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CHAPTER 11

Holding a Tunnel Face With Its Own Muck Through Sixty-Six Stops

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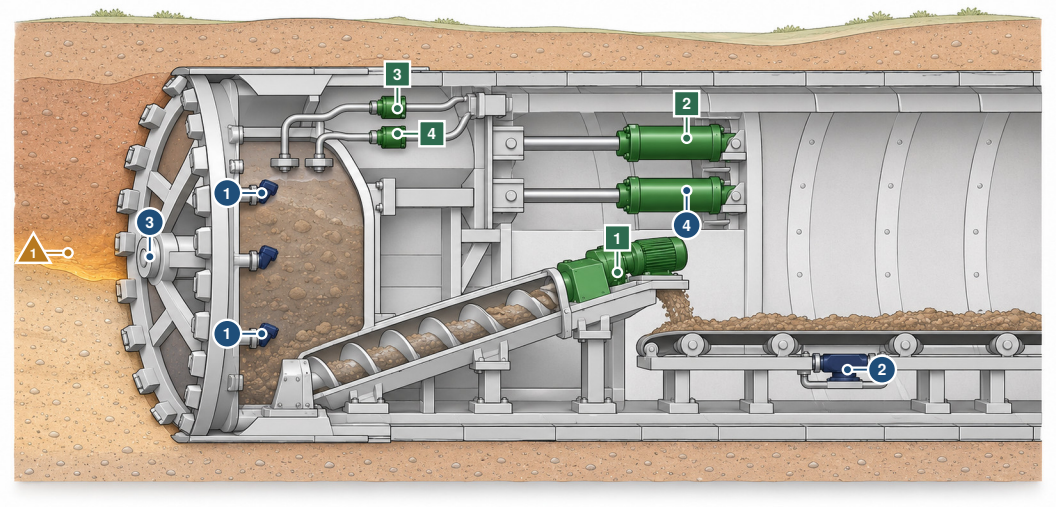
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CHAPTER 11

Holding a Tunnel Face With Its Own Muck Through Sixty-Six Stops



The controller moves 1 screw speed, which lets the soil out 2 push cylinders, which move the shield forward 3 foam mixed into the soil 4 clay slurry that holds the pressure while a ring is built

The controller reads 1 pressure cells in the chamber 2 belt scale, two minutes late 3 twisting load on the cutting wheel 4 push force of the cylinders

What disturbs it 1 a change from clay to sand at the face

An earth pressure balance shield holds the face with its own muck: notice that the screw lets soil out while the push cylinders, slowed by the wheel's load and their own force, bring it in. Illustration, not to scale.

IN PLAIN TERMS **Holding Up the Ground With the Dug Soil**

The main idea. A tunneling machine pushes a turning cutting wheel through soft ground. The loosened soil packs a closed chamber behind the wheel, and its pressure holds up the ground in front while a screw lets soil out as fast as it comes in.

The challenge. The machine stops for twenty minutes to line each short stretch of tunnel. The soil, a river above and buried boulders change what is safe, and the street sinks hours later, too late to act.

Why it matters. Separate control layers, one for each cause, keep the street level while the machine digs as fast as the strain on its wheel allows.

THREE WAYS TO READ THIS CHAPTER

Explore	12 min	the first page, the fact in the Introduction (Section 11.1), the two history segments (Section 11.2), the try-it segment on the ring build (Section 11.4), the try-it segment and the fact on the drive (Section 11.6) and the key points
Study	60 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 11.6), Technology in Practice (Section 11.8), Limitations (Section 11.9) and the open challenge

The control question An earth pressure balance shield holds the tunnel face with the muck in its chamber, whose pressure integrates what the cutterhead brings in and the screw takes out, and every ring of lining stops both for twenty minutes. Which control layers hold the face through sixty-six forced stops, a change of soil and a river, when the street's settlement is reported only hours after it can be prevented?

Learning objectives

- Explain why the chamber pressure is an integrator whose gain is set by the foam, and compute that gain from the chamber's stiffness.
- Compute the face's target pressure and the blow-out limit from the ground's stresses, and explain why no fixed setpoint serves both land and river.
- Describe the layers that hold the face: the screw loop with its advance feedforward, the bentonite hold, the chainage feedforward and the advance supervisor with its mid-ranging limit.
- Run the shield's cases and the challenge, and tell which layer each failure calls for.
- Judge a settlement claim against a survey that reports late.

Prerequisites Sections 1.6.2 (velocity-form PID), 1.4.3 (selectors), 1.4.4 (external reset), 1.4.7 (mid-ranging) and 1.6.4 (scenarios and exported files). Section 1.6.3 is needed only for the predictive coordinator.

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See also Volume 6, Chapter 3, where a traversing gauge reports the product late, and Volume 6, Chapter 7, where inventory loops pass flows around a recycle. Volume 3, Chapter 6 for feedforward from the cause of a disturbance, and Volume 3, Chapter 2 for matching the loop structure to where a disturbance enters.

11.1 Introduction

A soft-ground tunnel is held up at its face before it is lined. In an earth pressure balance shield the cutterhead feeds the excavated soil into a closed chamber behind it, the chamber is kept full, and the pressure of that muck must balance the earth pressure on the excavation face [1]. In the generic drive simulated here a shield 6.5 m in diameter advances at 40 mm/min and cuts 1.33 m^3 of clay a minute into a 30 m^3 chamber, and a screw conveyor turning 1 rpm slower than the speed that balances it takes out 0.26 m^3 a minute too little. The axis pressure cell then rises 0.168 bar in the first minute and keeps rising, and the crown reaches its total overburden, the blow-out limit of the model, 2.9 min after the mismatch began.

> **DID YOU KNOW? A Cutterhead Almost 15 Meters Across**
>
> An earth pressure balance machine built for a road tunnel had a cutterhead almost 15.2 m in diameter [2], more than twice the 6.5 m of the shield simulated in this chapter.

Several established problems meet in the chamber. The face must be held inside a band between collapse and blow-out [3]. The ground lost into the face appears at the surface as a trough whose shape was described empirically in 1969 and has been refined with field data since [4], and the buildings over the tunnel tolerate it only to a limit [5]. The muck leaves through a screw whose pressure gradient is set by the shear of the soil plug against the casing [6], and conditioning is what makes the muck suitable for pressure control and for extraction through the screw [7]. While a ring is built the screw stands still, and in permeable ground the chamber loses pressure through the face [8, 9]. A predictive controller for the chamber identified the screw speed and the advance speed as the major factors in its pressure [1]. The arrangement that results, a fast handle that holds a variable and a slow one that the operation wants at a limit, is the mid-ranging structure of process control [10] (Section 1.4.7), and the plant shares its inventory character with a level, a drum or a bin whose content is seen only through a pressure.

The simulator corrects a specific belief, that a face pressure held on its setpoint means the street is safe. The pressure is an integrator whose gain depends on the foam, so the loop that is calm in clay

rings in sand. Once in every 1.5 m of advance the screw cannot act at all. The setpoint that keeps the street is fixed by ground conditions that change along the drive, and the settlement it produces is measured hours after anything can be done about it. In case 4 of the simulator the survey's first report of the point at 27.5 m reads 12.3 mm, under a 15 mm budget, while that point is heading for 18.8 mm.

The published work on this plant is divided among the disciplines that own its parts. Face stability, settlement prediction, screw mechanics, foam conditioning and standstill losses are geotechnical subjects [3, 4, 6, 8, 11], while the control work poses the chamber pressure as an optimal-control problem with face stability as its objective [12] or as predictive control on a model learned from field data [1]. This chapter brings the chamber's inventory, the foam's stiffness, the plug, the seepage, the ring sequence and the late survey together on one simulated drive, and measures which control layers the drive needs and why. The chamber pressure model, the standstill loss and two-handle chamber control are each established already, and the methods used here are standard ones. The simulator rests on a full-chamber model with a closed-form pressure and mass ledgers that close to 2×10^{-13} of the throughput, and on an instrument packet that is the only thing any controller is allowed to read. Its nine cases and a graded drive each carry a completion rule.

Section 11.2 follows the closed shield, face support and the settlement trough. Section 11.3 sets out the drive as modeled, from the ground's target pressure through the full chamber, the screw and its plug, the seepage and the trough to the instruments. Section 11.4 explains why the face is hard to hold: an integrator whose gain is the foam, a stop the screw cannot cover, a plug that can fail at any speed, and a target that moves while the product arrives late. Section 11.5 describes the control layers as implemented, with an optional predictive coordinator. Section 11.6 measures the cases, the drive and the predictive and classical comparisons, Section 11.7 separates the kinds of evidence, Section 11.8 sets the layers on a real shield's hardware, Section 11.9 states the limitations, Section 11.10 concludes, and Section 11.11 holds the exercises.

11.2 Closed Shields, Face Support and the Trough

A shield is a steel tube the diameter of the tunnel, pushed forward by cylinders that bear on the lining already built behind it. The reference text of the method covers open, compressed-air, slurry, earth pressure balance and combined shields [13], and of the closed-face types the slurry shield supports the face with a pressurized bentonite suspension while the earth pressure balance shield supports it with the excavated soil itself. A horizontal directional drill, the trenchless machine of Chapter 7, also crosses under roads and rivers and holds its mud pressure under a limit set by the cover. The two systems were compared for soft ground in 1991 [14]. A 2010 review of the development steps of soft-ground machines reports that they handle unstable faces against water pressures up to 15 bar [15], and the same reference text treats the planning of a drive against the geology, the groundwater and the settlement requirements together [13].

> ⧖ HISTORY **1818 to the 1970s: From an Open Shield to a Closed Face**
>
> Soft-ground tunneling did not become viable until the tunnel shield. Marc Brunel patented a circular shield in 1818, with the aim of opening no more ground than the shell of the tunnel would fill. Ground that needed more support was held with compressed air from the mid-1800s into the 1980s. From the late 1960s excavators were built into shields, but these digger shields lost ground ahead of the face, and keeping the right soil plug in the invert was always a headache. Japanese industry then developed pressurized-face machines and within a decade or so exported them to the United States. In the earth pressure balance machine, control is obtained by matching the volume the advance displaces with the volume the screw conveyor removes [2].

The band in which the face pressure must sit has two sides. Too little and the ground moves into the face, too much and the face lifts the ground above it, and the face stability conditions of an earth pressure balance shield were analyzed in 1996 [3]. What the street feels is the volume lost. How the trough it leaves came to be described is told in the history segment after this paragraph.

Analytical methods relate the loss to the gap around the tunnel and the soil [16], and a 2008 lecture on advances in earth pressure balance tunneling named face pressure, soil conditioning and effective screw conveyor operation as key factors in the volume loss [17].

> ⧖ HISTORY **1969 to 2024: Reading the Trough Over a Tunnel**
>
> The empirical method that describes the transverse trough by a Gaussian curve originated with Peck in 1969. O'Reilly and New gave its width in 1982 as $i = Kz_0$, with $K = 0.5$ for cohesive and 0.25 for granular soils, and Mair and Taylor found in 1997 that K for clays lies mostly between 0.4 and 0.6, and for sands and gravels between 0.25 and 0.45 with a mean of 0.35. A 2024 review that summarizes them back-calculated the volume loss of 78 troughs over earth pressure balance drives, from 0.03 % to 0.83 % of the face area with a median of 0.41 % [4].

Those factors are where the control problem lives. Model tests on a screw conveyor measured a casing shear stress constant along the conveyor and close to the undrained strength of the clay, so the total pressure falls linearly along the screw and its torque rises with the casing stress [6]. A laboratory screw that draws sand from a pressurized tank was built to verify the effects of foam on a noncohesive soil [7], and pressure infiltration tests found that the water permeability of foam-infiltrated sand falls as the foam injection ratio rises [11]. During a standstill for the lining the chamber pressure decreases in coarse soils, an effect linked to the permeability outside the machine that increases the settlement [8]. A simplified chamber pressure model for granular soil carries the gas volume, the liquid volume and the amount of gas as its states, through excavation and standstill, with muck compression and seepage as two of its physical processes [9]. On the control side, optimal control of the shield has been posed with face stability as its objective [12], and a predictive controller on a learned model identified the screw speed and the advance speed as the major factors in the chamber pressure [1]. The simulator of this chapter takes a layered arrangement, a pressure loop on the screw with the stops, the geology and the machine each handled by a separate layer.

