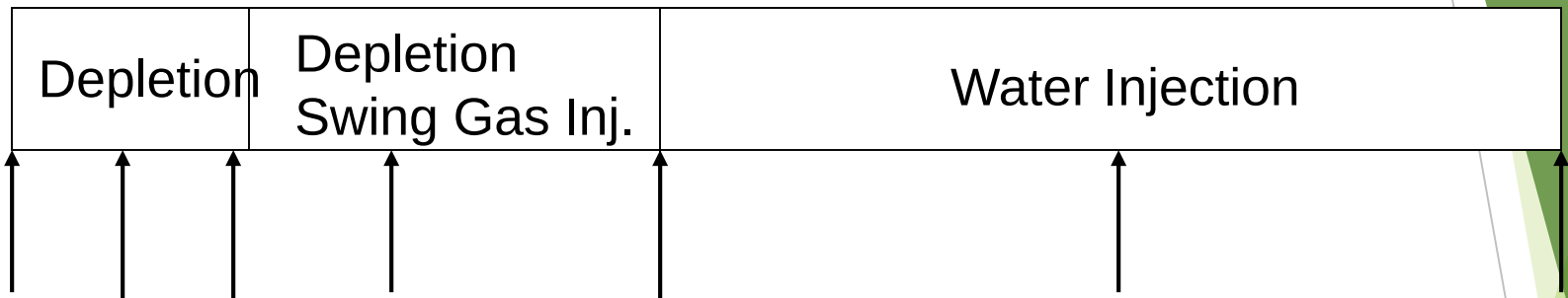
New Casing Design Criterion for Reservoirs with High Porosity

Nobuo Morita
Professor
Petroleum Engineering Department
Texas A&M University

Development Timeline

Ekofisk



1969
Discovery

1971
Test Production

1974
Field Development

1981
Water Inj.Pilot

1987
Water Injection

1996
Eko II
Field Redevelopment

2005
Ekofisk
Area Growth



Reservoir Compaction – Seabed Subsidence

Picture of concrete protective wall around 2/4 T



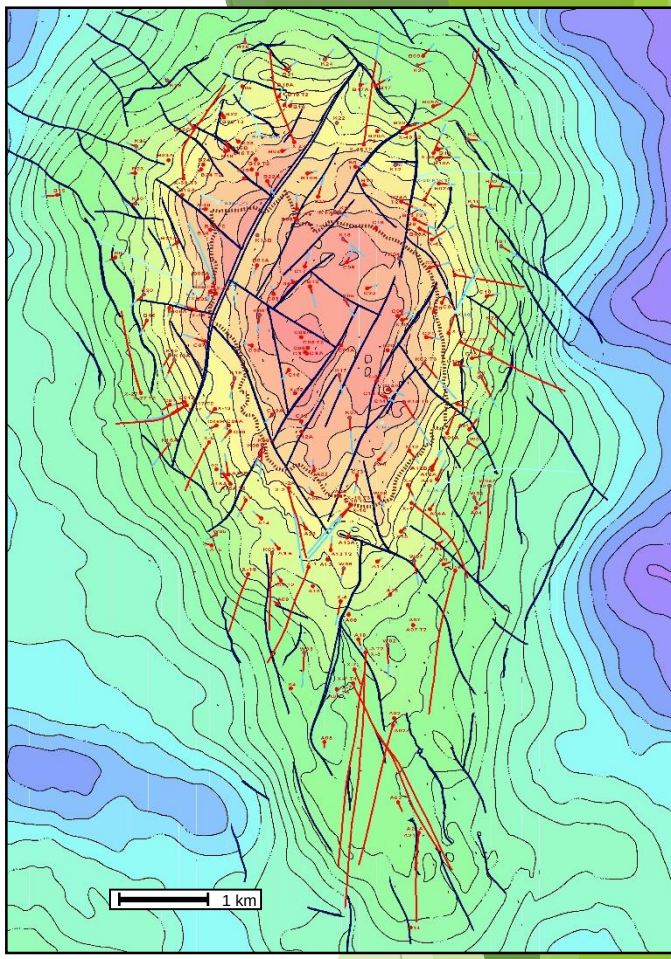


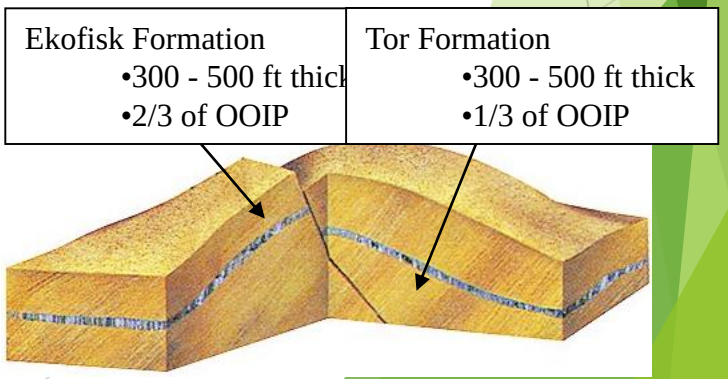
$600million
Jackup



Ekofisk Field

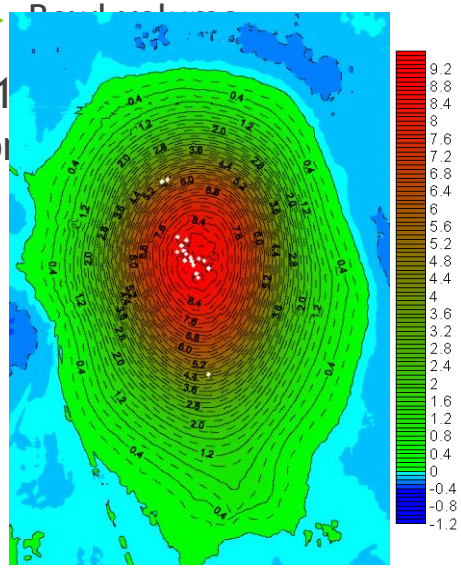
- Reservoir: Fractured Chalk
- Area ~ 10.1 x 5.4 kilometers
- Depth: 9500 – 10700 feet
- Pay thickness: ~ 980 ft. (~ 300 meters)
- High porosity matrix rock
  - 25-45%, avg. 31.7%
- Low matrix Permeability: 1-10 mD
- Max well test Permeability: 200 mD
- Initial Oil In Place 6,9 BSTB
  - Current RF : 37 %
  - Planned RF @ 2028 : 50 % (Ex. Ekofisk South)
- Drive mechanisms;
  - Solution gas drive
  - Waterflood
  - Compaction
  - Aquifer influx



