39(2)/57

University of Stavanger

FACULTY OF SCIENCE AND TECHNOLOGY

SUBJECT: MPE 680 Well Technology

DATE: December 3, 2013

TIME: 0900-1300

AID: Approved calculator

THE EXAM CONSISTS OF 3 PROBLEMS ON 8 PAGES + FORMULA SHEETS

REMARKS: Formula sheet is attached. It is considered a part of the exam for the candidate to make appropriate assumptions if confusions are encountered.

YOU ARE REQUIRED TO STATE ALL ASSUMPTIONS!

You are designing a vertical exploration well (see Figure 1, page 5).
The curves shown in Figure 1 are as follows, listed from left side towards right side:

1. Hydrostatic gradient (vertical at 1.03 s.g.)
2. Pore pressure gradient – low estimate
3. **Pore pressure gradient – medium estimate**
4. Pore pressure gradient – high estimate
5. Fracture gradient – low estimate
6. **Fracture gradient – medium estimate**
7. Fracture gradient – high estimate
8. **Overburden gradient**
9. The two line-dot curve sections are designed for problem 2d+2e.

Note also that the description of the formations, the formation group comes below the horizontal dotted lines (i.e. the first dotted line is marking the top of the Rogaland group, so that the Rogaland group is BETWEEN the first two dotted lines, and so on).

Problem 1: Casing strength under combined load (25%)

Assume a 9 5/8" casing of P110 quality and 53,5 lb/ft (see other specifications on attached data sheet). Such a casing has a minimum tensile yield strength of 110 000 psi. For this problem you may assume this yield strength is valid for all type of failures.

Now an axial load is applied simultaneously as an internal pressure. You are now supposed to define the failure envelope for this casing (i.e. internal pressure vs. axial load at failure) during a pressure testing scenario.

Internal pressure should have the unit of bar, and axial load should have unit kN.

Remember to state all other assumtions you make!
Make large figures, and include failure envelopes in problem a) and b) in the same figure!

a) Define the failure envelope using Rankine (σ_{max}) failure criteria (**make figure!**)

b) Define the failure envelope using Tresca (τ_{max}) failure criteria. (**make figure!**)

c) Which of the two failure envelopes are largest, and why? (*Hint: think on the general stress tensor and which part of it that governs the failure*).

d) Which of the two failure criteria do you consider the most correct to use for a combined load, and why?

Problem 2: Pore pressure/fracture gradient/casing design/stuck pipe (43,75%)

a) Looking at the water depth, we expect that a jack-up rig is being used. Do we have to account for the riser margin? Explain what the riser margin means, and then explain why or why not you would like to account for it!

b) Should the 13 3/8" casing be designed for full or reduced well integrity? Explain your answer. (see Table 1 for details).

c) What is the maximum allowable pore pressure if the 13 3/8" casing should have full well integrity? Also, what is the minimum and maximum allowable LOT-value below the 13 3/8" casing shoe?

d) You feel that the fracture gradient curves are poorly documented, and you need to do a quick estimate of the fracture gradient in the Shetland group and the Vestland group. You should assume the medium pore pressure gradient curve, BUT at the depths of interest, you should imagine that the pore pressure is continuously increasing (see the line-dot curve). You may assume that that the minimum horizontal stress equals 85% of the overburden. The geology suggests that there is an isotropic horizontal in-situ stress field. Calculate the fracture gradient at 2400 mTVD and at 3000 mTVD.

e) Now you should use the real medium pore pressure gradient to calculate the real fracture gradient. This means that the drop in pore pressure is a result of depleted pressure, and you should use the compaction model to calculate the fracture gradient. Calculate the expected real fracture gradient at 2400 mTVD and at 3000 mTVD.

f) It is a possibility that you need to plan for a sidetrack to this well. Calculate the expected fracture gradient at 2400 mTVD and at 3000 mTVD if the sidetrack has a 30 degree inclination.

g) Imagine that you actually drill the sidetrack and go stuck. Calculate the depth of stuck point if

- Kick off point @ 1080 mTVD
- DLS = 3 deg/30m
- Pipe elongation @ pull test = 2,70 m
- Pull force @ pull test = 841 kN
- 5" drill pipe, 19,5 ppf (see table 1 on page 4 and Figure 4 on page 8)

What is the name of the formation where the pipe is stuck?

Problem 3: Casing design (31,25%)

Perform design calculations for the 9 5/8" liner for this well (Figure 1).

PS! See input data in Table 1 and Figure 2+3 on the next pages.

Evaluate different collapse, burst and tension design criteria and calculate the following design factors:

PS! *You must explain if you should or should not account for biaxial stresses, wear, corrosion and bending moments*

a) Full well integrity or reduced well integrity? Explain.

b) Collapse design factor

c) Burst design factor

d) Tension design factor

e) Based on casing mechanical properties alone, is there another casing grade that would be a better choice than the P110? (assuming same nominal weight)

YOU ARE REQUIRED TO MAKE FIGURES FOR ALL DESIGN CRITERIA

Table 1 – Input data for all problems

The following well data applies:

Water depth:	90	m
Depth to sea level, MSL:	30	m
Mud weight:	1.72	s.g.
Cement density:	1.92	s.g.
Friction coefficient:	0.23	
Poisson ratio:	0.20	
Formation fluid density @ kick:	0.50	s.g.