11.3 The Drive as Modeled

The drive runs 100 m from a launch shaft at chainage 0 to a reception shaft, with the tunnel axis $z_0 = 15\,\mathrm{m}$ under a street and 11.75 m of cover over the crown, as shown in Figure 11.1. The ground is a silty clay to the boundary at $x_b = 50\,\mathrm{m}$ and sand after it, with a 1 m transition, and the water table stands $z_{wt} = 3\,\mathrm{m}$ under the street. A building stands over 22 to 38 m. A river $h_r = 8\,\mathrm{m}$ deep, held between flood walls over its bed at street level, crosses 62 to 82 m. Survey points every 2.5 m on the street's centerline, 39 of them, measure the settlement. Units are seconds, kilograms, meters and pascals, with pressures quoted in bar gauge, the advance in mm/min and the screw in rpm.

Each variable in Table 11.1 carries its role. Twenty-one states are integrated. Seven are physical, the condensed mass m_c and its volume w_c at zero gauge pressure, the gas mass m_g, the chainage x, the screw speed ω, the advance rate v and the chamber's conditioning c_F. Two integrate the ground lost and over-excavated, and twelve are ledgers of the mass entering and leaving by each route, the theoretical cut and the spewed volume.

11.3.1 The Ground's Target and Its Limit

The pressure the face needs is the at-rest earth pressure plus the pore water pressure at the axis, as shown in Equation (11.1).

$$\begin{aligned} \sigma_v &= \rho_w g\, h_r r(x) + \gamma z_0 \\ u &= \rho_w g \big(z_0 - z_{wt}(1-r) + h_r r\big) \\ p_t(x) &= K_0(\sigma_v - u) + u \\ \sigma_{v,crown} &= \rho_w g\, h_r r + \gamma(z_0 - R) \end{aligned} \tag{11.1}$$

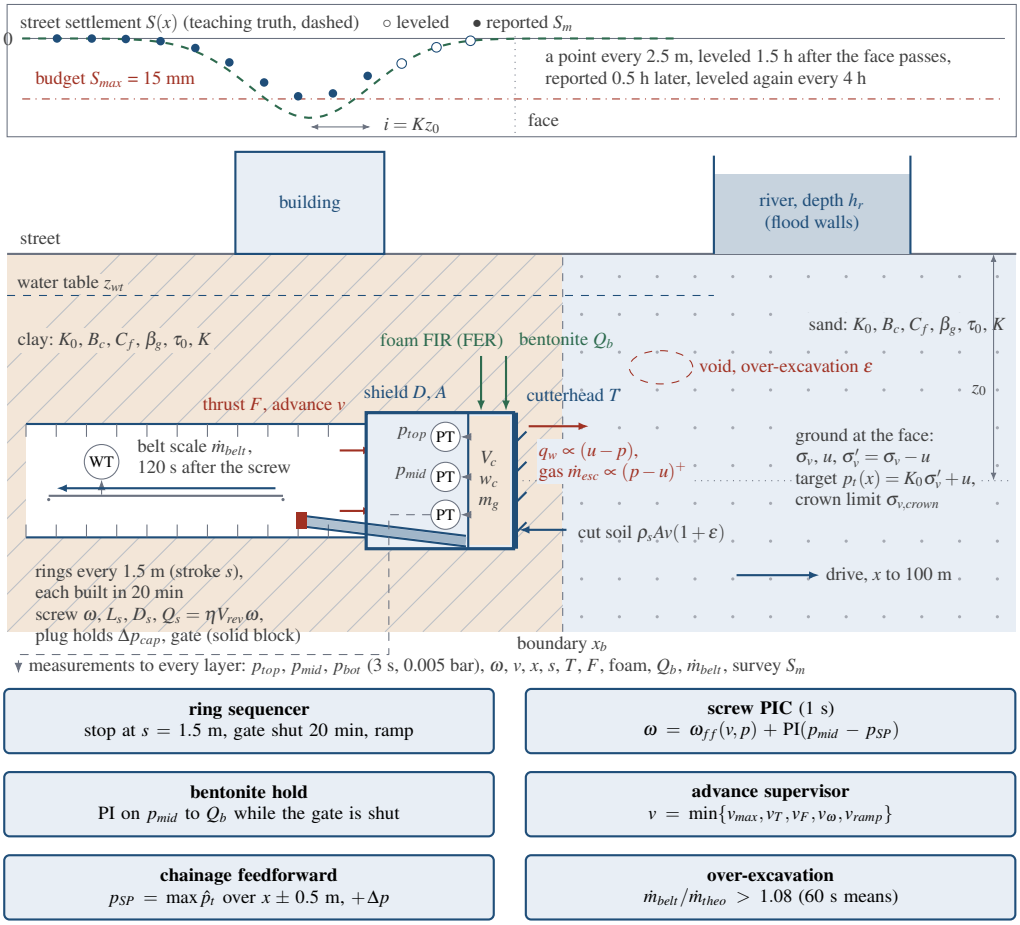


Figure 11.1 The drive as modeled, mirroring the simulator's Section view. The shield of diameter D and face area A advances at v through clay and then sand. Its full chamber of volume V_c holds condensed muck w_c and foam gas m_g at the axis pressure p, read by three cells, and receives cut soil, foam and bentonite. The screw at speed ω discharges through a gate onto a belt whose scale reads $\dot{m}_{belt}$ a conveyor delay later. The face exchanges water q_w and gas with the ground, a planted void adds ε, and the lost volume settles the street in a trough $S(x)$ of width $i = Kz_0$ that the survey reports late. In the strip the true trough is the thick dashed curve, the budget the dash-dotted line, the leveled points open circles and the reported points filled dots. The screw's gate is the solid block at its discharge. Control blocks read only the instruments, along the dashed signal line. Not to scale.

where $r(x)$ is the river's presence (0 on land, 1 under it, with 1 m cosine banks), γ the soil's unit weight, $R = D/2$, and K_0, γ and the other soil constants blend over the boundary with the sand fraction $s(x)$ (permeability terms on a logarithmic scale). The coefficient K_0 is a teaching value of the class that friction angle and stress history predict [18], 0.60 in the clay and 0.45 in the sand. The target is 2.226 bar in the clay, 1.997 bar in the sand on land and 2.944 bar under the river, where the pore pressure is 2.256 bar against 1.177 bar on land. A blow-out risk is flagged while the crown's chamber pressure $p - \rho_{mix} gR$ exceeds $\sigma_{v,crown}$, which is 2.291 bar in the clay, 2.350 bar in the sand and 3.135 bar under the river. Because ρ_{mix} is the chamber's own density, the land's limit expressed at the axis cell moves with the muck, from 2.91 to 2.95 bar in the sand before the river.

Table 11.1 Signals and States, With Values in the Clay at 12 m (Case 2 Before Its Step)

Variable	Role	Value	Range
p_{mid}	CV, axis cell	2.40 bar	SP 1.0–3.5 bar
ω	MV, screw speed	6.63 rpm	0–22 rpm
Q_b	MV, bentonite (ring builds)	0	0–8 m^3/h
v	MV, advance rate	50 mm/min	0–100 mm/min
FIR	MV, foam injection ratio	30 %	0–100 %
S	product, settlement (truth)	0	budget 15 mm
S_m	measured, survey report	—	noise 0.5 mm
T, F	constraints, torque, thrust	62, 55 %	≤ 90, ≤ 90 %
geology	DV, soil, water, river	clay	clay, sand, river
ε	DV, void (case 8)	0	0–0.3
seepage, boulder	DV, events	1, none	0–4×, +30 points
m_c, w_c, m_g	states, chamber	—	full chamber
x, c_F	states, chainage, conditioning	12 m, 0.30	0–100 m
V_L, V_o	states, lost, over-excavated	0	≥ 0
B	output, chamber stiffness	21.3 bar	—

11.3.2 A Full Chamber and Its Stiffness

The chamber is always full. Its condensed phase (soil with its pore water, foam liquid, bentonite) of volume w_c at zero gauge pressure and its gas of mass m_g occupy V_c at the one pressure that solves Equation (11.2).

$$w_c\left(1-\frac{p}{B_c}\right)+\frac{m_g R_a T}{p+p_{atm}}=V_c, \qquad \frac{1}{B}\approx\frac{1-n_g}{B_c-p}+\frac{n_g}{p+p_{atm}} \tag{11.2}$$

where B_c lumps the stiffness of the condensed muck, the bulkhead and the face (40 bar in the clay and 800 bar in the sand, teaching values), $R_a = 287.05\,\mathrm{J/(kg\,K)}$, $T = 293.15\,\mathrm{K}$ and n_g is the gas fraction. The first relation is a quadratic in p solved in closed form at every stage of the integrator, with $p = 0$ (a part-full chamber at atmospheric pressure) when no positive root exists. The second is the mixture's stiffness $B = -V\,\mathrm{d}p/\mathrm{d}V$, which the code evaluates by a finite difference of the first. Lined out 0.15 bar over the target at 50 mm/min with 40 % foam, the gas fraction is 9.9 % and $B = 18.82$ bar in the clay at 48 m, and 8.0 % and 37.72 bar in the sand at 52 m, which a hand evaluation of the second relation reproduces to within 0.1 %.

11.3.3 The Inventory

Soil enters at the advance, foam brings liquid and gas in proportion to the cut volume, and the screw and a failed plug take a fraction of the well-mixed contents, as shown in Equation (11.3).

$$\begin{aligned}
\dot{m}_c &= \rho_s A v(1+\varepsilon)+\rho_w\frac{\mathrm{FIR}\,A v}{\mathrm{FER}}+\rho_b Q_b+\rho_w q_w-f_o m_c\\
\dot{w}_c &= A v(1+\varepsilon)+\frac{\mathrm{FIR}\,A v}{\mathrm{FER}}+Q_b+q_w-f_o w_c\\
\dot{m}_g &= \mathrm{FIR}\,A v\left(1-\frac{1}{\mathrm{FER}}\right)\rho_{a,0}-\dot{m}_{esc}-f_o m_g\\
\dot{c}_F &= (\mathrm{FIR}-c_F)\,q_{in}/V_{mix}
\end{aligned} \tag{11.3}$$

where $f_o = (Q_s + Q_{sp})/V_{mix}$ is the fraction of the contents leaving per second, $A = 33.18\,\mathrm{m}^2$, ρ_s is 1990 or 2040 kg/m^3, FER = 10 is the foam expansion ratio, $\rho_{a,0} = 1.204\,\mathrm{kg/m}^3$, $\rho_b = 1030\,\mathrm{kg/m}^3$, V_{mix} is the mixture's volume (equal to V_c when full) and q_{in} the volume entering at p. The conditioning c_F is the foam ratio the chamber's contents carry, which lags the injected ratio by the chamber's turnover and is what the plug and the seepage see.

11.3.4 The Screw, Its Plug and Spewing

The screw discharges a volume per revolution, and the muck plug in it can hold only so much pressure, as shown in Equation (11.4).

$$\begin{aligned} Q_s &= g_a\,\eta V_{rev}\frac{\omega}{60}\,\phi, \qquad \Delta p_{cap} = \frac{4\,\tau_{plug} L_s}{D_s} \\ \tau_{plug} &= \left[\tau_{0,c}\mathrm{e}^{-c_F/0.8}(1-s) + \tau_{0,s}\frac{c_F^2\,s}{c_F^2+0.35^2}\right] \\ &\quad \times \left(1+0.15\frac{\omega}{\omega_{max}}\right) \\ Q_{sp} &= g_a\,k_{sp}\left(p+0.9\rho_{mix}gR-\Delta p_{cap}\right)^{+}\phi \end{aligned} \tag{11.4}$$

where g_a is the gate (shut only in ring builds), $\eta = 0.75$, $V_{rev} = 0.35\,\mathrm{m}^3$, $L_s = 12\,\mathrm{m}$, $D_s = 0.9\,\mathrm{m}$, $\tau_{0,c} = 15\,\mathrm{kPa}$, $\tau_{0,s} = 10\,\mathrm{kPa}$ and $\phi = \min(1, V_{mix}/0.25V_c)$ starves both flows in a part-full chamber. The plug law is the linear total pressure gradient set by the casing shear stress that model tests measured [6], with the sand's dependence on foam a teaching closure of the direction that laboratory screw tests show [7]. The inlet sits at the invert, so its pressure carries $0.9\rho_{mix}gR$ of muck head. The spew is a fast collapse toward the plug's capacity with $k_{sp} = 2\times10^{-6}\,\mathrm{m}^3/(\mathrm{s\,Pa})$, capped so that its time constant $V_{mix}/(B\,k_{sp})$ is never under 1 s. At 25 % foam in the sand the plug holds 1.80 bar still and 2.07 bar at full speed, while at 40 % it holds 3.17 bar.