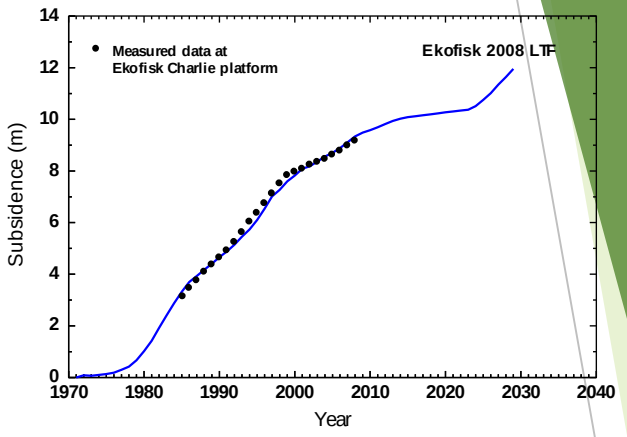


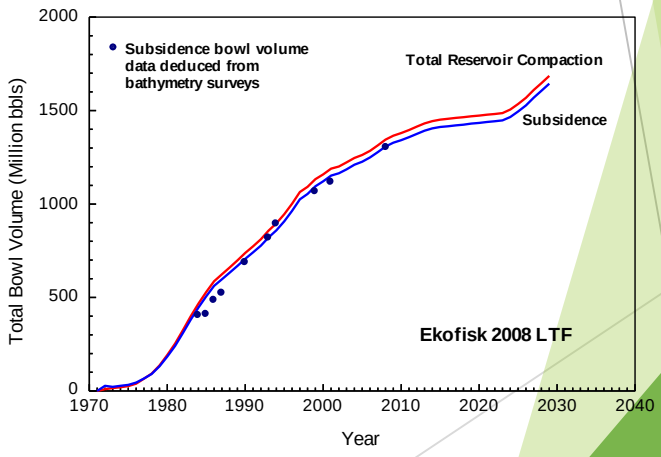
Matching the subsidence

- Matching the following parameters
  - Platform subsidence data
  - Bathymetry data
    - Bowl volume
  - C11 mor