The following casing data applies (See Figure 2+3 Casing data):

- 13 3/8" grade P110, 72.00 lb/ft casing (setting depth 1050 mTVD)
- 9 5/8" grade P110, 53.50 lb/ft liner
  - setting depth 2750 mTVD
  - top of liner @ 900 mTVD
  - top of cement @ 1900m
- Open hole section to 3200 mTVD

burst pressure = internal yield pressure

The following minimum casing design factors applies:

Tension	1.3
Burst	1.1
Collapse	1.1

Drill pipe and casing Youngs modulus: 200 kN/mm^2

Maximum allowable test pressure = 90% of casing strength

Some conversion factors:

- 1 kN/mm^2 = 10 000 bar = 1000 MPa = 1 GPa = 145 038 psi

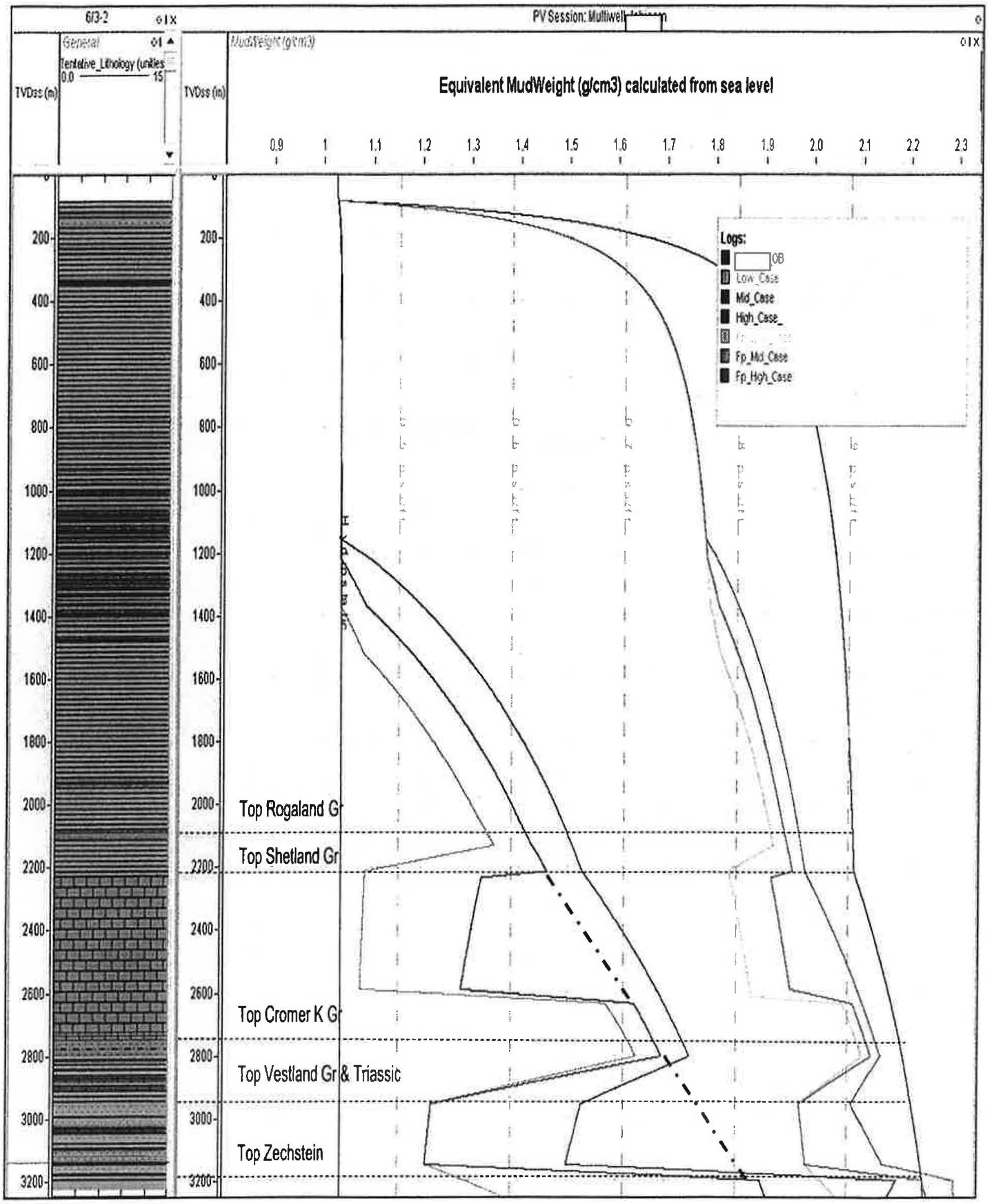


Figure 1 – Pore pressure gradient and fracture gradient curves

GEOMETRICAL CHARACTERISTICS AND MECHANICAL PROPERTIES OF CASING (continued)