11.3.5 Seepage Through the Face

Water moves through the face with the pressure difference and gas escapes into the ground while the chamber is over the pore pressure, as shown in Equation (11.5).

$$\begin{aligned} q_w &= \frac{\sigma_s C_f}{1+c_F/0.3}(u-p) \\ \dot{m}_{esc} &= \sigma_s\beta_g\frac{(p-u)^{+}}{1\,\mathrm{bar}}\,m_g \end{aligned} \tag{11.5}$$

where C_f is 4×10^{-11} in the clay and $1.2\times10^{-9}\,\mathrm{m}^3/(\mathrm{s\,Pa})$ in the sand, β_g is 2×10^{-6} and 3×10^{-4}/s per bar, and σ_s scales both (1 by default, 4 after a water inflow). The foam factor follows the measured fall of the infiltrated sand's permeability with the foam ratio in direction only [11]. Sealed for twenty minutes at 58 m with 60 % foam, the sand chamber falls from 2.147 to 1.529 bar, toward the pore pressure, while a clay chamber at 20 m falls from 2.353 to 2.348 bar.

11.3.6 Ground Lost and the Street's Trough

A face under its target lets the ground move in at a rate set by the relative deficit, and every lost volume settles the street in a Gaussian bowl, as shown in Equation (11.6).

$$\begin{aligned} \dot{V}_L &= A\,d\,(c_x v + c_t), \qquad d = \mathrm{clip}\left(\frac{p_t-p}{K_0\sigma_v'},0,1\right) \\ S(x_q) &= \sum_j \frac{\Delta V_j}{2\pi i_j^2}\exp\left(-\frac{(x_q-\xi_j)^2+y_q^2}{2i_j^2}\right), \quad i_j = Kz_0 \end{aligned} \tag{11.6}$$

where $c_x = 0.05$, $c_t = 1.4\,\mathrm{mm/min}$ (a standing face still moves), ΔV_j is the volume lost and over-excavated while the face crossed the 0.5 m cell centered at ξ_j, and y_q is the point's offset from the axis (0 for the survey). The trough width uses $K = 0.50$ in the clay, O'Reilly and New's cohesive value, and $K = 0.35$ in the sand, Mair and Taylor's mean [4], so $i = 7.5\,\mathrm{m}$ and 5.25 m. A void planted 1 to 2 m ahead of the face runs in at $\varepsilon = 0.3\,\mathrm{clip}((p_t+\Delta h-p)/\Delta h,0,1)$ with $\Delta h = 0.4\,\mathrm{bar}$. The face-loss law is zero whenever $p \geq p_t$. No shield-gap, tail-void or consolidation loss is modeled, so a face held on its target settles nothing, a point taken up in Section 11.7.

Table 11.2 Parameters, Their Defaults and Their Status. A = Adjustable in the Advanced Panel, T = Teaching Value, S = Inside a Cited Range. Two Values Are Clay, Sand

Symbol	Meaning	Value	Unit	Status
D, A	shield diameter, face area	6.5, 33.18	m, m^2	declared
V_c	chamber volume	30	m^3	T
z_0, z_{wt}	axis depth, water table	15, 3	m	T
h_r	river depth	8	m	T
γ	unit weight	19.5, 20.0	kN/m^3	T
ρ_s	muck density	1990, 2040	kg/m^3	T
K_0	at-rest coefficient	0.60, 0.45	—	S [18]
B_c	condensed stiffness	40, 800	bar	T, A
FER	foam expansion ratio	10	—	T
C_f	seepage conductance	4×10^{-11}, 1.2×10^{-9}	m^3/(s Pa)	T
β_g	gas loss per bar	2×10^{-6}, 3×10^{-4}	l/s	T
σ_s	seepage scale	1	—	A
ρ_b	bentonite density	1030	kg/m^3	T
$Q_{b,max}$	bentonite capacity	8	m^3/h	T
η	screw efficiency	0.75	—	T, A
V_{rev}	screw volume per revolution	0.35	m^3	T
L_s, D_s	screw length, diameter	12, 0.9	m	T
ω_{max}, τ_ω	screw range, drive lag	22, 3	rpm, s	T
$\tau_{0,c}$, $\tau_{0,s}$	plug shear strength	15, 10	kPa	T, A
k_{sp}	spew conductance	2×10^{-6}	m^3/(s Pa)	T
c_x, c_t	face loss per unit deficit	0.05, 1.4	—, mm/min	T, A
K	trough width factor	0.50, 0.35	—	S [4], A
a, T_0	torque per mm/min, at rest	1.52, 2.04 / 20	%	T
F_{skin}, k_F	skin friction, per mm/min	10, 12 / 0.08	MN	T
F_{max}, τ_v	thrust rating, cylinder lag	40, 10	MN, s	T
ring	width, build time	1.5, 20	m, min	declared, A
survey	leveling, report, round	1.5, 0.5, 4	h	T, A
limits	budget, torque	15, 90	mm, %	T

11.3.7 Machine, Instruments and Survey

The screw and the advance follow their commands through first-order lags of 3 s and 10 s. Cutterhead torque in percent of a 5 MN m rating is $T = 20 + a\,v\,\mathrm{e}^{-\mathrm{FIR}/0.5} + T_b$ with v in mm/min, $a = 1.52$ in the clay and 2.04 in the sand, and a boulder T_b that ramps 30 points over 0.15 m and back. Thrust in percent of 40 MN is $100(pA + F_{skin} + k_F v)/F_{max}$ with F_{skin} 10 and 12 MN and $k_F = 0.08$ MN per mm/min. Three cells on the bulkhead, 2.5 m above, at and below the axis, read $p \mp \rho_{mix} g\, 2.5\,\mathrm{m}$ through a 3 s lag with colored noise of 0.005 bar. The belt scale reads the screw's discharge 120 s later through a 10 s lag with 2 % noise. Each survey point is armed when the face passes it, leveled 1.5 h later, reported 0.5 h after the leveling with 0.5 mm of noise, and leveled again every 4 h. A reported value holds until the next one, and the instruments draw their noise from their own seeded stream.

11.3.8 Parameters, Initialization and Numerics

Table 11.2 lists the parameters with their status. Each case starts lined out at its chainage, advance, foam and pressure. A bisection finds the chamber turnover at which inflow fills V_c at the starting pressure, the gas is polished so the pressure is exact, and the screw starts at the speed that holds it. The plant advances by fourth-order Runge-Kutta steps of $\Delta t = 0.5$ s with every ledger carried through the same stages, the controller runs every 1 s and the log every 10 s, on the three clocks of Section 1.6.1. Each step's lost volume is assigned to the cell the face crossed and its bowl is added to every point. The chamber's mass balance closes to 2.0×10^{-13} of the mass that entered over a disturbed two-hour run.

11.3.9 Assumptions

The chamber is full and well mixed, with one pressure at the axis and a hydrostatic gradient over the bulkhead, so a chamber run part-full under compressed air is out of scope, and the model is least

reliable just after a large mismatch has emptied it. The condensed stiffness B_c lumps the muck, the bulkhead and the face. Its two values were chosen so that the stiffness about doubles at the boundary, and no measurement fixes them. The gas is ideal and isothermal and decays only by escaping into the ground. The plug, seepage and gas-loss laws carry the directions of the cited tests and teaching magnitudes. The ground loss is a closure proportional to the deficit, the face never collapses, and no loss arises at the shield gap, the tail void or by consolidation. The trough is a greenfield sum of bowls, so the building neither stiffens the ground nor changes the trough. The river is a uniform 8 m of water over a level bed, and the sand under it is the sand on land. The settlement budget, the blow-out limit at the crown's overburden and the 90 % torque limit are teaching values. Real ones come from the project's ground-movement criteria and a building damage assessment [5], from a face stability analysis [3] and from the machine's rating, and a pass here is no assessment of any real drive.

11.4 Why the Face Is Hard to Hold

11.4.1 An Integrator Whose Gain Is the Foam

With the chamber full, a screw 1 rpm faster removes $\eta V_{rev} = 0.2625\,\mathrm{m}^3$ a minute, and the pressure falls at $B\eta V_{rev}/(60V_c)$. That is 274 Pa/s per rpm in the clay at 48 m and 550 Pa/s per rpm in the sand at 52 m, at the same 40 % foam. On the plant a 1 rpm step falls at 266 and 512 Pa/s between 10 and 20 s, the gap being the screw drive's lag and, in the sand, a stiffness that falls to 31.9 bar within a minute as the pressure drops 0.27 bar. In case 1 the stiffness is 21.3 bar, which predicts 0.187 bar a minute for the 1 rpm error against the 0.168 bar measured in the first minute through the drive and cell lags. There is no self-regulation. Balancing the flows stops the pressure where it is and does not bring it back.

Pause. Try Exercise 11.1 before reading on.

The doubling at the boundary has two causes. The stiffness rises from 18.82 to 37.72 bar, a factor of 2.00. With no gas escaping into the sand the same chamber would be 30.4 bar stiff, so 1.62 of the factor comes from the two teaching values of B_c, and the rest from the gas that the sand's pores take (it keeps 78 % of its gas at this turnover). More foam softens the chamber. In the sand of case 6 the stiffness averaged over three hours 43.9 bar at 40 %, 31.1 bar at 60 % and 21.3 bar at 95 %, so the foam ratio is the loop gain as well as the plug's strength.

11.4.2 A Stop the Screw Cannot Cover

Every 1.5 m of stroke the advance comes to rest, the screw stops and its gate closes for twenty minutes. Nothing enters and nothing leaves by the screw, so the pressure moves only by seepage, as shown in Figure 11.2a. In the sand at 55.5 m with 60 % foam, the chamber starts the build 0.15 bar over its 1.997 bar target, falls under it 2.2 min into the build and reaches 1.516 bar at its end, heading for the 1.177 bar pore pressure. The face meanwhile lost enough ground to settle the 57.5 m point 1.76 mm after the first build from this stop. The 1.78 mm figure occurs only after the second build has begun. The second handle is bentonite slurry injected into the crown, which with its hold loop kept the chamber at or above 2.056 bar with 1.10 m^3 through the build and a peak of 5.78 m^3/h.

> **TRY IT IN THE APP 3 · The Ring Build: Twenty Minutes With Nothing Coming In**
>
> Load the scenario and press Run on the Chamber view. Watch the chamber pressure through the shaded ring build: with the gate shut it falls under its dashed at-rest target 2.2 min into the build and ends near 1.52 bar. Set Bentonite hold in the ring build to On, press Reset and run again. The chamber now stays at or above 2.06 bar.

