5) The status: the return, a cuttings bed in the hole, and a rod change under way. The torque had reached 91.1 % before the exit (Table 7.6).

Agreement with the literature is limited to forms and published ranges. An independent coding of the Delft equation reproduces the app's limit at 1, 3 and 6 m of cover to 0.1 kPa (stiff clay 314.5, 407.2 and 474.4 kPa, sand 164.2, 580.8 and 932.5 kPa), and the general form tends to the cohesive one as $\phi \to 0$ (3.96 % off at 1°, 0.039 % at 0.01°). For stiff clay at 6 m the app's 474 kPa lies between the rigid-plastic $2\ln(R_p/R_o)$ form at 652 kPa and the cavity limit $c_u[1+\ln(G/c_u)]$ at 478 kPa [3]. The half-cover plastic radius in clay is the one the cohesive analysis recommends [4], and the far field is isotropic where that analysis treats K_0 explicitly. The Bingham slot gradient equals the drilling field form at 478, 485 and 507 Pa/m for 100, 115 and 168 L/min. Specific energy is Teale's definition [1], 108.52 MPa by hand at 80 kN, 100 rpm, 3 kN m and 1.8 m/min. The mud-to-soil ratios (sand 2, stiff clay 4, gravel 2.5) sit inside ranges found in trade guidance during the app's review, which no peer-reviewed source fixes, so they remain teaching values with the soil rates, curvatures and the rock's ratio of 1.5. No magnitude was fitted to a field record, and none of the returns, rates or locates reported here predicts a real crossing. The cases have not been tried with students, so nothing is claimed about what a learner gains from them.

7.7 Technology in Practice

A real drill reads the same signals and moves the same handles as the layers of Section 7.4. Figure 7.6 draws the low selector, its two overrides and the optimizer with field hardware in place of the schematic's symbols.

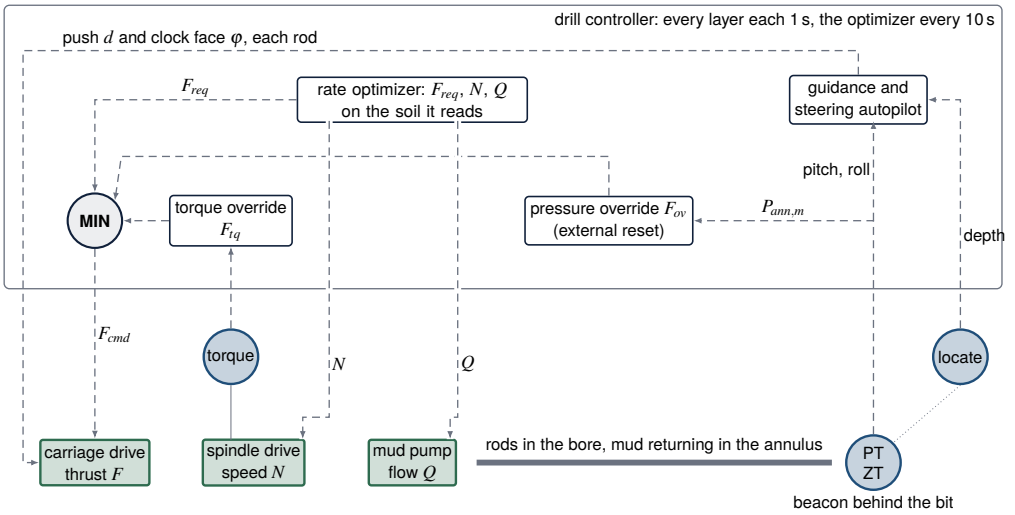


Figure 7.6 The pilot bore's control on real hardware. The beacon behind the bit sends its pitch, roll and annular pressure (PT, ZT) to the drill, and a walkover locate gives the depth where the surface can be walked. Three thrust requests meet in the low selector ahead of the carriage drive: the optimizer's request, the pressure override's limit and the torque override's limit. The optimizer also sets the spindle speed and the mud flow. Notice that both overrides act on the thrust alone and leave the mud flowing.