Pipe body	1	Nominal size (OD)	1	**7.000** in				177.8 mm			**7.000** in				177.8 mm		
	2	Nominal weight	2	**41.00** lb/ft				59.8 daN/m			**44.00** lb/ft				64.2 daN/m		
	3	Wall thickness	3	0.590 in				15.0 mm			0.640 in				16.3 mm		
	4	Inside diameter	4	5.820 in				147.8 mm			5.720 in				145.3 mm		
	5	Steel cross-section	5	11.88 in^2				7665 mm^2			12.79 in^2				8250 mm^2		
	6	Capacity	6	1.38 gal/ft				17.16 l/m			1.33 gal/ft				16.58 l/m		
	7	Displacement (1)	7	2.00 gal/ft				24.83 l/m			2.00 gal/ft				24.83 l/m		
	8	Grade	8	K55	L80	N80	C90	T95	P110	Q125	K55	L80	N80	C90	T95	P110	Q125
	9	Collapse resistance (MPa)	9	58.5	85.1	85.1	95.8	101.1	117.1	133.0	63.0	91.6	91.6	103.1	108.8	126.0	143.2
	10	Internal yield pressure (MPa)	10	56.9	81.4	81.4	91.5	96.6	111.9	127.1	60.7	88.3	88.3	99.3	104.8	121.3	137.9
	11	Pipe body yield strength (1000 daN)	11	291	423	423	476	502	581	661	313	455	455	512	540	626	711
Tensile strength (10^3 daN)	12	Buttress Standard	12	370	370	390	390	409	487	526	370	370	390	390	409	487	526
	13	Buttress Special Clearance	13	237	237	250	250	262	312	337	237	237	250	250	262	312	337
	14	API STC	14	279	356	362	393	414	483	541	303	387	394	427	450	526	589
	15	API LTC	15	307	391	398	431	455	531	589	334	426	433	469	495	577	641

GEOMETRICAL CHARACTERISTICS AND MECHANICAL PROPERTIES OF CASING (continued)

Pipe body	1	Nominal size (OD)	1	**9.625** in				244.5 mm			**9.625** in				244.5 mm		
	2	Nominal weight	2	**53.50** lb/ft				78.1 daN/m			**58.40** lb/ft				85.2 daN/m		
	3	Wall thickness	3	0.545 in				13.8 mm			0.595 in				15.1 mm		
	4	Inside diameter	4	8.535 in				216.8 mm			8.435 in				214.2 mm		
	5	Steel cross-section	5	15.55 in^2				10 030 mm^2			16.88 in^2				10 890 mm^2		
	6	Capacity	6	2.97 gal/ft				36.91 l/m			2.90 gal/ft				36.05 l/m		
	7	Displacement (1)	7	3.78 gal/ft				46.94 l/m			3.78 gal/ft				46.94 l/m		
	8	Grade	8	K55	L80	N80	C90	T95	P110	Q125	K55	L80	N80	C90	T95	P110	Q125
	9	Collapse resistance (MPa)	9	35.4	45.6	45.6	49.1	50.6	54.8	58.2	41.3	54.4	54.4	59.1	61.3	67.3	72.7
	10	Internal yield pressure (MPa)	10	37.6	54.7	54.7	61.5	64.9	75.2	85.4	41.0	59.7	59.7	67.1	70.9	82.0	93.2
	11	Pipe body yield strength (1000 daN)	11	380	553	553	622	657	761	864	413	601	601	678	713	826	939
Tensile strength (10^3 daN)	12	Buttress Standard	12	509	572	591	616	648	764	841	553	621	642	669	704	830	913
	13	Buttress Special Clearance	13	416	416	437	437	459	547	591	416	416	437	437	459	547	591
	14	API STC	14	311	405	411	448	473	551	618	342	446	452	493	520	606	680
	15	API LTC	15	359	466	472	515	543	633	710	395	512	519	566	596	696	780

GEOMETRICAL CHARACTERISTICS AND MECHANICAL PROPERTIES OF CASING (continued)

Pipe body	1	Nominal size (OD)	1	**13.375** in				339.7 mm			**13.375** in				339.7 mm		
	2	Nominal weight	2	**68.00** lb/ft				99.2 daN/m			**72.00** lb/ft				105.1 daN/m		
	3	Wall thickness	3	0.480 in				12.2 mm			0.514 in				13.1 mm		
	4	Inside diameter	4	12.415 in				315.3 mm			12.347 in				313.6 mm		
	5	Steel cross-section	5	19.45 in^2				12 545 mm^2			20.77 in^2				13 398 mm^2		
	6	Capacity	6	6.29 gal/ft				78.10 l/m			6.22 gal/ft				77.25 l/m		
	7	Displacement (1)	7	7.30 gal/ft				90.65 l/m			7.30 gal/ft				90.65 l/m		
	8	Grade	8	K55	L80	N80	C90	T95	P110	Q125	K55	L80	N80	C90	T95	P110	Q125
	9	Collapse resistance (MPa)	9	13.4	15.6	15.6	16.0	16.1	16.1	16.1	15.4	18.4	18.4	19.2	19.5	19.9	19.9
	10	Internal yield pressure (MPa)	10	23.8	34.6	34.6	39.0	41.1	47.6	54.1	25.5	37.1	37.1	41.7	44.1	51.0	58.0
	11	Pipe body yield strength (1000 daN)	11	476	692	692	778	822	951	1081	508	739	739	831	878	1016	1155
Tensile strength (10^3 daN)	12	Buttress Standard	12	578	687	705	749	788	925	1026	618	734	753	800	842	989	1096
	13	Buttress Special Clearance	13														
	14	API STC	14	370	424	428	470	490	577	649	345	458	463	508	535	623	701
	15	API LTC	15														