11.4.3 A Plug That Fails at Any Speed

The screw's inlet pressure is the chamber's pressure plus the head of muck over the invert, while the plug's capacity depends on the muck and only 15 % on the speed. At 25 % foam in the sand the plug

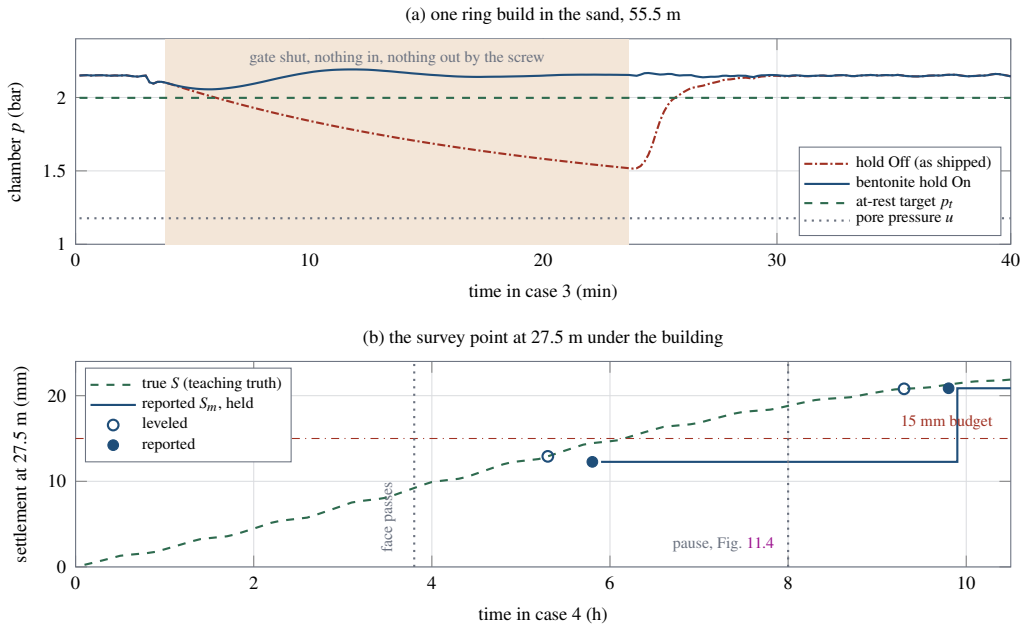


Figure 11.2 The forced stop and the late product, from the simulator. (a) Case 3 in the sand, the chamber through one ring build (shaded) without the bentonite hold (dash-dotted) and with it (solid), against the at-rest target (dashed) and the pore pressure (dotted). (b) Case 4 at the 27.5 m point, the true settlement (dashed), the leveling marks (open circles) and the held reports (solid steps, filled dots), with the budget dash-dotted. The first report, 12.3 mm at 5.80 h, is under the budget while the point is already at 14.5 mm and on its way to 21.3 mm.

holds at most 2.072 bar at full speed, and with the chamber at the land's 1.997 bar target the inlet sees at least 2.284 bar even for a muck as light as water. No screw speed, setpoint, advance or bentonite rate can then hold the chamber without spewing, which is the honestly infeasible variant of case 6. A sweep of 936 hand-set and automatic runs over four chainages including the river found none.

11.4.4 A Target That Moves and a Product That Arrives Late

The target rises by 0.947 bar from the sand on land to the river, because the water adds to the pore pressure and to the vertical stress. The river's 2.944 bar is level with the land's blow-out limit expressed at the axis, so no flat setpoint passes over one with room and under the other.

🕮 **Pause.** Try Exercise 11.3 before reading on.

The settlement is late for two reasons. A loss at the face spreads a bowl $i = 7.5$ m either way in the clay, so a point keeps settling until the face is well past, and a point's first report comes 2 h after the face passed it. In case 4 the 27.5 m point, passed at 3.80 h, was leveled at 5.30 h at 12.9 mm, reported 12.3 mm (with the survey's noise) at 5.80 h with the truth at 14.5 mm, and reported again 20.9 mm at 9.80 h, as shown in Figure 11.2b. A first report under 15 mm can still fail. A paper machine's traversing gauge, which posts a quality only after a whole scan and holds it until the next, poses the same problem of a product measured late in Volume 6, Chapter 3.

11.5 The Control Layers as Implemented

Every layer runs each $\Delta t_c = 1$ s from a measurement packet filled once per physics step with the three cells, the screw speed and torque, the cylinders' stroke and rate, the chainage, the cutterhead torque and thrust, the foam and bentonite flows, the belt scale and the survey reports, plus the declared

site investigation (the soils and target profile of the default plant). A source check in the test suite confirms that the controller and the ring sequencer contain no read of a plant state, a settlement, a score or a truth output.

11.5.1 The Screw Loop and Its Feedforward

The pressure loop is the velocity-form PI of Section 1.6.2, with the limit on the output alone and back-calculation on the integral. It acts on the axis cell in bar and speeds the screw when the pressure is over its setpoint (action $a = -1$ in Equation (1.12)), as shown in Equation (11.7).

$$
\begin{aligned}
e_k &= p_{mid,k} - p_{SP,k}, \qquad s_k = s_{k-1} + K_c(e_k - e_{k-1}) \\
\hat{u}_k &= s_k + I_{k-1} \\
u_k &= \min(\omega_{max} - \omega_{ff},\ \max(-\omega_{ff},\ \hat{u}_k)) \\
I_k &= I_{k-1} + \left[\frac{K_c}{\tau_I} e_k + \frac{u_k - \hat{u}_k}{\tau_I}\right]\Delta t_c \\
\omega_{cmd} &= \omega_{ff} + u_k \\
\omega_{ff} &= \frac{60 A v_m}{\eta V_{rev}}\left[\left(1 + \frac{\mathrm{FIR}}{\mathrm{FER}}\right)\left(1 - \frac{p_{mid}}{B_c}\right)\right. \\
&\qquad \left. + \mathrm{FIR}\left(1 - \frac{1}{\mathrm{FER}}\right)\frac{p_{atm}}{p_{mid} + p_{atm}}\right]
\end{aligned}
\tag{11.7}
$$

where the running sum s_k is never clamped, v_m is the measured advance, and B_c and FER inside ω_{ff} are the declared soil's. In the symbols of Equations (1.12) to (1.15), s_k is S_k with no derivative term, $\hat{u}_k$ is v_k and $T_t = \tau_I$. The defaults are $K_c = 15\,\mathrm{rpm/bar}$ and $\tau_I = 90\,\mathrm{s}$. The feedforward is the speed that discharges what the measured advance brings in, and the PI's range is shifted by it, so the integral never winds up against a limit the feedforward has already used. While the gate is shut the PI tracks a stopped screw, and switching the feedforward, the mode or the gate moves the command by 0.000, 0.000 and 0.043 rpm.

11.5.2 The Hold and the Ring Sequence

The ring sequencer reads only the stroke and the advance. At a stroke of 1.5 m it asks the advance to stop, keeps the screw loop running until the advance reads under 0.5 mm/min, then shuts the gate for twenty minutes, and on restart ramps the advance cap at 20 mm/min per minute. During the build a second PI on the same axis cell sets the bentonite flow, which rises when the pressure is under its setpoint, with $K_{c,b} = 18\,\mathrm{m^3/h}$ per bar and $\tau_{I,b} = 60\,\mathrm{s}$ with an output range of 0 to $8\,\mathrm{m^3/h}$, and in the original layered structure at every other time it tracks zero.

11.5.3 The Advance Supervisor and the Mid-Ranging Limit

With the supervisor on, the advance request is the least of five limits, each an integrator on the request actually selected, as shown in Equation (11.8). The minimum is a low selector (Section 1.4.3), and starting every limit from the selected request is external reset (Section 1.4.4).

$$
\begin{aligned}
b &= \min(v_{k-1}, v_{cap}) \\
v_k &= \max\left(0, \min\{v_{max}, v_T, v_F, v_\omega, v_{ramp}\}\right) \\
v_T &= b + k_T(T_{SP} - T)\Delta t_c \\
v_F &= b + k_F(90 - F)\Delta t_c \\
v_\omega &= b + k_\omega(0.85\,\omega_{max} - \omega)\Delta t_c \\
v_{ramp} &= b + r_v \Delta t_c
\end{aligned}
\tag{11.8}
$$

where v_{cap} is the ring sequence's ceiling, $k_T = 0.08\,\mathrm{mm/min}$ per percent second, $k_F = 0.02\,\mathrm{mm/min}$ per percent second, $k_\omega = 0.15\,\mathrm{mm/min}$ per rpm second, $r_v = 10\,\mathrm{mm/min}$ per minute, $v_{max} =$

100 mm/min and $T_{SP} = 82\,\%$ by default. Because every limit starts from the same selected base, none winds up while another holds the advance or a ring build stops it. The screw-room limit v_ω is the mid-ranging piece [10]. The fast screw holds the pressure, and when it nears the top of its range the slow advance yields. It is the valve-position law of Section 1.4.7 acting as one input of a selector, while Chapter 10 stacks three mid-ranging layers on one power block. A torque interlock stops the advance at 100 % and releases it under 95 %.

11.5.4 Foam, the Chainage Feedforward and the Detector

The foam ratio is fixed, or by soil from the declared consistency target of the soil half a meter ahead (30 % in clay, 60 % in sand). The chainage feedforward sets $p_{SP} = \max\{\hat{p}_t(x-0.5), \hat{p}_t(x), \hat{p}_t(x+0.5)\} + \Delta p$ from the declared target with a margin $\Delta p = 0.15$ bar, so the setpoint covers the span the face occupies. The over-excavation detector compares the belt scale with the theoretical mass rate $\hat{\rho}_s A v_m + \rho_w \,\mathrm{FIR} A v_m/\mathrm{FER} + \rho_b Q_b$ (plus the foam's gas) delayed by the same 120 s, both through 60 s averages, and alarms while their ratio exceeds 1.08 with the face advancing faster than 5 mm/min.

11.5.5 Nominal Predictive Coordination

The plant model is that of Section 11.3. A reader who identifies the screw's effect from case 1 finds an integrating gain of about 0.17 bar a minute per rpm. The shipped controllers' model is the declared soil and machine inside ω_{ff} and the declared target profile, which a change to a ground parameter in the Advanced panel does not update.

The optional MPC optimizes screw and advance [19], in the general form of Section 1.6.3, using measured pressure p_m (bar), screw speed ω (rpm) and advance v (mm/min) as states. Its coefficients use declared geometry, soil and commanded foam f. Define liquid and gas volume factors $L = (1 + f/\mathrm{FER})(1 - p_m/B_c)$ and $G = f(1 - 1/\mathrm{FER})p_{atm}/(p_m + p_{atm})$. Then $n_g = G/(L+G)$ gives the nominal stiffness B from Equation (11.2), without reading the chamber's actual gas. The local balance is

$$\begin{aligned} \dot{p}_m &= g_\omega g\omega + g_v v + BQ_b/V_c + \hat{d}, \\ \dot{\omega} &= (u_\omega - \omega)/3, \qquad \dot{v} = (u_v - v)/10, \\ g_\omega &= -B\eta V_{rev}/(60V_c), \qquad g_v = BA(L+G)/(60000V_c). \end{aligned} \tag{11.9}$$

Here g is the current gate state, Q_b is the applied injection in m^3/s, and $\hat{d}$ is a pressure-rate disturbance in bar/s. At the clay design point $B = 21.2933$ bar, $g_\omega = -0.00310527$ bar/s/rpm and $g_v = 0.000411525$ bar/s per mm/min. Torque is predicted as $a_f v + b_T$, with $a_f = a\exp(-f/0.5)$, and thrust as $a_p p_m + a_v v + b_F$, with $a_p = 8.29577$ percentage points/bar and $a_v = 0.2$ percentage points per mm/min. The biases b_T and b_F match the current measured outputs.

Bidirectional steps over 120 s, with 240 samples at 0.5 s, give pressure RMS residuals of 0.001549 and 0.001 763 bar for screw and advance. The independent 0.01 s reference integration includes the known 3 s transmitter lag omitted from the prediction. The descriptive screw IPDT fit is $k' = -0.00293016$ bar/s/rpm with 4.428 s effective delay. It summarizes lags, not transport delay.

Offset correction [20] subtracts the nominal rate from measured pressure increments every 1 s, using mean measured speeds, the previous gate and applied injection. It is clipped to ± 0.05 bar/s and filtered with $\alpha = 1 - \exp(-1/45)$ as $\hat{d}_k = (1-\alpha)\hat{d}_{k-1} + \alpha d_{res,k}$. The correction keeps updating under Layers and in Manual and starts again at Reset. No Kalman gain is used.

The model is discretized exactly every 10 s for 60 samples (600 s). Ten blocks of 1, 1, 2, 3, 4, 6, 8, 10, 12 and 13 samples give 20 command variables and three nonnegative horizon-wide slacks. With

$u_j = (u_{\omega,j}, u_{v,j})$, the fixed default objective, up to a reference-only constant, is

$$\begin{aligned} J = \sum_{j=1}^{60} \big[& 30(p_j - r_j)^2 + 0.04(u_{\omega,j} - \bar{u}_{\omega,j})^2 \\ & + 0.002(u_{v,j} - \bar{u}_{v,j})^2 \big] \\ & + \sum_{b=1}^{10} \big[(\Delta u_{\omega,b})^2 + 0.02(\Delta u_{v,b})^2 \big] \\ & + 10^4 s_p^2 + 3 s_T^2 + 3 s_F^2 . \end{aligned} \tag{11.10}$$

The weights are in bar, rpm, mm/min and percentage points. The terminal weight is zero and the Hessian carries a ridge of 10^{-7}. The pressure and move priorities multiply the tracking and slack terms and the move terms, and both stay at 1 in this chapter. Normally $\bar{u}_\omega = 11$ rpm and $\bar{u}_v$ is the allowed advance request.