2008 Ekofisk Subsidence Bowl

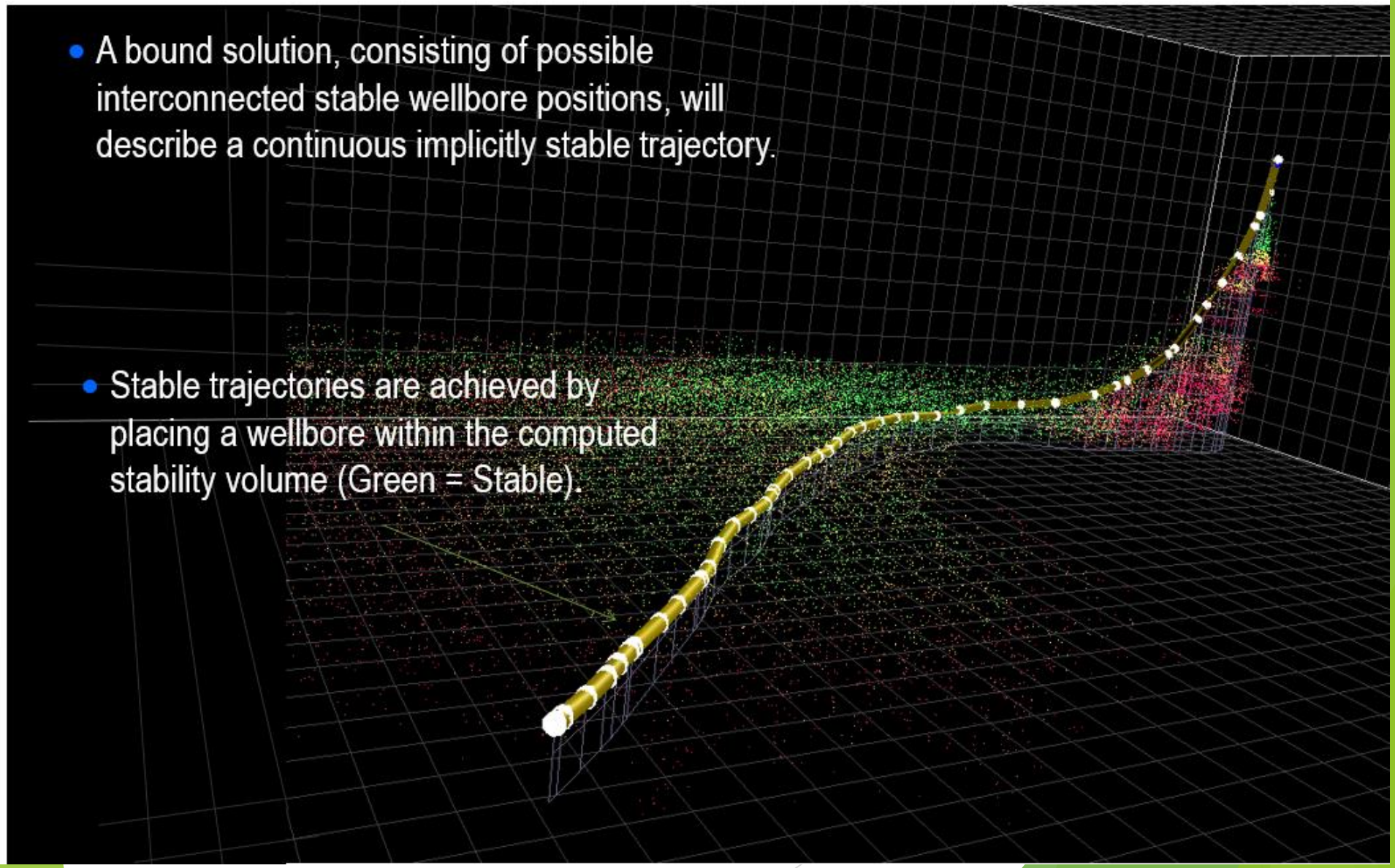




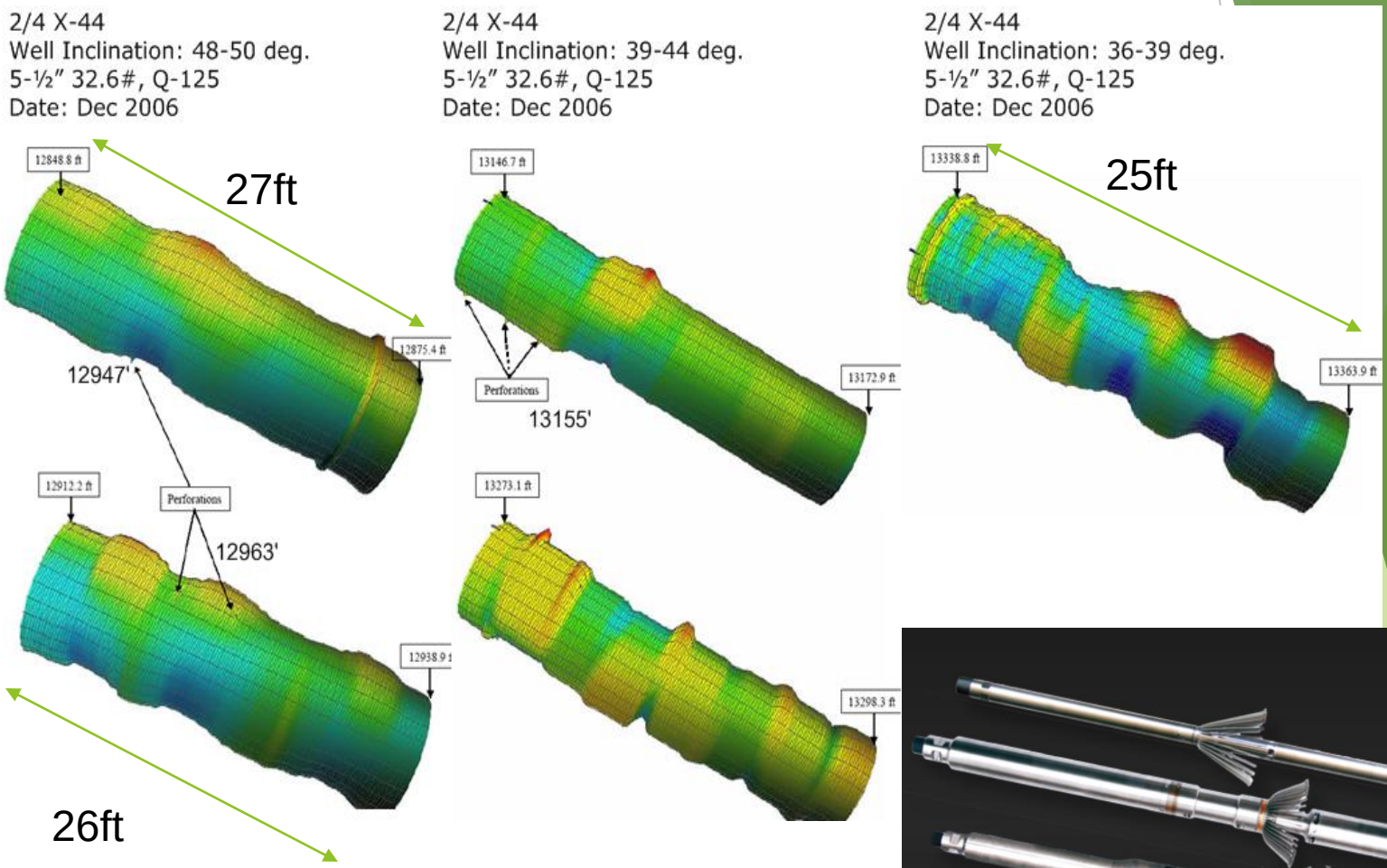
Stability Volumes: Trajectory-Stability Integration

- A bound solution, consisting of possible interconnected stable wellbore positions, will describe a continuous implicitly stable trajectory.

- Stable trajectories are achieved by placing a wellbore within the computed stability volume (Green = Stable).



In oil and gas fields, casings are used beyond the yield strength. Designing casings beyond yield strength requires casing properties beyond elastic limit.





Standard casing design

API recommendation: Collapse, Burst, Extension within Elastic limit
Assuming internal and external of casings are filled with liquid

Our proposition

Standard casing design

API recommendation: Collapse, Burst, Extension within Elastic limit
Assuming internal and external of casings are filled with liquid

Plus

Stable Yield or Buckling Limit Design

For geomechanicsl loading
assuming casing loaded with solid formation and cement

Casing grade and D/t selections are significantly different.

Casing tests

1. Extension tests up to failure
2. Compression tests without confining pressure
3. Compression tests with confinement
4. Line load tests
5. Casing collapse tests

Extension tests





Table 5- Size and type of specimens

Grade	JIS specification	Casing size			Width (inch)	Marker distance (inch)	Grade & specimen type
		OD (inch)	ID (inch)	T (inch)			
H-40	14B	2.36	1.89	0.236	0.492	1.969	c-H-40-A1
							c-H-40-A2
	14B	3.50	2.91	0.300	0.492	2.362	c-H-40-B1
							c-H-40-B2
J-55	14C	2.756	2.244	0.256		7.874	p-J-55-2
							p-J-55-3
	14B	2.756	2.244	0.256	0.492	1.969	c-J-55-1
							c-J-55-2
K-55	14B	4.216	3.374	0.421	0.787	3.346	c-K-55-1
L-80	14C	2.244	1.795	0.224		7.874	p-L-80-1
							p-L-80-2
							p-L-80-3
	14B	2.756	2.244	0.256	0.492	1.969	c-L-80-1
							c-L-80-2
P-110	14B	4.512	3.610	0.452	0.787	3.346	c-P-110-1
							c-P-110-2
Q-125	14B	4.535	3.630	0.452	0.787	3.346	c-Q-125-1
							c-Q-125-2
V-150	14B	10.625	9.020	0.803	1.575	6.693	c-V-150-1
							c-V-150-2