Figure 2 – Casing data

NEW (N), PREMIUM CLASS (P) AND CLASS 2 (2) DRILL PIPE, TORSIONAL AND TENSILE DATA (continued)
(API RP 7G, 15th edition, January 1, 1995)

Size OD	Nominal weight	Class	Torsional yield strength[1]								Tensile yield strength							
			E		95		105		135		E		95		105		135	
(in)	(lb/ft)		(ft lb)	(daN.m)	(ft lb)	(daN.m)	(ft lb)	(daN.m)	(ft lb)	(daN.m)	(lb)	(10³ daN)	(lb)	(10³ daN)	(lb)	(10³ daN)	(lb)	(10³ daN)
5	16.25	N	35 044	4 749	44 389	6 015	49 062	6 648	63 079	8 547	328 073	145.8	415 559	184.7	459 302	204.1	590 531	262.5
		P	27 607	3 741	34 969	4 738	38 650	5 237	49 693	6 733	259 155	115.2	328 263	145.9	362 817	161.3	466 479	207.3
		2	23 974	3 249	30 368	4 115	33 564	4 548	43 154	5 847	275 316	100.1	285 400	126.6	315 442	140.2	405 568	180.3
	19.50	N	41 167	5 578	52 144	7 066	57 633	7 809	74 100	10 041	395 596	175.8	501 087	222.7	553 833	246.1	712 070	316.5
		P	32 285	4 375	40 895	5 541	45 199	6 125	58 113	7 874	311 535	138.5	394 612	175.4	436 150	193.8	560 764	249.2
		2	27 976	3 791	35 436	4 802	39 166	5 307	50 356	6 823	270 432	120.2	342 548	152.2	378 605	166.3	486 778	216.3
	25.60	N	52 257	7 081	66 192	8 969	73 159	9 913	94 062	12 746	530 144	235.6	671 515	298.5	742 201	329.9	954 259	424.1
		P	40 544	5 494	51 356	6 959	56 762	7 691	72 979	9 889	414 690	184.3	525 274	233.5	580 566	258.0	746 443	331.8
		2	34 947	4 735	44 267	5 998	48 926	6 630	62 905	8 524	358 731	159.4	454 392	202.0	502 223	223.2	645 715	287.0

NEW (N), PREMIUM CLASS (P) AND CLASS 2 (2) DRILL PIPE, COLLAPSE AND BURST PRESSURE DATA (continued)
(API RP 7G, 15th edition, January 1, 1995)

Size OD	Nominal weight	Class	Collapse pressure								Burst pressure							
			E		95		105		135		E		95		105		135	
in	(lb/ft)		(psi)	(MPa)	(psi)	(MPa)	(psi)	(MPa)	(psi)	(MPa)	(psi)	(MPa)	(psi)	(MPa)	(psi)	(MPa)	(psi)	(MPa)
5	16.25	N	6 938	47.8	8 108	55.9	8 616	59.4	9 831	67.8	7 770	53.6	9 842	67.9	10 878	75.0	13 986	96.4
		P	4 490	31.0	4 935	34.0	5 067	34.9	5 661	39.0	7 104	49.0	8 998	62.0	9 946	68.6	12 787	88.2
		2	3 275	22.6	3 696	25.5	3 850	26.5	4 065	28.0	6 216	42.9	7 874	54.3	8 702	60.0	11 189	77.1
	19.50	N	9 962	68.7	12 026	82.9	12 999	89.6	15 672	108.1	9 503	65.5	12 037	83.0	13 304	91.7	17 105	117.9
		P	7 041	48.5	8 241	56.8	8 765	60.4	10 029	69.1	8 688	59.9	11 005	75.9	12 163	83.9	15 638	107.8
		2	5 514	38.0	6 262	43.2	6 552	45.2	7 079	48.8	7 602	52.4	9 629	66.4	10 643	73.4	13 684	94.3
	25.60	N	13 500	93.1	17 100	117.9	18 900	130.3	24 300	167.5	13 125	90.5	16 625	114.6	18 375	126.7	23 625	162.9
		P	11 458	79.0	14 514	100.1	16 042	110.6	20 510	141.4	12 000	82.7	15 200	104.8	16 800	115.8	21 600	148.9
		2	10 338	71.3	12 640	87.1	13 685	94.4	16 587	114.4	10 500	72.4	13 300	91.7	14 700	101.4	18 900	130.3