Pressure $p_{SP} \pm 0.10$ bar, torque 85 % and thrust 90 % are soft, using one slack per output across all 60 samples. The pressure constraint remains centered on p_{SP} even when the objective reference r_j is boosted. Planned screw commands are hard-bounded at 0–18.7 rpm, and advance at zero to the live ceiling, also limited by the operator request when the supervisor is off. Block changes are at most 4 rpm and 10 mm/min, with exact holds inside each block. Initial measured speeds can exceed lowered command bounds while decaying. Sequence stops, interlocks, fallback and ceiling changes can reduce applied commands immediately, beyond planned move limits. The original gate, stop/restart sequence, 100 % torque interlock and capped 8 m^3/h hold retain priority.

The arrival preview divides the measured remaining stroke by the measured advance. The prediction sets both input references to zero after this estimated arrival, adds 0.03 bar to the pressure objective before arrival when it is less than 60 s away, and can pre-arm the existing hold in the last 20 s. Current gate and injection are otherwise held in the prediction. Setting the preview Off removes this forecast, and a declared timing error shifts only its time. Future restarts and events, hidden voids, the settlement and the live plant coefficients are not available to the plan. The layers have no forecast input, so each comparison below sets an MPC row with the preview Off beside the Layers row.

A plan is accepted only with an optimal status, correct shapes, a finite cost and iteration count, nonnegative finite slacks and finite predictions after conversion to pascals, and every sample must satisfy the command boxes, the block moves, the exact holds and the equality of the first move. A rejected plan holds the last applied commands for the first failed decision and then hands over to the tracked layered law within the hard bounds. A valid plan takes over again automatically. Thirteen injections of malformed results exercise these checks. Without noise, a failure or a manual transfer moves the first command by zero.

11.6 Results

The cases appear in Table 11.3. Each number below is a headless measurement on the default seed, taken in the page's own 0.5 s steps after any change a sentence names had been entered ahead of Run. Each case gives an identical run whether it is opened first, opened after some other case, or restarted with Reset. The exported file logs each instrument beside the quantity it measures, in a column whose name starts with `truth`.

11.6.1 The Inventory and the Loop

In case 1 the screw 1 rpm slow raised the axis cell from 2.397 to 2.565 bar in a minute and to 2.754 bar in two. Balancing the chamber set the screw to 5.22 rpm at the higher pressure, and the cell read 2.767 bar five minutes later, not 2.40 bar. A screw 1 rpm fast lowered it 0.190 bar in a minute. In case 2 the advance step of 50 % needed 3.37 rpm more screw (the feedforward computes 3.31 rpm). Without the feedforward the PI found it only as the pressure rose, which peaked 0.180 bar over

Table 11.3 The Cases, as Shipped

#	Start and settings	Teaching point
1	Manual, clay 8 m, 40 mm/min, screw 5.3 rpm	the inventory
2	Auto, clay 12 m, PI 15/90 s, screw feedforward Off, advance 50 to 75 mm/min at 15 min	loop and feedforward
3	Sand 55.5 m, 60 % foam, SP 2.15 bar, hold Off, 0.15 m to a ring	the forced stop
4	Clay 20.5 m, SP 2.05 bar under the building, pause at 8 h	budget and late survey
5	Sand 59 m, 60 % foam, SP 2.40 bar, river ahead, pause at 6 h	chainage feedforward
6	Sand 52 m, 25 % foam, SP 2.15 bar	plug, stiffness, infeasibility
7	Clay 47.5 m, 40 % foam, PI 80/20 s, chainage feedforward On	gain change at the boundary
8	Clay 34 m, SP 2.40 bar, void at 36–37 m, pause at 6 h	belt scale before survey
9	Auto, sand, 0.15 m stroke remaining, hold On, MPC pinned	arrival forecast comparison
10	Whole drive, screw held (gain 0), 50 mm/min, 25 % foam, no hold, no feedforward, boulder at 31 m	the whole problem

Table 11.4 Measured Results on the Cases. Settlement Is the Worst True Value at a Survey Point at the Instant Named

Case, instant	Setting	Settlement (mm)	Other
3, end of build	hold Off	1.76	min 1.516 bar
	hold On	0.00	min 2.056 bar
4, 8 h	SP 2.05 bar (shipped)	18.81	deficit 0.222 bar
	SP 2.10 bar	13.44	
	SP 2.16 bar	7.00	
	SP 2.20 bar	2.70	
	SP 2.23 bar	0.09	
	SP 2.40 bar	0.00	
5, 6 h	SP 2.40 bar (shipped)	100.5	blow-out 0
	chainage feedforward	0.0	blow-out 0
	SP 2.88 bar	11.8	blow-out 0
	SP 2.94 bar	1.2	blow-out 48.2 min
	SP 3.10 bar	0.0	blow-out 78.0 min
6, 3 h	foam 25 % (shipped)	60.6	spew 120 min
	foam 40 %	0.0	*B* 43.9 bar, torque 66 %
	foam 95 %	0.0	*B* 21.3 bar, torque 35 %
8, 6 h	SP 2.40 bar (shipped)	15.5	5.52 m^3 over
	SP 2.55 bar	5.2	1.87 m^3 over
	SP 2.65 bar	0.0	none over

setpoint 44 s after the step and stayed outside ± 0.02 bar for 227 s. With it the peak was 0.023 bar and the band was regained in 41 s, while retuning alone reached 0.074 bar at 40 rpm/bar and 40 s and 0.464 bar at 5 rpm/bar and 200 s. Acting on the cause instead of waiting for its effect is the same move as the coagulant feedforward of Volume 3, Chapter 6.

11.6.2 The Building, the River and the Boundary

Case 4 holds 2.05 bar, 0.18 bar under the clay's target, and at the 8 h pause the worst point had truly settled 18.81 mm at 27.5 m. The budget fixes a band, and raising the setpoint before the face arrives is the only remedy, as listed in Table 11.4. In case 5 the fixed 2.40 bar left the face 0.605 bar short under the river and settled the 65 m point 100.5 mm by 6 h, a trough already 60.2 mm deep at 4 h as shown in Figure 11.4b, while the chainage feedforward kept the chamber on or over its target and nothing settled. In case 7 the tight tuning held the clay within 0.028 bar with the screw between 5.0 and 8.6 rpm, and in the sand, whose chamber averaged 42.4 bar against 18.8 bar while mining, the screw swung from 0.3 to 17.0 rpm with the pressure 0.206 bar off. Halving the gain restored 0.060 bar in the sand, and the shipped 15/90 s is calm in both (0.039 and 0.076 bar).

🕮 **Pause.** Try Exercise 11.2 before reading on.

11.6.3 Foam and the Void

At 25 % foam in case 6 the muck spewed every minute the gate was open, 120 min in the first 3 h, the screw stopped at 0.0 rpm as the loop asked for less outflow, and the street settled 60.6 mm. At 40 % the plug held 3.17 bar against an inlet of 2.68 bar. More foam softened the chamber and needed more bentonite in the same three ring builds, 2.33, 3.26 and 4.67 m^3 at 40, 60 and 95 %. In case 8 the void began to run in at 62.0 min and the detector alarmed 228 s later, at 65.8 min with the face at 36.19 m, while the pressure loop simply took the extra muck out. The survey's first report of the damage came at the 35 m point at 140 min, 15.4 mm.

11.6.4 The Drive

The challenge asks for the 100 m in at most 48 h with every survey point at most 15 mm (true), no spewing, no blow-out risk and the torque at most 90 %, judged when the survey has reported every point. Most of the drive time is fixed by the lining. As shipped the drive took 57.56 h, of which 66 ring builds were 22.00 h, the restarts 2.73 h and the mining 31.97 h at 50 mm/min. The suggested configuration took 46.85 h, of which 65 builds were 21.67 h and the mining 24.24 h at a mean 68.1 mm/min, so the supervisor wins about a fifth of the time and only from the mining. Table 11.5 lists the configurations. The hold, the chainage feedforward and the supervisor are each necessary on wide sweeps. Without the hold the drive fails in all 15 combinations of a margin from 0.15 to 0.60 bar with a sand foam of 60, 80 or 100 %. Without the chainage feedforward it fails at all 31 fixed setpoints from 2.60 to 3.20 bar in steps of 0.02 bar, and without the supervisor at every fixed advance tried from 46 to 60 mm/min, on time at 46 to 47.9 mm/min (58.9 to 60.3 h) and on torque from 48 mm/min up. The screw feedforward is sufficient but not necessary. Without it the suggested 15/90 s loop fails on 3.1 min of blow-out risk, while four retuned loops pass, from 25/60 s at 4.0 mm to 40/20 s at 1.2 mm, and the two most aggressive (60/30 s and 80/20 s) fail on blow-out minutes again. Figure 11.3 sets the peak torque and the drive time of every configuration against the challenge's two limits.

> **TRY IT IN THE APP** **Challenge · The 100 m Drive, the Street Kept**
>
> Run the drive as shipped. It takes 57.6 h, the boulder takes the torque to 96.1 %, and the verdict is a fail. Press Reveal suggested tuning, press Reset and run again. With the advance supervisor slowing the advance at its torque target, the drive takes 46.9 h, the torque peaks at 86.1 %, and the verdict is a pass.

The mid-ranging limit is idle on the drive as shipped. With the suggested settings the supervisor's binding limit was the torque target for 37.7 % of the mining, its climb for 39.0 % and the ceiling for 23.3 %, and the screw never passed 17.8 rpm against its 18.7 rpm room limit. With a screw efficiency of 0.50 the limit bound for 31.6 % of the mining, held the chamber within 0.37 bar of its setpoint and slowed the drive to 48.5 h. Switched off by a test hook, the same screw sat at full speed for 347 min and the crown spent 48.4 min over its overburden. The challenge is built so that the reader must assemble the layers, and the full drive is shown at its building reach in Figure 11.4a from case 4.

> **DID YOU KNOW?** **No Fixed Advance Rate Passes the Drive**
>
> From the simulator: with the supervisor off, a fixed 48 mm/min took the boulder's torque to 90.04 %, over the 90 % limit, while 47.9 mm/min held it to 89.9 %. Both needed 58.9 h against the 48 h allowed (Table 11.5). Only a limit that moves with the ground wins both.

11.6.5 Predictive and Classical Comparisons

Table 11.6 compares the laws on matched seeds, instruments, events and settings, over windows of 6 h at the boundary, 2 h for each ring and 60 h for the challenge. The held ring is case 9, which starts

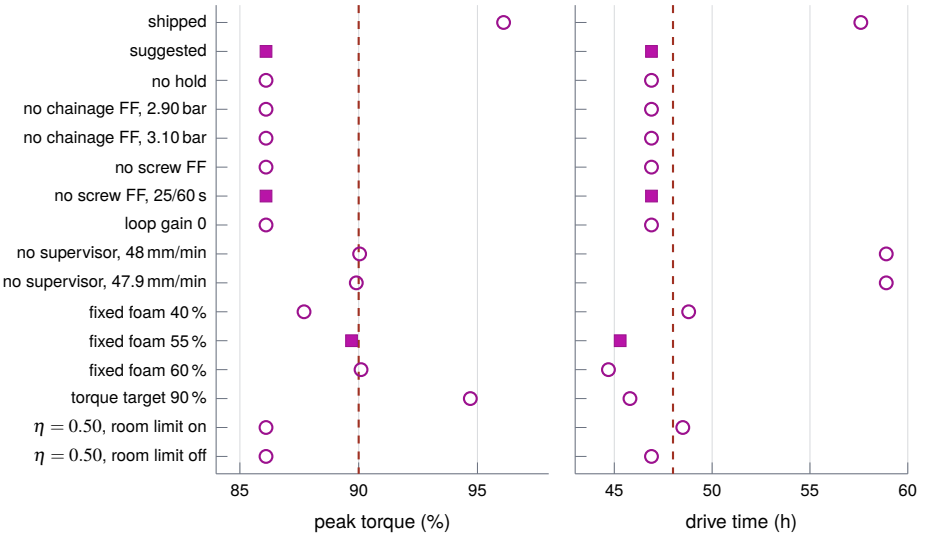


Figure 11.3 Peak torque and drive time of every configuration of Table 11.5, against the challenge's limits of 90 % and 48 h (dashed). Filled squares pass, open circles fail. Notice that the two fixed advances near 48 mm/min cannot meet both limits at once, while with the supervisor on the torque stays at or under 89.7 % unless its target is raised to 90 % or the foam is fixed at 60 %. Runs that fail inside both lines failed on settlement, spewing or blow-out minutes.