What Measures It

The constraint of this chapter is read at the head. During the pilot bore a downhole steering probe measures where the bit is against the designed path, and the information gathered includes the survey data, the rate of penetration, the rotary torque of the string and any loss of drilling fluid into the ground [13]. High annular pressure can come from cuttings left in the hole, a collapse or an excessive rate of penetration, and a blocked annulus can over-pressurize and fracture the ground [13], which the loaded annulus of case 6 imitates. The model's beacon stands for the probe and its pressure tool, with the declared pitch bias b of Table 7.1 as its one systematic error.

> **TECHNOLOGY** **Sensor: An Annular Pressure Tool Behind the Bit**
>
> Contractors monitor the annular pressure during the pilot bore with a downhole annular pressure tool [13]. The sensor sits several meters behind the bit as an integral part of the downhole steering system and shows the pressure live at the driller's console [18], and the steering probe that carries it typically sits 6 to 30 ft behind the bit [13]. In a field study a calibrated sensor in the orienting sub read the total annular pressure, the hydrostatic pressure and the friction loss together, and its readings reached a data logger every 10 s [7]. No open source read gives its accuracy. The model's beacon reads the pressure once a second, rounded to 1 kPa, and an interference event holds its last reading for 60 s, a flat line on the trend.

What Moves It

The overrides have one handle, the thrust. When cuttings build up in the annulus, the rotary torque on the string typically rises along with the risk of inadvertent returns [13], so the torque limit and the pressure limit often meet the same event. Both act through the carriage, and neither cuts the pump, because the mud that keeps flowing is what cleans the hole.

> **TECHNOLOGY** **Final Element: The Drill's Push, Turn and Pump**
>
> The drill moves three things from the surface: the thrust on the string, its rotation and the mud pumped down it. Hydraulically powered rigs improved the safety and efficiency of the early drills [13]. Hydraulic drives give a good ratio of power to weight but are inherently less efficient than mechanical or electric ones, and an electric drive needs an inverter that takes space beside its motor [15]. Some utility companies require a breakaway swivel, a mechanical limit on the force used when pulling polyethylene pipe [19]. No open source read gives the response time of a drill's drives. The model's carriage, spindle and pump follow their commands through lags of 1, 2 and 1.5 s.

Where the Controller Runs

A drill's console holds its own controller. A programmable logic controller can be the primary controller of such a smaller system, providing closed-loop control without a central control server, and supervisory and lower loops run with cycle times from milliseconds to minutes [20]. In the application every layer runs each 1 s and the optimizer every 10 s, so the optimizer sits in a supervisory layer above the overrides. Each override is an integrator on the request actually in force. In a PID function block this is the feedback input, once called external reset: connected to the output of the limiting block, it tells a deselected controller that winding up has no effect, and its integration stops [21].

What Is Modernizing It

Two developments bear on the drill and its limits. The first is the electric drive. Hybrid mobile machines can use about 10 to 50 % less fuel than diesel-mechanical or diesel-hydraulic ones, full electric machines could save more, and the limited specific energy of lithium-ion batteries forces a compromise between battery capacity, availability and charging [15]. Case 7 meets that compromise on a shore supply. The second is the downhole probe. Advanced survey probes let contractors determine the path of the pilot hole more quickly and more accurately [13], and a pressure sensor built into the steering system gives early warning of hydraulic fracture in real time [18]. An automatic override needs exactly that reading, and the estimator of Section 7.4 shows what a filter adds to the probe's pitch once the walkover locates run out.

> **IN PRACTICE** **Pressure on a Display Beside Its Limits**
>
> In practice the annular pressure is often shown together with the maximum allowable and minimum required pressures, so that the operator can adjust the drilling quickly and keep it in range. If it leaves that range, the operation should be stopped and investigated [18]. A state permit guide asks that drilling fluid pressures not exceed what the overburden can support, that the bore be plotted from readings on every rod, and that the plan state the pumping capacity, pressures and flow rates [19]. Crews walk the alignment to watch for released fluid [13]. The pressure override of this chapter makes the operator's adjustment automatic.