API DRILL PIPE LIST AND BODY AND UPSET GEOMETRY
(API Spec 5D, 3rd edition, August 1, 1992)

Nominal diameter		Nominal weight	Wall thickness of pipe body	Inside diameter of pipe body	Steel grade	Upset					
						IU		EU		IEU	
(in)	(mm)	(lb/ft)	(mm)	(mm)		OD (mm)	ID (mm)	OD (mm)	ID (mm)	OD (mm)	ID (mm)
5	127.0	16.25	7.52	112.0	E	127.0	95.2				
5	127.0	19.50	9.19	108.6	E X-G-S			– 146.1	– 100.0	131.8 131.8	93.7 90.5
5	127.0	25.60	12.70	101.6	E X-G-S			– 149.2	– 96.9	131.8 131.8	87.3 84.2

Figure 3 – Drill String data

STRESS AND STRAIN

$$[\sigma]=\begin{bmatrix}\sigma_x & \tau_{xy} & \tau_{xz}\\ \tau_{xy} & \sigma_y & \tau_{yz}\\ \tau_{xz} & \tau_{yz} & \sigma_z\end{bmatrix}$$

$$I_1=\sigma_x+\sigma_y+\sigma_z$$

$$I_2=\tau_{xy}^2+\tau_{xz}^2+\tau_{yz}^2-\sigma_x\sigma_y-\sigma_x\sigma_z-\sigma_y\sigma_z$$

$$I_3=\sigma_x\left(\sigma_y\sigma_z-\tau_{yz}^2\right)-\tau_{xy}\left(\tau_{xy}\sigma_z-\tau_{xz}\tau_{yz}\right)+\tau_{xz}\left(\tau_{xy}\tau_{yz}-\tau_{xz}\sigma_y\right)$$

$$\sigma^3-I_1\sigma^2-I_2\sigma-I_3=0$$

$$\text{Center}=\frac{1}{2}\left(\sigma_{xx}+\sigma_{yy}\right),\ \text{Radius}=\sqrt{\frac{\left(\sigma_{xx}-\sigma_{yy}\right)^2}{4}+\tau_{xy}^2},\ \tan(2\theta)=\frac{2\tau_{xy}}{\sigma_{xx}-\sigma_{yy}}$$

$$\sigma_{oct}=\frac{1}{3}\left(\sigma_1+\sigma_2+\sigma_3\right)\qquad \tau_{oct}=\frac{1}{3}\sqrt{\left(\sigma_1-\sigma_2\right)^2+\left(\sigma_1-\sigma_3\right)^2+\left(\sigma_2-\sigma_3\right)^2}\qquad \sigma_m=\frac{1}{3}\left(\sigma_1+\sigma_2+\sigma_3\right)$$

$$\varepsilon_{xx}=\frac{\partial u}{\partial x},\ \varepsilon_{yy}=\frac{\partial v}{\partial y},\ \varepsilon_{zz}=\frac{\partial w}{\partial z},\ \gamma_{xy}=2\varepsilon_{xy}=\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}$$

$$\sigma_{rr}=\frac{p_ir_i^2-p_or_o^2}{r_o^2-r_i^2}-\frac{r_i^2r_o^2}{r^2\left(r_o^2-r_i^2\right)}\left(p_i-p_o\right)$$

$$\sigma_{\theta\theta}=\frac{p_ir_i^2-p_or_o^2}{r_o^2-r_i^2}+\frac{r_i^2r_o^2}{r^2\left(r_o^2-r_i^2\right)}\left(p_i-p_o\right)$$

$$\sigma_{zz}=\frac{p_ir_i^2-p_or_o^2}{r_o^2-r_i^2}+\frac{F}{\pi\left(r_o^2-r_i^2\right)}$$

$$\sigma_{rr}=\frac{\alpha E\left(T_i-T_o\right)}{2(1-\nu)\ln\left(\frac{r_o}{r_i}\right)}\left[-\ln\frac{r_o}{r}+\frac{r_i^2\left(r_o^2-r^2\right)}{r^2\left(r_o^2-r_i^2\right)}\ln\frac{r_o}{r_i}\right]$$

$$\sigma_{\theta\theta}=\frac{\alpha E\left(T_i-T_o\right)}{2(1-\nu)\ln\left(\frac{r_o}{r_i}\right)}\left[1-\ln\frac{r_o}{r}-\frac{r_i^2\left(r_o^2+r^2\right)}{r^2\left(r_o^2-r_i^2\right)}\ln\frac{r_o}{r_i}\right]$$

$$\sigma_{zz}=\sigma_{rr}+\sigma_{\theta\theta}$$

$$u_{\text{(closed end)}}=\frac{r}{E\left(r_o^2-r_i^2\right)}\left[(1-2\nu)\left(p_ir_i^2-p_or_o^2\right)+\frac{(1+\nu)r_i^2r_o^2}{r^2}\left(p_i-p_o\right)-\nu\frac{F}{\pi}\right]$$

$$u_{\text{(open end)}}=\frac{r}{E\left(r_o^2-r_i^2\right)}\left[(1-\nu)\left(p_ir_i^2-p_or_o^2\right)+\frac{(1+\nu)r_i^2r_o^2}{r^2}\left(p_i-p_o\right)\right]$$