Table 11.5 The Drive. Worst True Settlement, Spewing and Blow-Out Minutes, Peak Torque and Drive Time

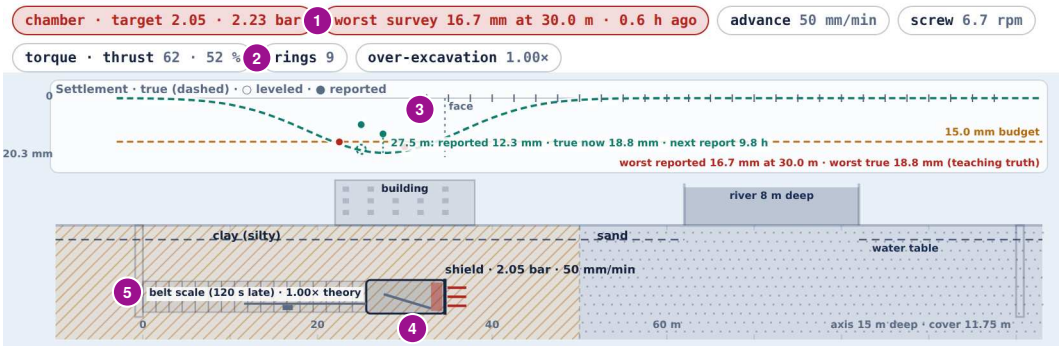
Configuration	S (mm)	Spew (min)	Blow (min)	T (%)	Drive (h)	Verdict
shipped	245.3	2079.1	1675.3	96.1	57.6	fails
suggested	0.0	0	0	86.1	46.9	passes
no hold	21.7	0	0	86.1	46.9	fails
no chainage FF, 2.90 bar	14.3	0	102.3	86.1	46.9	fails
no chainage FF, 3.10 bar	0.0	0	2302.7	86.1	46.9	fails
no screw FF	10.3	0	3.1	86.1	46.9	fails
no screw FF, 25/60 s	4.0	0	0	86.1	46.9	passes
loop gain 0	45.6	6.5	36.8	86.1	46.9	fails
no supervisor, 48 mm/min	0.0	0	0	90.04	58.9	fails
no supervisor, 47.9 mm/min	0.0	0	0	89.9	58.9	fails
fixed foam 40 %	69.6	371.1	0	87.7	48.8	fails
fixed foam 55 %	0.0	0	0	89.7	45.3	passes
fixed foam 60 %	0.0	0	0	90.1	44.7	fails
torque target 90 %	0.0	0	0	94.7	45.8	fails
$\eta = 0.50$, room limit on	1.6	0	0	86.1	48.5	fails (time)
$\eta = 0.50$, room limit off[a]	2.4	0.5	48.4	86.1	46.9	fails

[a] A test hook only, not a setting in the Control panel.

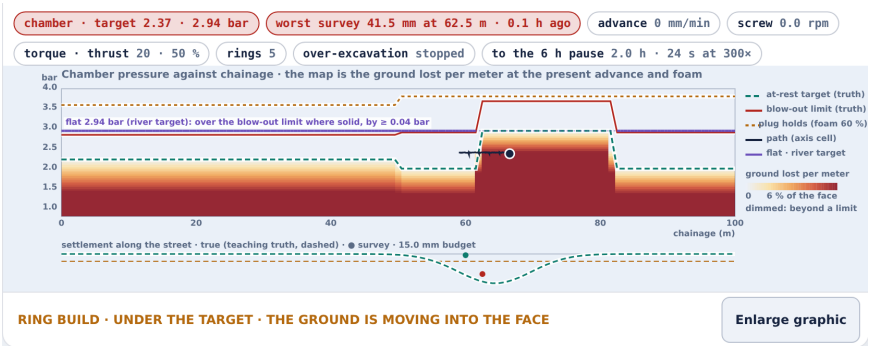
in sand with 0.15 m of stroke remaining and the hold On, and its Layers row selects Layers explicitly. The hold-Off ring is case 3, which keeps its hold Off.

The classical row applies the integrating SIMC rule [21] once, with $\lambda = \theta = 4.4\,\text{s}$ from the descriptive screw fit. It gives $K_c = 1/[|k'|(\lambda+\theta)] = 38.78159438$ rpm/bar and $\tau_I = 4(\lambda+\theta) = 35.2\,\text{s}$. The PI receives the pressure in bar. In the challenge the classical settings otherwise equal the suggested configuration. No tuning search or MPC adjustment was used.

Define control-band depth $d_c = \max(0, |p_m - p_{SP}| - 0.10)$ in bar and $I_c = \int d_c\,dt/60$ in bar min, with seconds as the integration variable. Physical depth instead uses the true target and blow-out limit, $d_g = \max(0, p_t - p, p - p_{blow})$, expressed in bar, with integral I_g. The two bands differ. The



(a)



(b)

Figure 11.4 The late survey and the moving target. (a) Case 4 on the Section view at the 8 h pause, cropped to the readouts, the survey strip and the section, with the setpoint held at 2.05 bar against a 2.23 bar target (callout 1). The face had reached 34.6 m by the pause, and the rings readout counts nine builds. The screw turns at 6.7 rpm at 50 mm/min, and the torque and thrust, the supervisor's two machine limits, read 62 and 52 % (2). The survey's worst report is 16.7 mm at 30.0 m, 0.6 h old, and the dotted drop at 27.5 m (3) joins a held report of 12.3 mm to the true 18.8 mm, next reported at 9.8 h. The shield (4) carries the belt scale (5) behind it, which reads the discharge 120 s late. (b) Case 5 on the Envelope view at 4 h, during a ring build under the river with the fixed 2.40 bar setpoint. The axis cell reads 2.37 bar against a 2.94 bar target, the trough under the river has reached 60.2 mm (true) at 65 m and the survey's worst report is 41.5 mm at 62.5 m. The flat line at the river's target (violet in the app) is solid where it lies over the land's blow-out limit, by at least 0.04 bar at the present muck density of 1734 kg/m^3.

settlement is evaluation truth and never controller feedback.

On the held ring the MPC loses to the layers (0.26259 versus 0.04993 bar min), and with the hold Off it also loses (15.76819 versus 15.38332). The classical loop has the lowest integral in all four cases. With the preview On the MPC beats the preview Off on the held ring (0.26259 versus 5.45064 bar min), which supports the preview within this policy.

At 160 s the chamber under MPC On, Layers and MPC Off reads 2.19868, 2.08392 and 1.654 60 bar, as shown in Figure 11.5. The control changes when each run reaches the ring. A wrong preview can even help: an error of −120 s gives 0.02681 bar min on the held ring.

In the challenge the suggested and the classical layers pass at 46.8508 h of drive time. MPC On reaches the end at 44.7519 h but fails on 9 s of blow-out risk, MPC Off passes at 43.4329 h with 6.1221 mm of settlement, and the wrong preview fails on time at 50.9667 h. The survey is first complete at 48.0032, 45.5221, 44.2564 and 51.5776 h, in the same order. The 60 h integrals include

Table 11.6 Fixed-Law Comparisons at the Default 0.5 s Step. t_c Is Time Outside the Control Band, d_c Its Maximum Depth, S Worst True Settlement, X Advance and B_q Bentonite. All Solves Succeed.

Case	Law	I_c bar min	t_c min	d_c bar	I_g bar min	S mm	X m	B_q m^3	T_{max} %	F_{max} %	Solves
Boundary, 6 h	Layers	1.925	71.608	0.110	0.640	0.538	10.561	4.776	65.832	60.130	0
Boundary, 6 h	Classical	0.000	0.000	0.000	0.000	0.000	10.561	4.499	65.832	59.000	0
Boundary, 6 h	MPC On	0.302	15.508	0.072	0.011	0.004	10.524	5.119	65.832	58.883	2160
Boundary, 6 h	MPC Off	1.355	23.717	0.105	0.318	0.098	10.560	5.838	65.832	59.015	2160
Boundary, 6 h	MPC −120 s	0.050	3.158	0.066	0.002	0.001	9.724	4.261	65.832	58.697	2160
Hold Off, 2 h	Layers	15.383	53.192	0.539	12.740	4.158	3.176	0.000	50.722	57.923	0
Hold Off, 2 h	Classical	14.326	49.058	0.530	11.855	3.850	3.176	0.000	50.722	57.973	0
Hold Off, 2 h	MPC On	15.768	52.050	0.580	13.174	4.295	3.160	0.000	50.722	57.922	720
Hold Off, 2 h	MPC Off	20.323	56.633	0.616	17.400	5.643	3.176	0.000	50.722	57.921	720
Hold Off, 2 h	MPC −120 s	12.302	39.400	0.581	10.299	3.363	3.070	0.000	50.722	58.037	720
Held ring, 2 h	Layers	0.050	5.458	0.021	0.000	0.000	4.146	3.522	81.444	67.915	0
Held ring, 2 h	Classical	0.000	0.000	0.000	0.000	0.000	4.146	3.307	81.444	67.969	0
Held ring, 2 h	MPC On	0.263	9.600	0.046	0.000	0.000	4.543	3.599	75.962	66.073	720
Held ring, 2 h	MPC Off	5.451	25.833	0.402	4.253	1.362	4.712	5.110	76.086	66.154	720
Held ring, 2 h	MPC −120 s	0.027	0.908	0.058	0.001	0.000	3.162	3.212	75.936	66.056	720
Challenge, 60 h	Layers	6455.591	3568.808	2.913	5731.508	245.269	100.008	0.000	96.096	79.913	0
Challenge, 60 h	Suggested	0.601	48.867	0.070	0.001	0.000	100.017	41.987	86.127	75.812	0
Challenge, 60 h	Classical	0.001	0.333	0.008	0.000	0.000	100.017	37.423	86.127	75.855	0
Challenge, 60 h	MPC On	4.584	125.192	0.309	0.670	0.162	100.016	47.713	89.255	74.156	21600
Challenge, 60 h	MPC Off	94.380	862.375	0.634	56.027	6.122	100.010	77.305	89.753	74.192	21600
Challenge, 60 h	MPC −120 s	2.010	30.767	0.439	1.295	0.371	100.014	41.048	87.906	74.118	21600

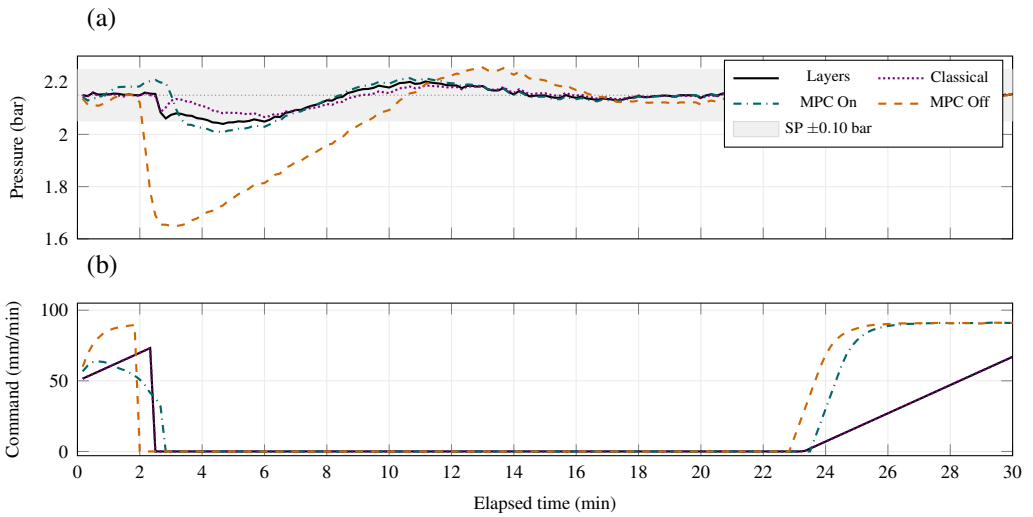


Figure 11.5 Measured ring-arrival transient over the first 30 min of the 2 h held-ring case, with Layers solid, the classical loop densely dotted, MPC On dash-dotted and MPC Off dashed. (a) Common pressure axes retain the Off minimum and show the setpoint band (shaded). (b) Applied advance commands on the same time axis. The full-run integrals in Table 11.6 include later ring cycles.

the holding after the drive has ended, 0.75607 bar min for MPC On. The advance averaged over the window differs from the productive rate, which uses the first arrival at 100 m. MPC On exceeds its soft 85 % torque target for 486.5 min, against 0.933 min for the suggested layers, both below the challenge's 90 % limit.