7.8 Limitations

The drill is a teaching design. The soils, the rate, torque and drag coefficients, the push curvatures, the mud ratios, the bed closure and the safety numbers follow the cited work in sign and form, and their sizes were picked so that every case shows its effect. The annulus is lumped, so a pack-off is spread over the whole hole rather than local, and the bed's cubic factor overstates its effect on a yield-dominated friction. The cavity limit is the isotropic Delft form at one soil per node, so layered ground, the free face of the exit pit and fractures are absent, and the allowable radius is a declared fraction of the cover. The optimizer's soil models are the plant's own soil table, so its model error is only what the soil read, the bed and the learned offsets leave. Reaming, pullback, mud recycling, losses into the ground and diesel-hydraulic drills are outside the model. The challenge's limits, the overrides and the stop under the river exist to teach. They are not certified trip logic, and nothing simulated here can stand in for a crossing's design, its permit or a safety case.

OPEN CHALLENGE **Both Edges of the Pressure Window Are Uncertain**

The methods used in industry predict both edges of the window poorly. The Bingham plastic model, the usual estimate of the annular pressure, overestimates it, and the Delft cavity expansion method, the usual estimate of the allowable pressure, significantly overestimates that and can lead to hydraulic fracture of the ground [7]. Ground uncertainty makes both pressures hard to predict, and an extensive set of data from field projects and laboratory tests is recommended [18]. Research to measure actual pressures on projects and compare them with the predicted limits is encouraged [5]. This chapter uses both models, so progress would show directly in its override's target.

7.9 Conclusion

This chapter simulated a battery-electric utility drill on a steered pilot bore through changing soils, with the annular mud pressure tracked along the whole bore against a cavity-expansion limit that follows the cover. A pushed rod in clay turns the bore 9.4 points while cutting at half the rotating rate, so steering is a sampled duty cycle that costs rate. A different limit holds the rate in each soil, torque in clay, the mud ratio in sand and thrust in gravel, and on a shore supply the optimizer gains 6 % by cutting the flow and spending the power on thrust. The pressure risk peaks on the exit climb, where the river crossing as shipped breaks out at 173.1 m with a ratio of 0.996 a moment before, while the suggested layers exit 0.60 m from the target in 2.13 h with a worst ratio of 0.73. The model is lumped and its coefficients are teaching values. A fuller model would add a distributed bed, layered ground in the cavity limit and a reaming pass. The crossing gives one machine on which constrained rate optimization, guidance between sparse fixes and a pressure window that moves along the path are practiced together.

KEY POINTS

- The drill cuts only as fast as its tightest limit allows, and that limit changes with the soil: torque in clay, the mud ratio in sand, thrust in gravel.
- The mud pressure carries the friction of the whole annulus, so the risk of a return peaks on the exit climb, where the cover is thin.
- A pressure override and a torque override cap the thrust in a low selector, and the pressure override takes thrust off while the mud keeps flowing.
- On the river crossing the suggested layers exit 0.60 m from the target in 2.13 h with no return, while the shipped settings break out at 173.1 m.

Where else this applies. Chapter 11 builds the limits on its advance the same way, and Volume 10, Chapter 2 pushes an oil well's rate of penetration against an annular pressure window.

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7.10 Exercises

7.1 Concept check · 2 min

In scenario 2, Follow the plan, the steering autopilot aiming 9 m ahead reached the exit in 0.80 h with 14 of 20 rods pushed. Aiming 3 m ahead it held the plan more closely, within 0.11 m, but took 1.04 h with 17 of 19 rods pushed. Why did the short look-ahead take longer?

(a) It bent rods past their radius, and every bent rod had to be drilled again

(b) It lowered the thrust so that each correction could be placed more precisely

(c) It pushed more rods, and a pushed bit cuts this clay at about half the rotating rate

(d) It kept the walkover crew locating every rod, and each locate held the drill

7.2 Concept check · 2 min

In scenario 4, Sand, the rate optimizer holds the bit on the mud-ratio edge at about 5.4 m/min on the level run, with the torque peaking at 32 % and thrust to spare. Which change would let the drill cut this sand faster without leaving cuttings in the hole?