ROCK MECHANICS

$$J_2 = \frac{1}{6}\left[(\sigma_1-\sigma_2)^2 + (\sigma_1-\sigma_3)^2 + (\sigma_2-\sigma_3)^2\right]$$

$$\sigma_m - P_o = \frac{1}{3}(\sigma_1 + 2\sigma_3) - P_o$$

$$\tau = \tau_0 + \sigma' \tan\phi$$

$$\tau = \frac{1}{2}(\sigma_1' - \sigma_3')\cos\phi$$

$$\sigma' = \frac{1}{2}(\sigma_1' + \sigma_3') - \frac{1}{2}(\sigma_1' - \sigma_3')\sin\phi$$

$$\sigma_r = P_w$$

$$\sigma_\theta = \sigma_x + \sigma_y - P_w - 2(\sigma_x - \sigma_y)\cos(2\theta) - 4\tau_{xy}\sin(2\theta)$$

$$\sigma_z = \sigma_{zz}$$

$$\tau_{\theta z} = 2(\tau_{yz}\cos\theta - \tau_{xz}\sin\theta)$$

$$\tau_{rz} = \tau_{r\theta} = 0$$

$$\sigma_x = (\sigma_H \cos^2\beta + \sigma_h \sin^2\beta)\cos^2\gamma + \sigma_v \sin^2\gamma$$

$$\sigma_y = (\sigma_H \sin^2\beta + \sigma_h \cos^2\beta)$$

$$\sigma_{zz} = (\sigma_H \cos^2\beta + \sigma_h \sin^2\beta)\sin^2\gamma + \sigma_v \cos^2\gamma$$

$$\tau_{xz} = \frac{1}{2}(\sigma_H \cos^2\beta + \sigma_h \sin^2\beta - \sigma_v)\sin(2\gamma)$$

$$\tau_{yz} = \frac{1}{2}(\sigma_h - \sigma_H)\sin(2\beta)\sin\gamma$$

$$\tau_{xy} = \frac{1}{2}(\sigma_h - \sigma_H)\sin(2\beta)\cos\gamma$$

Borehole fracturing

$$P_{wf} = \sigma_x + \sigma_y - P_0 - 2(\sigma_x - \sigma_y)\cos(2\theta) - 4\tau_{xy}\sin(2\theta) - \frac{\tau_{\theta z}^2}{\sigma_z - P_0}$$

which for symmetric conditions and no shear stresses becomes $P_{wf} = 3\sigma_{min} - \sigma_{max} - P_0$

Borehole collapse

$$\sigma_1 = \frac{1}{2}(\sigma_\theta + \sigma_z) + \frac{1}{2}\sqrt{(\sigma_\theta - \sigma_z)^2 + 4\tau_{\theta z}^2}$$

The direction of failure is determined by the size of σ_x and σ_y (i.e. $\theta = 0^0$ or $\theta = 90^0$)

$$\frac{P_{LOT} + P_0}{\sigma_v} + \sin^2\gamma = (3\sin^2\beta - \cos^2\beta\cos^2\gamma)\frac{\sigma_k}{\sigma_v} + (3\cos^2\beta - \sin^2\beta\cos^2\gamma)\frac{\sigma_l}{\sigma_v}$$

which on short form becomes:

$P' = a\frac{\sigma_k}{\sigma_v} + b\frac{\sigma_l}{\sigma_v}$ where σ_H is the largest of σ_k, σ_l

PRESSURE

$$P[\text{bar}] = 0.098 \cdot MW[\text{s.g.}] \cdot D[\text{m}]$$

1 bar = 0.1 MPa

GEOMETRICAL PLANNING

$$\gamma = \tan^{-1}\left(\frac{H_t - R}{V_t - V_{KOP}}\right) + \sin^{-1}\left(\frac{R\cos(x)}{V_t - V_{KOP}}\right), \text{where } \tan(x) = \left(\frac{H_t - R}{V_t - V_{KOP}}\right) \text{ and } DLS = \frac{5400}{\pi R}$$

BUOYANCY

$$\beta = 1 - \frac{\rho_o A_o - \rho_i A_i}{\rho(A_o - A_i)}$$

$$\beta = 1 - \frac{\sum_{k=1}^{n} D_k(\rho_o R_k^2 - \rho_i r_k^2)}{\rho_{steel} \sum_{k=1}^{n} D_k(R_k^2 - r_k^2)}$$