Faults injected unannounced at 300 s show further losses. With a water inflow, Layers, classical, MPC On and MPC Off settle 0.98982, 0.83311, 4.25629 and 5.970 91 mm. On spews for 1.792 min

and exceeds the blow-out limit for 6.500 min, against zero for Layers and classical. Off gives 0.383 and 1.525 min. The foam fault reaches 94.37 % torque under On against 83.15 % under Layers. Soft constraints allow these violations without a failed solve.

At 0.25 s, water-fault settlement changes from 4.256289 to 8.301 382 mm for On and 5.970910 to 7.586 344 mm for Off, reversing their order. The same seed draws a different noise path at the changed step. Matched noise-free runs give On 5.462907 to 5.488 265 mm and Off 6.615624 to 7.913 211 mm, so deterministic sensitivity also remains. Neither numerical convergence nor noise as the sole cause is established. The main pressure conclusions named above, MPC On against the layers and the classical loop, and the challenge grades survive the refinement. Other rankings need not: the wrong-forecast challenge integral changes from 2.009838 to 0.595714 bar min, slightly below suggested Layers' 0.598859 at the finer step, while still failing time. The fault settlement estimates are resolution-sensitive.

11.7 Verification, Agreement and What Is Not Claimed

The application's own suite of checks, expanded from 42 to 51, verifies the code. The chamber's mass balance closes to 2.0×10^{-13} of the mass entered over a disturbed two-hour run, a chamber lined out at its setpoint does not drift in ten minutes open loop, and a sealed chamber with seepage off changes neither pressure nor mass. A uniform 1 % loss superposed bowl by bowl reproduces $S_{max} = V_s/(\sqrt{2\pi}\, i)$ to every printed digit, 17.651 mm in the clay and 25.215 mm in the sand, with $S(i)/S(0) = 0.6065$ and $S(2i)/S(0) = 0.1353$, the Gaussian values. Halving the step moves case 4's worst settlement from 18.813 to 18.790 mm and changes no challenge number. For the original layered challenge, seeds 1 to 5 leave every number unchanged, because the noise enters only the cells, the belt and the survey and none of them decides a verdict. Playback at 60, 3600 and 7200× pauses at the same instants with the same verdicts, as Section 1.6.1 requires of the engine, and in a browser tab at 7200× the drive's verdict arrives in 24 to 29 s. The whole 48 h drive costs 0.8 s of headless computing, 2.3 µs per step.

Agreement with the literature is limited to what the cited records state. The trough factors 0.50 and 0.35 sit inside the published ranges [4]. The standstill loss in sand and not in clay has the direction field measurements report [8], and the model's states match the gas and liquid states of a published chamber model [9], but no magnitude was fitted to either. The suggested drive's 0.0 mm is stricter than any real drive, because the model has no shield-gap or tail-void loss. At the published median volume loss of 0.41 % of the face area for earth pressure balance drives [4], Peck's formula over this tunnel gives about 7.2 mm over the clay and 10.3 mm over the sand, and at the largest reported 0.83 %, 14.7 and 20.9 mm. The face-loss law is therefore no prediction of a real trough. It is the part of the loss that the face pressure controls. No educational evaluation has been made, and no learning gain is claimed.

Two plant fixes made in the last review of the simulator, a screw that starves once the chamber is under a quarter full and a spew whose time constant cannot fall under 1 s, moved no shipped or suggested run. They keep a screw run flat out by hand and a sand chamber at 0 % foam finite.

All ten cases run 52 h under MPC with finite outputs, bounded commands and zero solver failures. Tests reject 13 malformed plans and a stale-history mutant. Browser observations cover five decisions in 45 s at real time, with means of 1.16 and 1.56 ms for the solver and the full decision and 0.0222 % of a core for the whole control, and 8664 decisions in 12 s at 7200×, with 240 and 317 µs at near 60 frames a second. The 25 ms frame guard, which limits catch-up without skipping a decision that is due, was not active in either window. A forced replay with 4800 stops and replays at the browser's speeds preserve every value except the wall-clock times. Node and the browser differ in 113 rows, by at most 6.22×10^{-14} bar. The timings are host observations, not bounds.

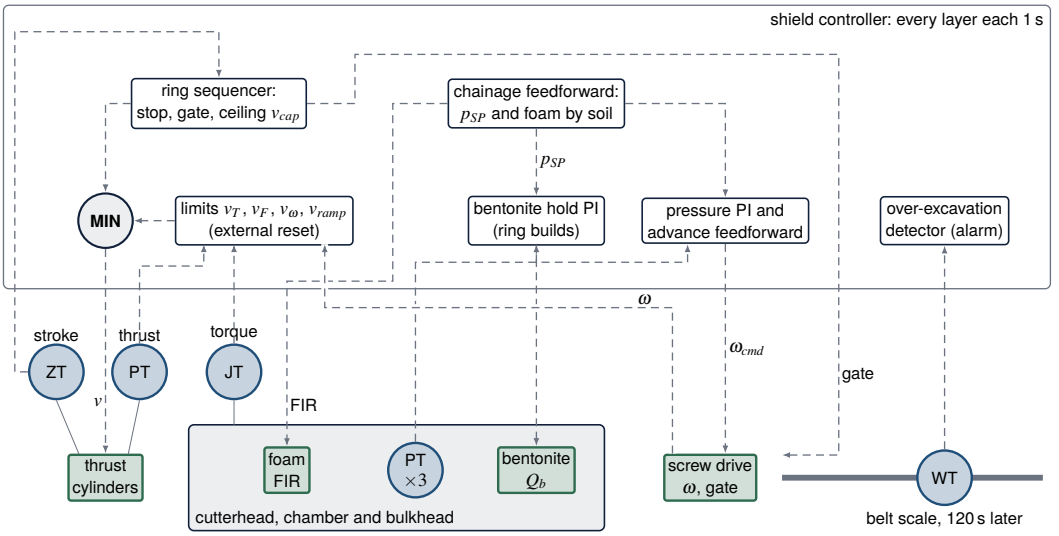


Figure 11.6 The face pressure's layers on real hardware. Three pressure cells (PT) on the bulkhead feed the pressure PI, which adds to the advance feedforward on the screw drive, and the bentonite hold, which injects slurry during ring builds. The chainage feedforward sets both setpoints and the foam. The thrust cylinders take the least of the ring sequencer's ceiling and the limits on torque (JT, from the cutterhead motors), thrust (PT, from the cylinder pressure) and screw speed. The belt scale (WT) reads the discharge 120 s late and only raises an alarm. Notice that every limit on the advance acts on the cylinders alone and leaves the screw loop free to hold the face.

11.8 Technology in Practice

A real shield reads and moves what the layers of Section 11.5 read and move. Figure 11.6 draws the screw loop, the bentonite hold and the advance supervisor's low selector with field hardware in place of the schematic's symbols.

What Measures It

In the earth pressure balance machine the pressure is transmitted to the face through the soil grains and is reduced by friction over the length of the screw conveyor. A slurry machine transmits it hydraulically and controls it with pressure gauges and control valves in a piping system, which gives a more precise and consistent control [2].

> **TECHNOLOGY Sensor: Pressure Cells on the Bulkhead**
>
> In an earth pressure balance machine the rotational speed of the screw is matched to the advance rate, and the pressure in the chamber is monitored with multiple sensors [2]. A process that carries solids tends to clog an instrument's impulse lines, as sludge does in wastewater service, and a remote seal's isolating diaphragm eliminates that problem. Its price is a time delay from the viscous fill fluid in the capillary, which makes the instrument slow, as if it carried a snubber [22]. No open source read gives a cell's range or accuracy. The model's three cells read through a 3 s lag with noise of 0.005 bar, and the loop uses the axis cell alone.

What Moves It

Conditioning agents are mixed with the soil through nozzles on the cutterhead, on the bulkhead and along the screw, to turn the muck into a plastic paste that keeps the screw full as a plug and lowers the torque of the cutterhead and the screw. Bentonite slurry is among those agents [23]. For a

rock machine, a high penetration rate does not by itself assure a high average advance rate, and the actual utilization typically runs in the range of 50 % [2]. The lining does the same to this drive: the suggested configuration spent 21.67 h of its 46.85 h building rings, so the supervisor can win time only from the mining.

> **TECHNOLOGY** **Final Element: Thrust Cylinders and the Screw Drive**
>
> The machine advances by shoving off the precast segments erected in its tail, and the force of its thrust cylinders passes from the pressure bulkhead onto the soil in the chamber. The amount of material removed is controlled by the speed of the screw and the opening of its discharge [2]. On one instrumented rock machine the thrust was read as hydraulic pressure in the cylinders, the cutterhead's load as the current of its motors, and the stroke by a device on the cylinder extension, which drew a sawtooth on the trend, one tooth for each stroke and retraction [24]. No open source read gives the speed of these drives. The model's screw and cylinders follow their commands through lags of 3 s and 10 s.

Where the Controller Runs

Manual or automatic operation of an earth pressure balance machine is possible through its integrated programmable logic controller and computer-control systems [2]. Supervisory and lower-level loops in such systems run continuously with cycle times from milliseconds to minutes [25]. Every layer of the application runs each 1 s, so the screw loop, the hold, the ring sequencer and the supervisor fit one controller scan, and the optional predictive coordinator plans on a 10 s grid in a supervisory layer above them.

What Is Modernizing It

Two developments bear on the face. The first is conditioning. New families of conditioning agents widen the range of both closed-face machine types and blur the line between them, and where the geology falls into more than one grading envelope a dual-mode open and closed machine, or a dual slurry and earth pressure balance system, may be developed [2]. The second is the machine's own data. On one instrumented rock machine a data acquisition system sent the pressures, currents, temperatures and the cylinder extension over a network to a laboratory's control system, where the mining cycle could be plotted from a distance [24], and a predictive controller built on a model learned from field data identified the screw speed and the advance speed as the major factors in the chamber pressure [1].

> **IN PRACTICE** **Face Pressure First, Then the Tail Void**
>
> Where ground is lost in the tunneling, the settlement can nearly always be mitigated. A highway tunnel manual names a closed, pressurized machine whose face pressure is at least the combined soil and groundwater pressure at tunnel level, and immediate, complete grouting of the space behind the segments, by automated systems that do not permit the machine to advance unless that void is grouted at the same time. Each percent of steering correction can translate to 1.5 % of ground loss. Good practice, with tight control of face pressure, is put at a volume loss of 0.5 % [2]. The grouting rule is one more interlock on the advance, like the torque interlock of Section 11.5.

11.9 Limitations

The drive is a teaching design, not a project. The condensed stiffness, the plug, the seepage and gas-loss coefficients, the face-loss closure and the torque law carry the directions of the cited work with magnitudes chosen so that each case teaches its point. The stiffness doubling across the boundary is mostly the two declared values of B_c. The street settles only through the face, so the absolute settlement is low against real drives and the comparison across configurations is the result. The trough is greenfield and transverse spreading is the only shape effect. The building does not interact with the ground, and no settlement develops with time once the face has stopped losing ground. The

chamber is always full, and a part-full chamber, face collapse, arching, steering, cutter wear and the slurry shield are outside the model. The declared site investigation equals the plant, so the chainage feedforward is exact except where a learner changes the ground. Rings are 1.509 m apart because the advance coasts about 8 mm through the cylinders' lag before each build, which gives 65 or 66 builds over the 100 m. The interlock and the flags are teaching devices rather than certified logic, and no part of the simulation is a safety case.