Extension tests

Start Loading

Uniform deformation

Max load

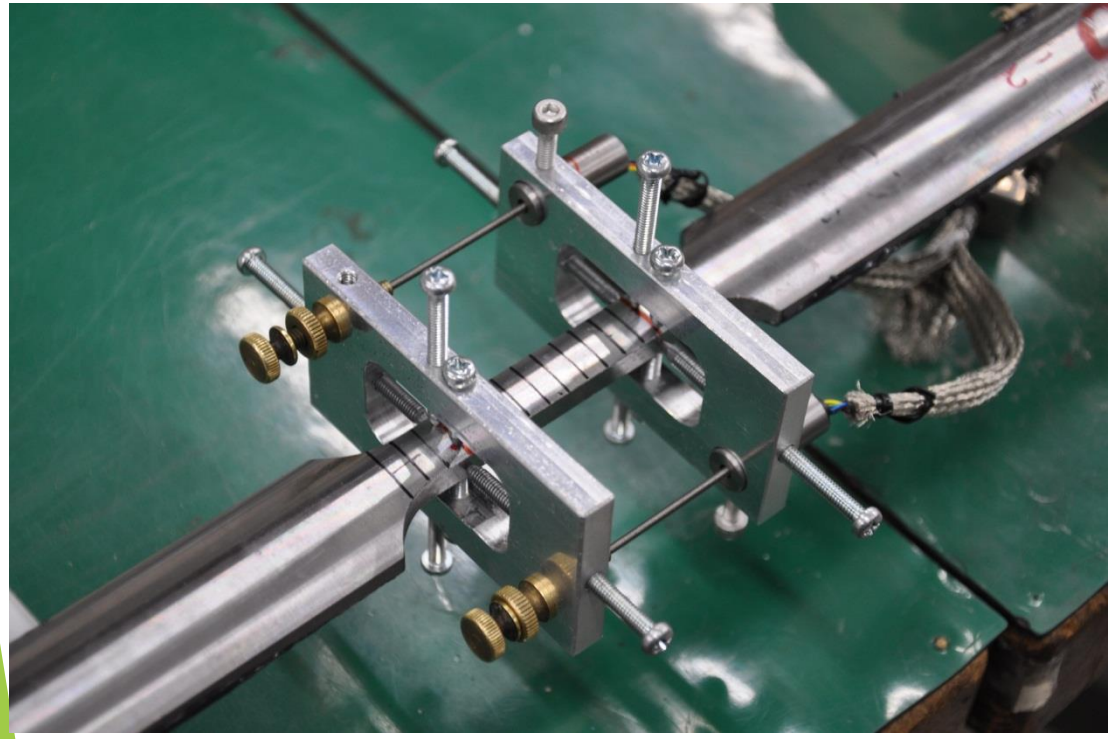
Necking

Failure



Casing（L80）

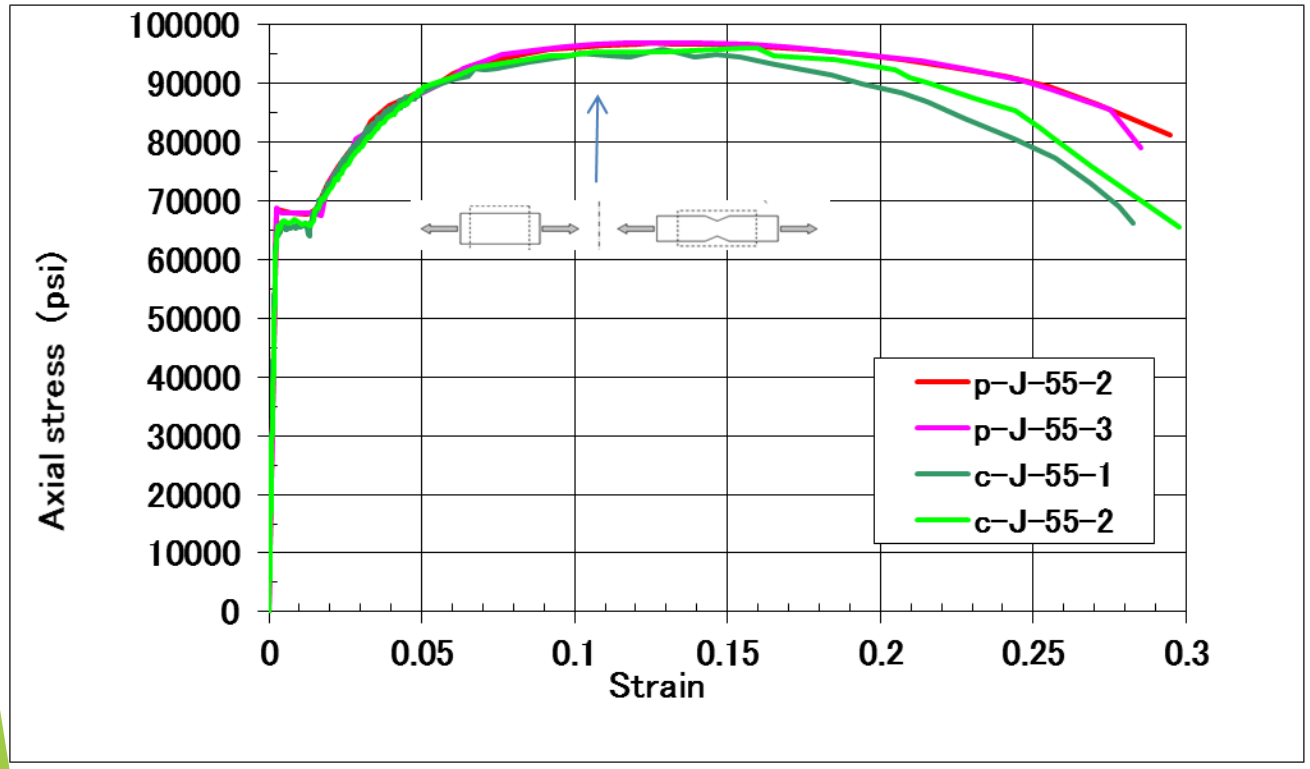
Standard specimen





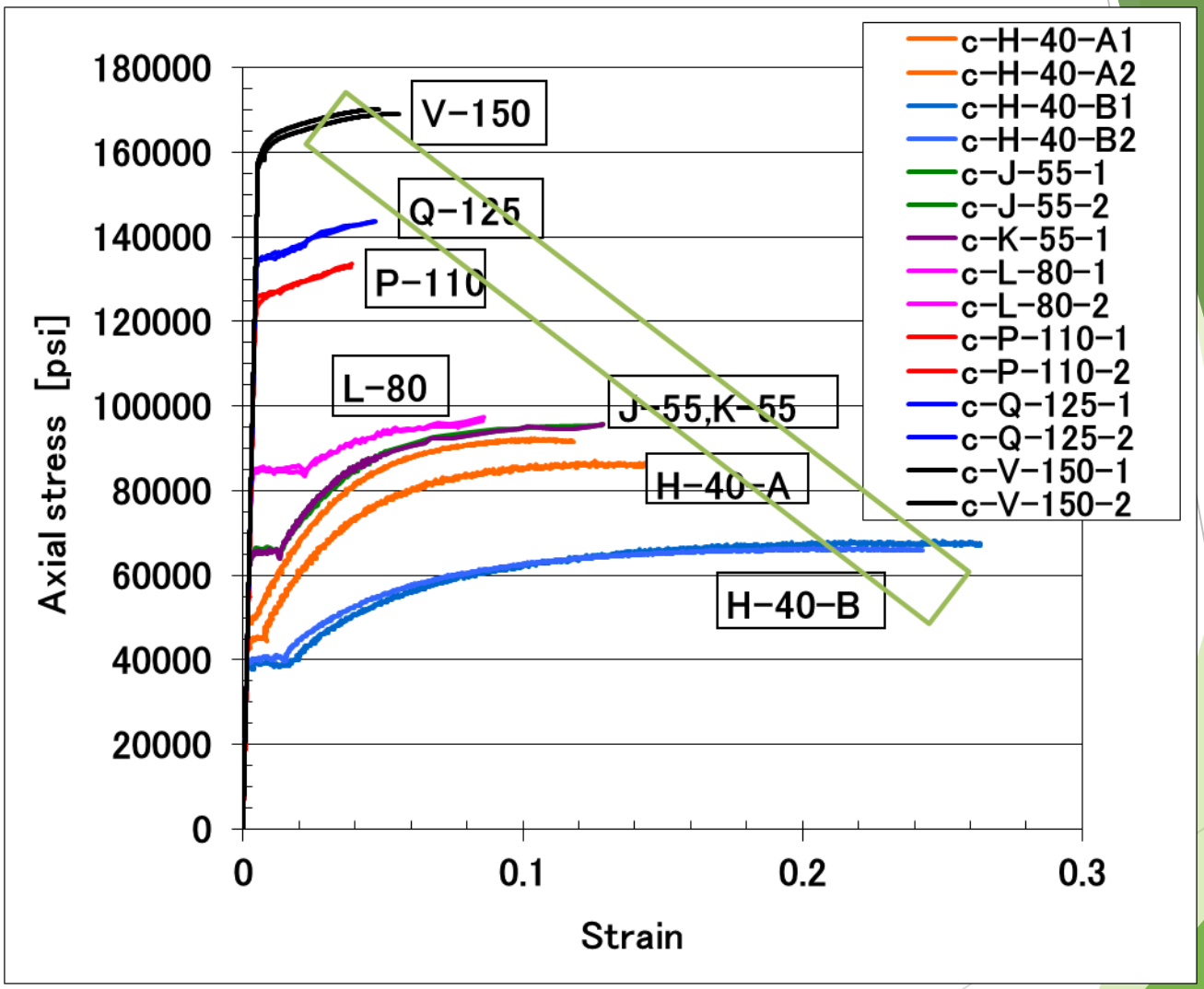
Test method for standard specimen(P110)