(a) More thrust, since the rate saturates only slowly in the thrust that reaches the bit

(b) A spindle speed closer to the sand's best speed of 160 rpm

(c) A higher torque ceiling for the optimizer, since the torque decides the cut

(d) More mud flow, which here needs a bit with larger jets, as the pump already runs at the jets' limit

7.3 Concept check · 1 min

On the river crossing as shipped, at 6080 s the annular pressure is 0.20 to 0.31 of the ground's limit under the river but 0.996 of it at 172.6 m on the exit climb. Why is the exit climb the dangerous place?

(a) The pressure there carries the friction of the whole annulus back to the entry, while the limit falls with the thin cover

(b) The river's water lowers the ground's limit under the river, so the returns lose pressure before they reach the climb

(c) The pump pressure rises with every rod added, and the bit's jets pass that rise into the annulus at the head

(d) The gravel lens behind the head forces the returns upward, so the mud is heaviest on the climb

7.4 Theory and calculation · 5 min

A whole 3 m rod pushed at 12 o'clock bends the bore on an arc of radius $1/\kappa_s$, Equation (7.1), and the console shows the pitch as $100\tan\theta$.

(a) In stiff clay ($1/\kappa_s = 32$ m), starting from -14.2 %, find the pitch after one fully pushed rod and the change in points. Compare with the 9.40 points measured in case 1. *Checkpoint:* -4.73 %, 9.47 points

(b) The autopilot caps the push fraction at $0.9/(R_{min}\kappa_s)$ with $R_{min} = 30$ m. Find the cap in stiff clay and in the soft silty clay cap ($1/\kappa_s = 22$ m). In which soil would a full push bend a rod past its radius? *Checkpoint:* 0.96 and 0.66, the cap

(c) In the soft rock of case 8 ($1/\kappa_s = 2000$ m), find the change of a level pitch after one fully pushed rod, and the change per rod that the plan's 50 m bend needs. *Checkpoint:* 0.15 and 6.0 points

7.5 Theory and calculation · 6 min

The mud-ratio constraint of Equation (7.11) bounds the rate at ROP $\le Qc/[A_h(1-c)]$ with $c = (1-m)\eta/(1+R)$, $\eta = v/(v+v_{set})$ and $v = Q/A_{ann}$. The bit is 115 mm and the rods 60 mm, A_h is the area of the hole and A_{ann} that of the annulus, and the margin is $m = 0.10$. Use Table 7.2.

(a) In sand at $Q = 167$ L/min, find v, η, c and the rate ceiling. *Checkpoint:* 0.368 m/s, 0.891, 0.267, 5.87 m/min

(b) Find the ceiling at the 100 L/min with which case 4 ships, and compare it with the 8.32 m/min the bit cut there. *Checkpoint:* 3.20 m/min, 2.6 times

(c) In stiff clay at the optimizer's 137 L/min, find the ceiling. Why does the torque, and not the mud, hold the clay at 2.65 m/min in Figure 7.2a? *Checkpoint:* 2.78 m/min

7.6 Theory and calculation · 6 min

The console dead reckons the depth from the beacon's pitch, Equation (7.8). A constant pitch bias b adds about b meters of depth error per meter drilled on a nearly level bore.

(a) In case 3 the beacon reads 1 % high, and with Locate reset the last locate before the road is at 20.8 m and the first after it at 47.8 m. Estimate the depth error just before that locate and compare it with the 0.246 m measured. *Checkpoint:* about 0.27 m

(b) On the river crossing the bias is 0.3 % and, with no far-side locates, about 125 m is drilled after the last locate. Find the depth error and how far it moves the point where the 12 % exit tangent

breaks the surface. Compare with the shipped exit miss of 2.54 m. *Checkpoint:* 0.375 m, about 3.1 m

(c) The estimator learned a bias of 0.90 % before the road. What depth error does the unlearned rest build across the road, and why was the estimator still up to 0.141 m off? Take the road's bore 3 m deep. *Checkpoint:* 2.7 cm, locate error 9.5 cm

7.7 App challenge · 8 min

Scenario 4, Sand: the rate map and the mud-ratio edge, default seed, at the 60 times real time the case loads with, with the unit switch in the header set to SI. Each run pauses when the head breaks the surface.