The MPC omits changing gas loss, conditioning, plug failure, voids and settlement. Residuals and output biases do not recover these dynamics. Its soft setpoint band differs from ground-support limits. Retained sequence and interlocks provide no actual-ground safety guarantee. The water-fault refinement limits quantitative settlement estimates. No retuning was used to force a ranking that holds in every case.

OPEN CHALLENGE **Choosing the Foam Without a Standard Test**

Foam conditioning is designed in the laboratory, yet no recognized standards are available for testing conditioned soil. The best foam injection ratio has to be found by specific tests, and pressure in the chamber lowers both the expansion and the injection ratio of the foam [23]. In this chapter the foam ratio sets the loop's gain as well as the plug's strength, so a standard test that links a laboratory mix to the stiffness and plug of a pressurized chamber would let a controller be tuned before the drive.

11.10 Conclusion

This chapter studied an earth pressure balance shield simulated as a full chamber whose pressure is its inventory, whose stiffness is set by the foam's gas, and whose outflow is a screw with a plug that can fail. One rpm of mismatch moves the clay chamber about 0.17 bar a minute and nothing returns it. Every ring build seals the chamber for twenty minutes, in which the sand drops it from 2.15 to 1.52 bar unless a bentonite hold keeps it over 2.06 bar. The target rises 0.95 bar under the river to the land's blow-out limit, so only a setpoint scheduled from the geology passes both reaches, and the survey's first report of a point under the building reads 12.3 mm while it is heading past 18.8 mm. Layered control drives the 100 m in 46.9 h against 57.6 h, with 21.7 and 22.0 h of them spent building rings, and the mid-ranging limit stays idle until the screw runs short. The settlement scale omits the losses no face pressure controls.

The optional MPC reduces the boundary band integral but fails the faster challenge on nine seconds of blow-out risk. A fuller model would add a tail-void and shield-gap loss fitted to published volume losses, a part-full chamber and a building that interacts with the trough, and improved predictive policies would sharpen the comparison. As it stands, the simulator is a plant for practicing inventory pressure control through forced stops against a product measured late.

KEY POINTS

- A shield holds up the ground with the muck in its chamber, and that pressure is an inventory that nothing returns once it drifts.
- Every ring build seals the chamber for twenty minutes, in which the sand drops it from 2.15 to 1.52 bar unless a bentonite hold keeps it over 2.06 bar.
- Only a setpoint scheduled from the geology passes both the land and the river.
- Layered control drives the 100 m in 46.9 h against 57.6 h.

Where else this applies. Chapter 7 caps a drill's thrust with pressure and torque overrides in the same kind of low selector, and Chapter 10 stacks three mid-ranging layers on one power block.

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11.11 Exercises

11.1 Concept check · 2 min

In case 1 the screw runs 1 rpm slower than the balance for two minutes, and the axis cell climbs from 2.397 to 2.754 bar. Balance the chamber then sets the screw to the speed that takes out what the advance brings in, and five minutes later the cell reads 2.767 bar. Why does the pressure not return to 2.40 bar?

(a) The screw drive's 3 s lag delays the return by several minutes

(b) The clay pushes water into the chamber, which holds the pressure up

(c) The pressure cells hold their old reading until the survey levels the face

(d) The pressure integrates inflow less outflow, so balanced flows stop it where it is

11.2 Concept check · 2 min

In case 7 a pressure loop tuned tight in the clay, 80 rpm/bar with a 20 s integral time, holds the axis cell within 0.028 bar. After the face crosses into the sand at the same 40 % foam, the screw swings between 0.3 and 17.0 rpm. What changed?

(a) The muck's stiffness about doubled, so each rpm moves the pressure about twice as fast

(b) The sand's seepage added a dead time between the screw and the pressure cells

(c) The screw's plug failed in the sand, so the screw speed no longer sets the outflow

(d) The chainage feedforward stepped the setpoint at the boundary and the loop overshot it

11.3 Concept check · 2 min

In case 5 a fixed setpoint of 2.40 bar settles the street 100.5 mm under the river. A fixed 2.88 bar still settles 11.8 mm, a fixed 2.94 bar spends 48.2 min at blow-out risk, and the chainage feedforward settles nothing. Why can no fixed setpoint pass both the land and the river?

(a) The plug cannot hold more than about 2.9 bar in sand, so a higher setpoint spews

(b) The river's target is level with the land's blow-out limit at the axis, so no flat line clears one and stays under the other

(c) The screw saturates under the river, so the loop cannot reach a higher setpoint

(d) The survey reports the river's settlement too late to correct a fixed setpoint

11.4 Theory and calculation · 6 min

The face's target and the blow-out limit, from Equation (11.1). The axis is 15 m deep, the water table 3 m below the street, the river 8 m deep, the shield's radius 3.25 m, and $\rho_w g = 9.81\,\mathrm{kN/m^3}$. The clay has $\gamma = 19.5\,\mathrm{kN/m^3}$ and $K_0 = 0.60$, the sand $\gamma = 20.0\,\mathrm{kN/m^3}$ and $K_0 = 0.45$.

(a) Find the vertical stress, the pore pressure and the target p_t at the axis in the clay on land. *Checkpoint:* 2.925 bar, 1.177 bar, 2.226 bar

(b) Find the target in the sand on land and under the river, and the rise between them. *Checkpoint:* 1.997 bar, 2.944 bar, 0.947 bar

(c) Find the crown's overburden $\sigma_{v,crown}$ in the sand on land. The blow-out flag compares the crown's chamber pressure $p - \rho_{mix} g R$ with it. At what axis pressure does the flag rise when the muck's density is 1734 kg/m^3, and how does that compare with the river's target? *Checkpoint:* 2.350 bar, 2.903 bar, 0.041 bar under it

11.5 Theory and calculation · 7 min

The screw as an integrator, from Section 11.4. One rpm of screw removes $\eta V_{rev} = 0.2625\,\mathrm{m^3}$ a minute from a chamber of $V_c = 30\,\mathrm{m^3}$.

(a) In case 1 the stiffness is $B = 21.3$ bar. Find the rate at which a 1 rpm mismatch moves the pressure, in bar a minute, and the time it takes to carry the axis cell from 2.40 to 2.91 bar. *Checkpoint:* 0.186 bar a minute, about 2.7 min

(b) Find the same rate in Pa/s per rpm in the clay at $B = 18.82$ bar and in the sand at $B = 37.72$ bar. By what factor does the loop gain of a PI with fixed tuning change at the boundary? *Checkpoint:* 274 and 550 Pa/s per rpm, a factor of 2.0

(c) A step test fits an integrating-plus-dead-time model with $k' = -0.002\,93$ bar/s per rpm and an effective delay of 4.4 s. Apply the SIMC rule for an integrating process with $\lambda = \theta$: $K_c = 1/[|k'|(\lambda + \theta)]$, $\tau_I = 4(\lambda + \theta)$. *Checkpoint:* 38.8 rpm/bar, 35.2 s

11.6 Theory and calculation · 6 min

The settlement trough, from Equation (11.6). A loss V_s per meter of tunnel spread evenly along the drive settles the axis by $S_{max} = V_s/(\sqrt{2\pi}\,i)$, with $i = Kz_0$, $z_0 = 15$ m, and the face area is $A = 33.18\,\text{m}^2$.

(a) Find S_{max} for a loss of 1 % of the face area in the clay ($K = 0.50$) and in the sand ($K = 0.35$). *Checkpoint:* 17.65 mm, 25.2 mm

(b) Find the settlement at a distance i and $2i$ from the trough's axis as fractions of S_{max}. How far from the axis is it half of S_{max} in the clay? *Checkpoint:* 0.607 and 0.135, about 8.8 m

(c) Repeat part (a) for the largest reported volume loss of 0.83 %. *Checkpoint:* 14.7 mm, 20.9 mm

11.7 App challenge · 8 min

Scenario 2, *The pressure loop on the screw*, default seed. Run it to 1500 s (25 min) at the case's 60× (about 25 s) and export the CSV file. The advance steps from 50 to 75 mm/min at 900 s.

(a) As shipped, with *Advance feedforward to the screw* Off, find the largest value of `p_mid_bar` less `p_sp_bar` after 900 s and its time, and the last row in which the two differ by more than 0.02 bar. *Checkpoint:* 0.177 bar at 940 s, 1120 s

(b) Set *Advance feedforward to the screw* to On, press Reset, run and export again. Find the largest deviation after 900 s, and `screw_rpm` at 890 and 1490 s. *Checkpoint:* 0.021 bar, 6.63 and 9.97 rpm

(c) From Equation (11.7), compute the change in ω_{ff} for the step, with $p_{mid} = 2.40$ bar, FIR 30 %, $B_c = 40$ bar, FER 10, $p_{atm} = 1.013$ bar, $A = 33.18\,\text{m}^2$ and $\eta V_{rev} = 0.2625\,\text{m}^3$. Compare it with `screw_ff_rpm` in the second file. *Checkpoint:* 3.31 rpm

Tolerance: 0.005 bar, 10 s and 0.03 rpm.

11.8 App challenge · 8 min

Scenario 3, *The ring build: twenty minutes with nothing coming in*, default seed. Run it to 2400 s (40 min) at the case's 60× (about 40 s) and export the CSV file.

(a) As shipped, with *Bentonite hold in the ring build* Off, find the rows in which `gate` is 0, the first row in which `truth_p_bar` is under `truth_target_bar`, and the lowest `p_mid_bar` while the gate is shut. *Checkpoint:* 230 to 1420 s, 370 s, 1.519 bar

(b) Read the scorecard tiles *Street · drive (true)* and *Face pressure deficit (true)*. *Checkpoint:* 1.8 mm at 57.5 m; 0.48 bar worst, 20 min under

(c) Set the hold to On, press Reset, run and export again. Find the lowest `truth_p_bar` while the gate is shut, the peak of `bentonite_m3h`, and the volume injected, the sum of `bentonite_m3h` times 10 s over 3600 s. *Checkpoint:* 2.056 bar, 5.78 m^3/h, 1.10 m^3

Tolerance: 10 s, 0.01 bar, 0.1 mm, 0.05 m^3/h and 0.05 m^3.

11.9 App challenge · 9 min

The challenge, *the 100 m drive, the street kept*, default seed, at 7200×. Each run pauses with the verdict when the survey has reported every point, after about 24 to 29 s.

(a) Run as shipped and read the verdict: worst settlement, minutes of spewing and of blow-out risk, peak torque and drive time. *Checkpoint:* 245.3 mm, 2079.1 min, 1675.3 min, 96.1 %, 57.6 h

(b) Press Reveal suggested tuning, then Reset and Run. Read the verdict, the clock when it arrives and the *Survey (reported)* tile. Why can the survey report more than the true settlement? *Checkpoint:* met, 0.0 mm, 46.9 h, 86.1 %; about 48.0 h; 1.0 mm at 87.5 m

(c) Set *Bentonite hold in the ring build* to Off, press Reset and Run. Read the verdict and the *Face pressure deficit (true)* tile. *Checkpoint:* not met, 21.7 mm at 97.5 m; 0.78 bar worst, 710 min under

Tolerance: 0.1 mm, 0.1 h and 0.1 min on the verdict values.

11.10 Application area · 4 min

The suggested drive settles the street 0.0 mm (true), and a project engineer wants to quote that number to the owner of the building over 22 to 38 m.

(a) Why is 0.0 mm no prediction of a real drive?

(b) Using Peck's formula of Exercise 11.6 and the published median volume loss of 0.41 % of the face area, what would a real drive add over the clay, and how much of the 15 mm budget would that leave for losses at the face? *Checkpoint:* 7.2 mm, 7.8 mm

(c) Where does a real settlement budget come from?

11.11 Application area · 4 min

In case 8 a loose pocket begins to run into the face at 62.0 min. The over-excavation detector alarms at 65.8 min, and the survey's first report of the damage, 15.4 mm at the 35 m point, comes at 140 min.

(a) What makes up most of the 228 s between the void and the alarm?

(b) How much earlier than the survey does the belt scale warn, and what fixes the survey's delay?

(c) The pressure loop holds its setpoint through the void. Why does it not see the over-excavation?

11.12 Review the agent · 5 min

An AI assistant reviews case 4 at its 8 h pause and writes: "The survey's first report of the 27.5 m point, the middle of the building, reads 12.3 mm, under the 15 mm budget. The 2.05 bar setpoint protects the building, and no change is needed." Find the flaw and say how you would check it in the application.