Stress strain for extension
pipe specimen vs standard specimen

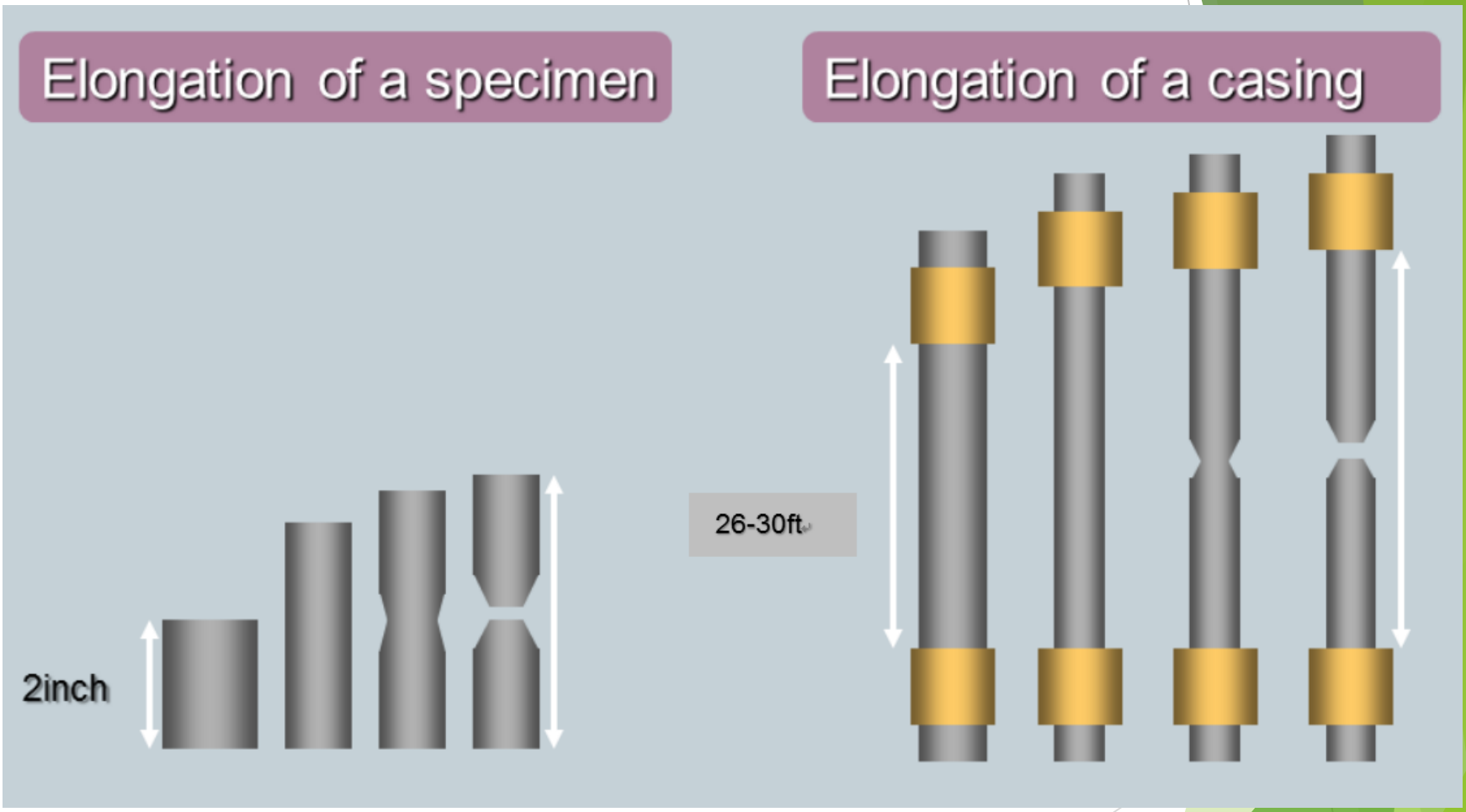




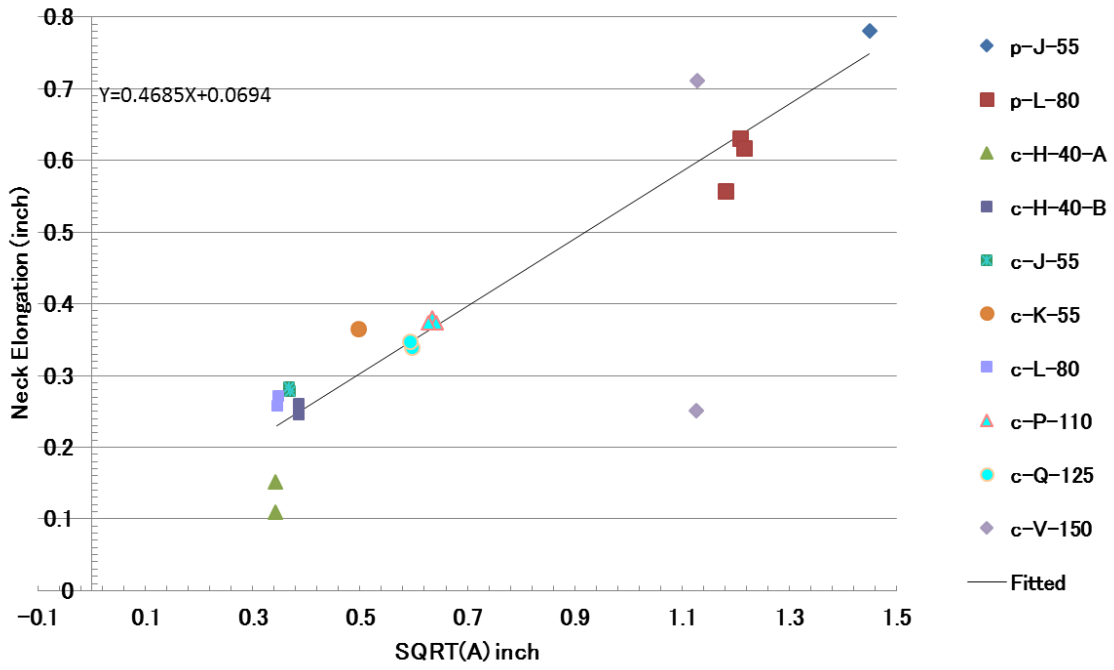
1. (Peak strength/Yield strength): high for lower grade casings
2. Strain at peak strength: large for lower grade casings



Elongation of casing



$$\varepsilon_{rupture}^{nominal} = 0.02 + 86 / \sigma_{Yield}^{1.62} + 0.4685\sqrt{A_o} / L_o$$



Comparison of API minimum elongation and real casing Max elongation

Table 7- Expected elongation at tensile rupture for 27~30 ft casing assuming one neck per one joint.

Grade	H-40	H-55	K-55	L-80	P-110	Q-125	V-150
API minimum elongation %	30	24	20	20	15	14	14
Uniform elongation per one casing %	18.65	12.90	10.80	8.57	3.84	4.69	4.90
Total elongation per one casing %	19.95	13.80	11.70	9.47	4.74	5.59	5.80

Compression tests without confinement





Fig.3- J-55 casing for local buckling (left) and J-55 for lateral buckling (right).