TORQUE AND DRAG

$$F_2 = F_1 + \beta \Delta L w\{\cos\alpha \pm \mu \sin\alpha\}$$

$$T = \mu r \beta w \Delta L \sin\alpha$$

$$F_2 = F_1 e^{\pm\mu|\theta_2 - \theta_1|} + \beta w \Delta L \left\{\frac{\sin\alpha_2 - \sin\alpha_1}{\alpha_2 - \alpha_1}\right\}$$

$$T = \mu r N = \mu r F_1 |\theta_2 - \theta_1|$$

$$\psi = \tan^{-1}\left(\frac{V_h}{V_r}\right) = \tan^{-1}\left(\frac{60V_h(m/s)}{2\pi N_r(rpm)) r(m)}\right)$$

$$F_2 = F_1 + \beta w \Delta L \cos\alpha \pm \mu \beta w \Delta L \sin\alpha \sin\psi$$

$$T = r\mu\beta w \Delta L \sin\alpha \cos\psi$$

$$F_2 = F_1 + F_1(e^{\pm\mu|\theta_2 - \theta_1|} - 1)\sin\psi + \beta w \Delta L \left\{\frac{\sin\alpha_2 - \sin\alpha_1}{\alpha_2 - \alpha_1}\right\}$$

$$T = \mu r N = \mu r F_1 |\theta_2 - \theta_1| \cos\psi$$

STUCK PIPE

$F_{FREE} = \mu(\beta w h \sin(\gamma) + dh\Delta P)$ where h is the effective length of stuck pipe

SURVEY CALCULATION

$$\theta = cos^{-1}(sin\alpha_1 sin\alpha_2 cos(\beta_2 - \beta_1) + cos\alpha_1 cos\alpha_2)$$

$$\Phi = \frac{2}{\theta} tan\left(\frac{\theta}{2}\right)$$

$$\Delta N = \Phi \frac{\Delta L}{2}(sin\alpha_1 cos\beta_1 + sin\alpha_2 cos\beta_2)$$

$$\Delta E = \Phi \frac{\Delta L}{2}(sin\alpha_1 sin\beta_1 + sin\alpha_2 sin\beta_2)$$

$$\Delta V = \Phi \frac{\Delta L}{2}(cos\alpha_1 + cos\alpha_2)$$

GEOMECHANIC EVALUATION

$$LOT = 2\sigma_a - P_0$$

$$P_{wf}(\alpha) = P_{wf}(0) + \tfrac{1}{3}(P_0 - P_0^*)sin^2\alpha$$

$$P_{wf}(0) = \frac{P_{wf}(\alpha) + (\sigma_o - \tfrac{1}{2}P_0\ )sin^2\alpha}{1 + \tfrac{1}{2}sin^2\alpha}$$

$$\Delta\sigma_a = \frac{1-2\nu}{1-\nu}\Delta P_0$$

$$\Delta P_{wf} = \frac{1-3\nu}{1-\nu}\Delta P_0$$

DATA NORMALIZATION

$$d_1^{RKB} = \frac{D}{D-\Delta h} d_2^{RKB}$$

$$d_2^{wf} = \frac{D_1}{D_2} d_1^{wf} + \frac{D_2^w - D_1^w}{D_2} d^{sw}$$

RISER MARGIN

$$d_{min} = \frac{d_{P_0}D - 1.03h_w}{D - h_f - h_w}$$

CASING DESIGN

$$P_{burst} = \frac{2t}{OD}\sigma_{tensile}$$

$$P_{collapse} = \frac{2CE}{1-\nu^2}\left[\frac{1}{\left(\frac{OD}{t} - 1\right)^2 \frac{OD}{t}}\right]$$

$$\frac{\sigma_t}{\sigma_{yield}} = \frac{\sigma_a}{2\sigma_{yield}} \pm \sqrt{1 - \frac{3}{4}\left(\frac{\sigma_a}{\sigma_{yield}}\right)^2}$$