(a) Run the case as loaded to the exit. Read the Average rate tile and the Inadvertent returns tile. *Checkpoint:* 126.0 m/h, one return at 114.6 m

(b) Set *Rate optimizer* On, press Reset and run to the exit. Read the same two tiles, and the limit the Drilling rate card names on the level run. *Checkpoint:* 108.4 m/h, none, worst ratio 0.71, the mud

(c) Read the Energy per meter tile at the end of each run. Why does the optimizer's bore cost more energy per meter? *Checkpoint:* 0.13 and 0.24 kWh/m

Tolerance: 0.2 m/h on the rates, 0.2 m on the station, 0.01 on the ratio and the energy.

7.8 App challenge · 9 min

Scenario 6, Shallow cover at the exit: the pressure override, default seed, at the 60 times real time the case loads with, unit switch on SI. Run each part to the exit, where the run pauses.

(a) Run the case as loaded. Read the Inadvertent returns tile and the Average rate tile. *Checkpoint:* one at 149.8 m, 105.9 m/h

(b) Set *Pressure override* On, press Reset and run again. Read the same tiles. *Checkpoint:* none, worst ratio 0.77, 44.2 m/h

(c) Reload the case, set *Rate optimizer* On with the override Off, press Reset and run again. Read the same tiles. Which layer would you commission first on a real drill, and what is the other one for? *Checkpoint:* none, worst ratio 0.76, 76.6 m/h

Tolerance: 0.2 m/h, 0.2 m and 0.01.

7.9 App challenge · 8 min

Challenge, The 180 m river crossing, default seed, at the 600 times real time the case loads with, unit switch on SI. Each run pauses at the exit.

(a) Run the case as loaded. Read the Challenge target tile. *Checkpoint:* not met: exit 2.54 m, return, 91.1 %

(b) Press Reveal suggested tuning, which applies the suggested settings, then press Reset and run again. Read the Challenge target tile. *Checkpoint:* met: 0.60 m, 2.13 h, cover 4.38 m

(c) Keep the suggested settings but set *Far-side locates* Off, press Reset and run again. Which target fails, and why? *Checkpoint:* exit 1.70 m

Tolerance: 0.05 m, 0.02 h and 0.2 %.

7.10 Application area · 3 min

The optimizer and the override keep the annular pressure under 0.97 of the allowable P_{lim}/FoS, with $\mathrm{FoS} = 1.3$.

(a) What fraction of the cavity limit is that? Over ten seeds the suggested crossing's worst ratio ran from 0.72 to 0.77. Is that consistent? *Checkpoint:* 0.746

(b) Where would a real crossing take its factor of safety, its minimum cover under the river and its allowable plastic radius from? Name two features of real ground that lower the limit and that the model leaves out.

7.11 Application area · 4 min

A crew is paid for meters per hour with every rod change included. Each 3 m rod costs 50 s of rod change.

(a) Find the rate with rod changes at a cutting rate of 8.32 m/min and at 5.36 m/min, the shipped and optimized cutting rates of case 4. By how much does the faster bit raise the average? Compare with the measured 126.0 and 108.4 m/h. *Checkpoint:* 150.8 and 129.2 m/h, 17 %

(b) Faster rod handling cuts the rod change to 35 s. Which gains more in percent, the fast or the slow bit, and what does that say about where a crew should look for time? *Checkpoint:* 26 % and 22 %

7.12 Review the agent · 5 min

An AI assistant reviewing case 6 writes: “The annular pressure on the exit climb is mostly friction, and friction grows with flow. Cut the mud flow from 100 to 60 L/min as the head starts to climb: the friction gradient falls roughly in proportion, and the inadvertent return goes away without slowing the bit.” Find the flaw, and say how you would check the claim with the chapter’s equations and with the app.