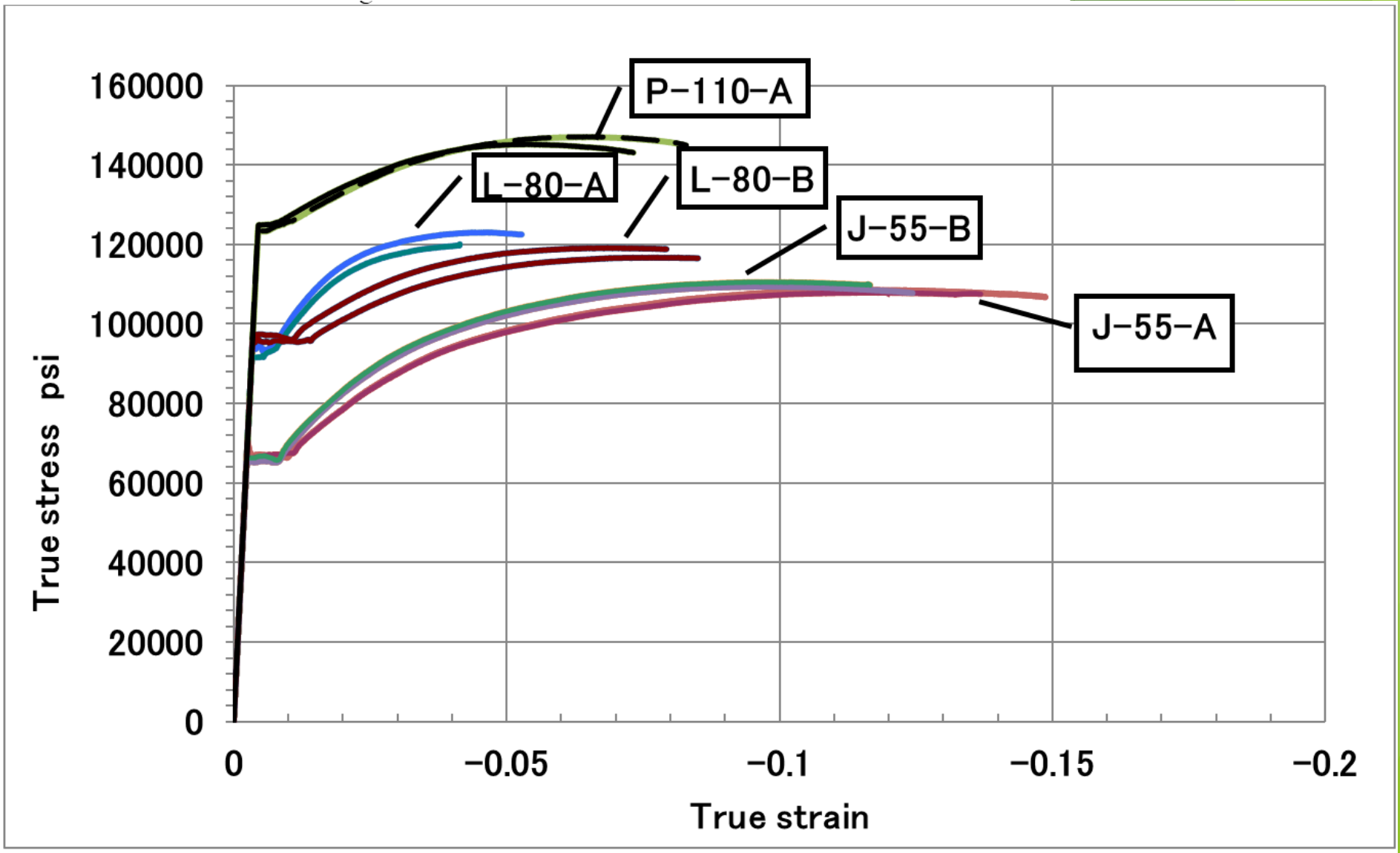


Fig.4- Measured stress strain curves for short casings
(note that true stress and true strain are used in this figure)