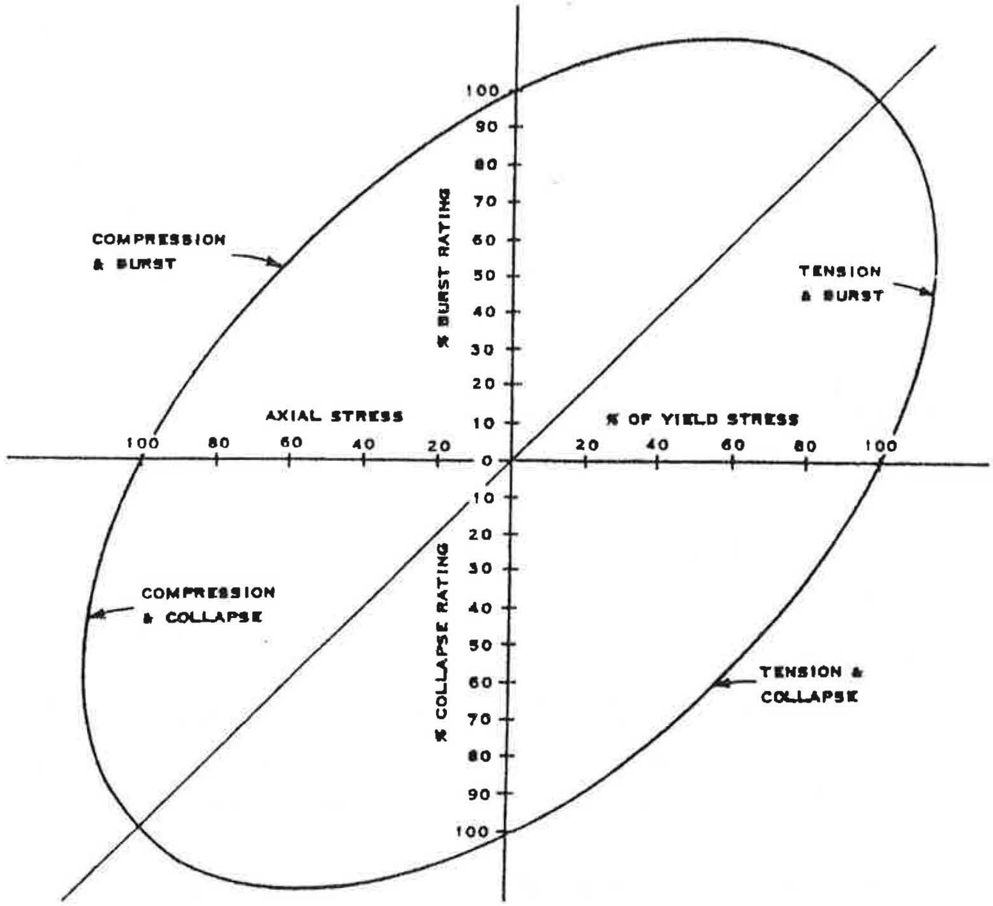
SOME UNITS

1 bar = 14.5 psi 1 ft = 12 in = 0.3048 m 1 lbf = 4.45 N

PRESSURE LOAD SUMMARY FOR CASING DESIGN

Note that the full casing design manual contains many more special cases and different correction criteria.

PIPE	*LOADING*	*INTERNAL PRESSURE*	*EXTERNAL PRESSURE*
Surface and intermediate casing	Burst while drilling	Gas gradient of 0.2 s.g. or actual	* Hydrostatic head from MSL before wellhead is installed. * Hydrostatic head from surface after wellhead is installed. Mud (previous section) above top of cement (TOC) Rock on outside: Pore pressure gradient below TOC Casing on outside: Seawater gradient below TOC
Surface and intermediate casing	Burst while in production	Mud plus trapped annular pressure	
Production casing	Burst	Leaking tubing: Shut-in tubing pressure plus 70 bar at top of completion fluid.	
Tubing	Burst	Shut-in tubing pressure plus 70 bar at surface plus gas gradient to reservoir.	Completion fluid gradient inside casing.
Surface and intermediate casing	Collapse during installation	1. Lost circulation: mud gradient 2. while cementing: displacing fluid gradient	* Hydrostatic head from MSL before wellhead is installed. * Hydrostatic head from surface after wellhead is installed. 1. Mud gradient 2. Cement gradient below TOC
Surface and intermediate casing	Collapse while drilling	Based on lost circulation while drilling next section.	* Hydrostatic head from MSL before wellhead is installed. * Hydrostatic head from surface after wellhead is installed. Mud (previous section) above top of cement (TOC) Rock on outside: Pore pressure gradient below TOC Casing on outside: Seawater gradient below TOC
Surface and intermediate casing	Collapse while in production	Mud base gradient	
Production casing	Collapse while in production	Plugged perforations / full evacuation to formation fluid	
Production casing	Collapse during installation	Mud gradient to fluid level.	Mud gradient to surface.
Tubing	Collapse	Full evacuation to formation fluid.	Completion fluid gradient inside casing.



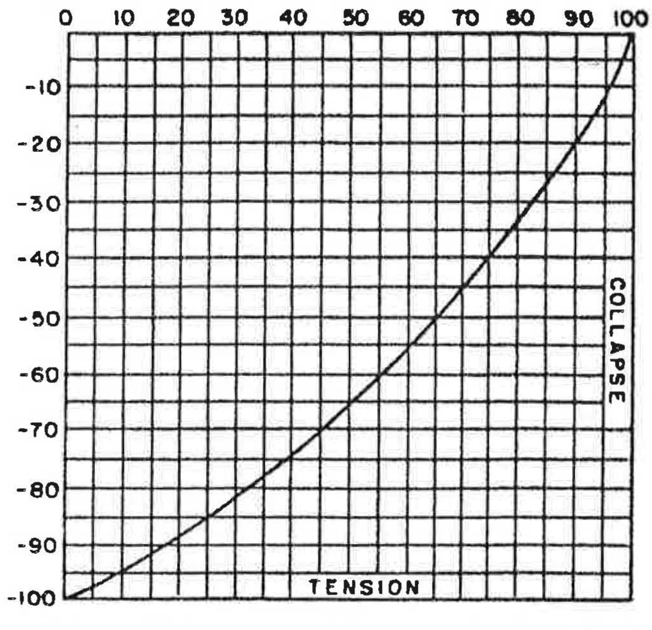


Figure 5.5. Ellipse of plasticity. a) Bi-axial relationships between tangential and axial stresses, b) Effects of axial tension on collapse resistance.