Stress strain curves for determining the constitutive relation

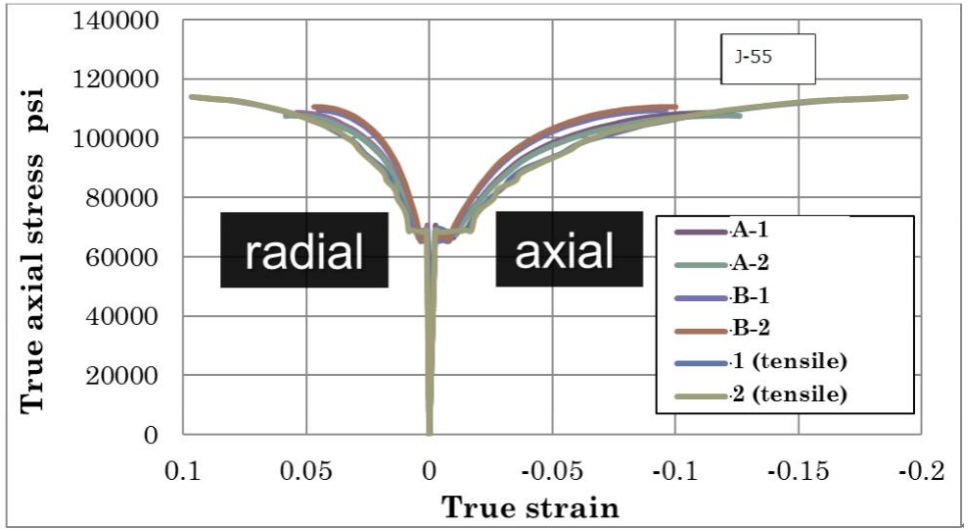


Fig.5- Stress strain curves of J-55 steel constructed from Fig.4

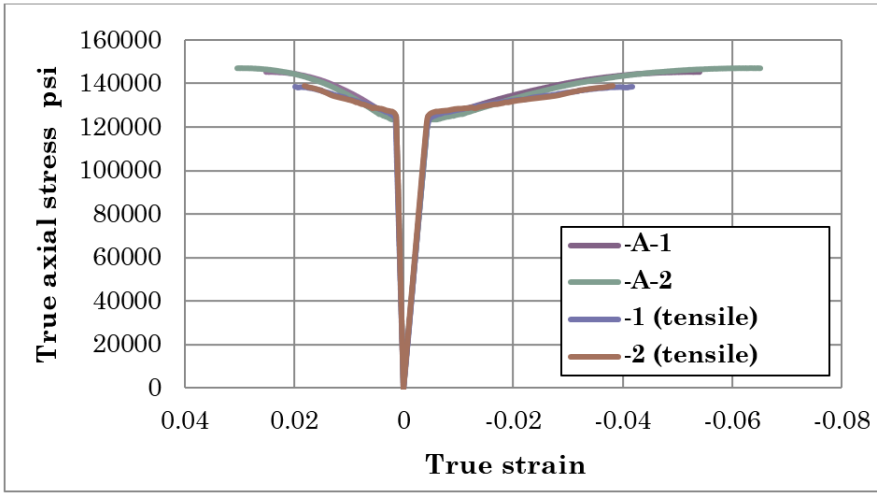


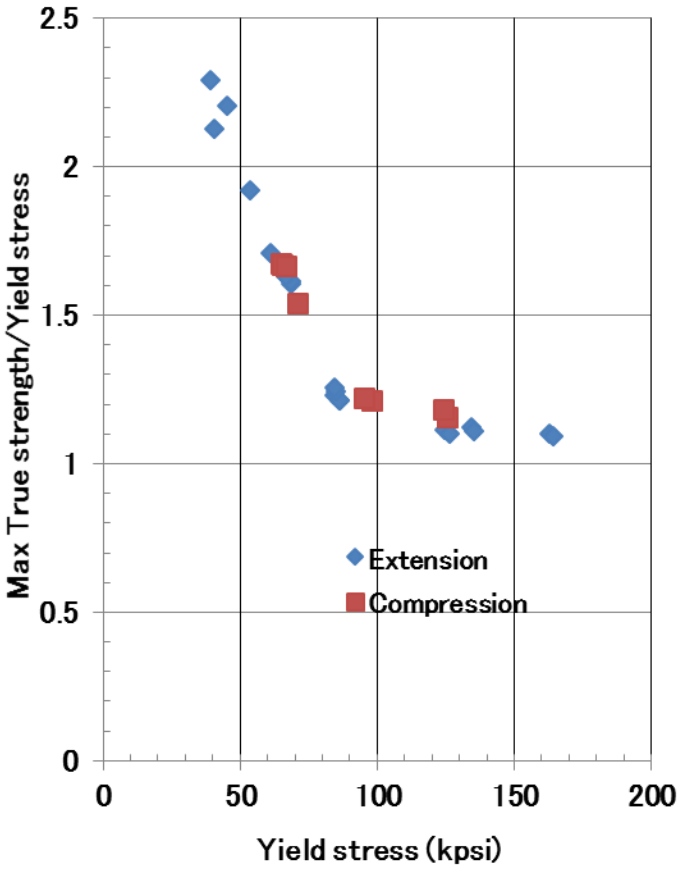
Fig.7- Stress strain curves of P-110 steel constructed from Fig.4

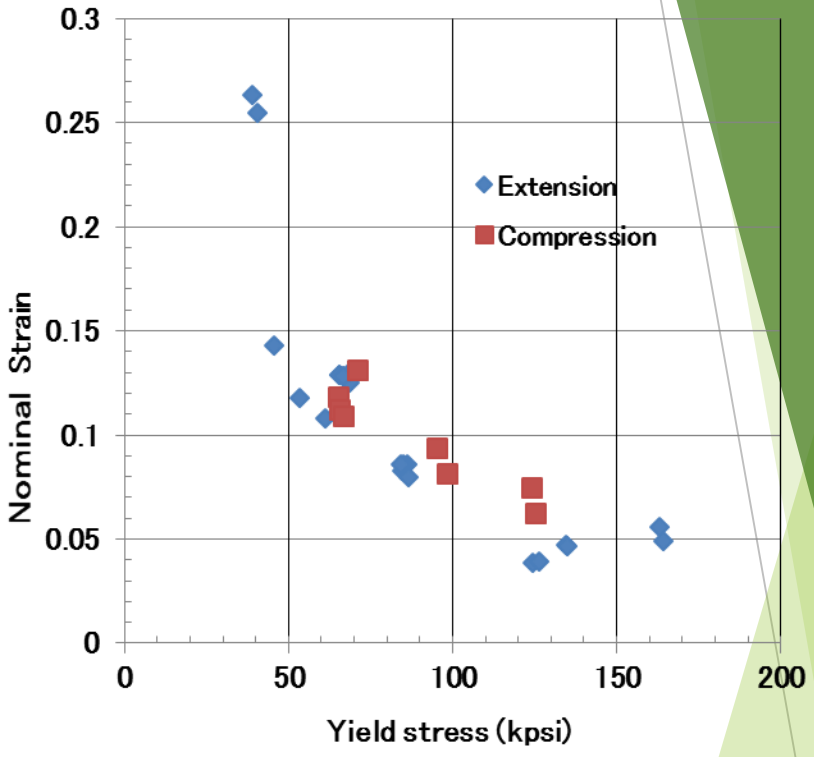
$$\sqrt{\bar{J}2} + G(\bar{J}1) = S_o^y + \int \exp(B_1 + B_2 K + B_3 K^2 + \ldots) dk$$

K is defined by

$K = \varepsilon^p$ for strain hardening or $K = W^p$ for work hardening

1. Ratio Max strength/Yield stress
2. Max strain with uniform extension and compression



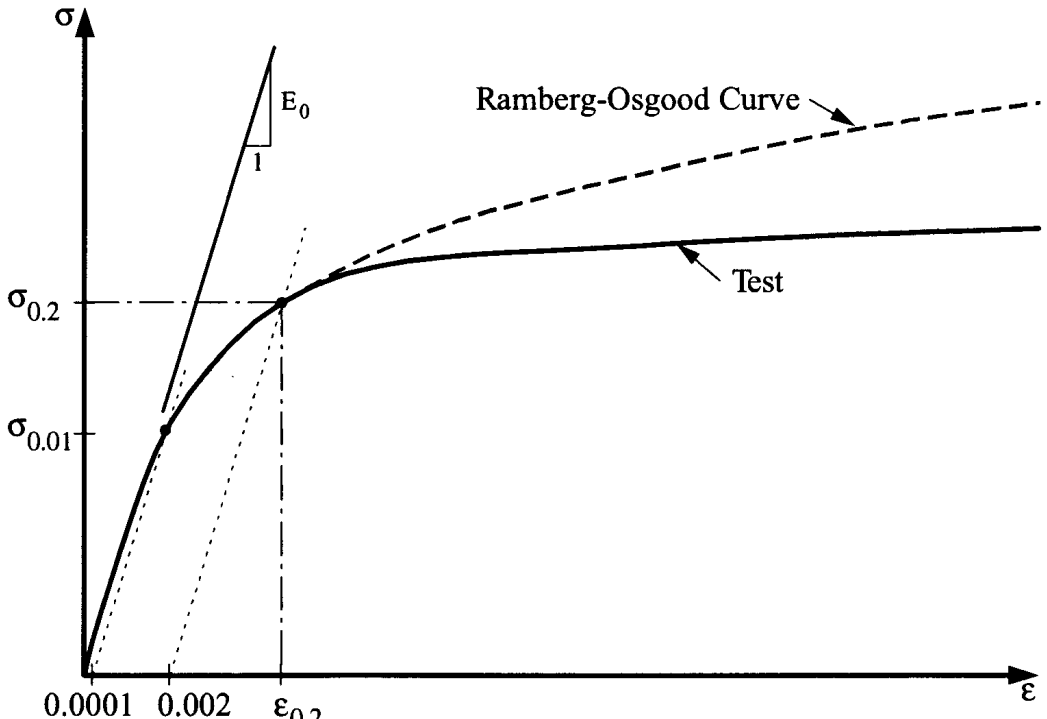


$$UltimateTrueStrength = \sigma_{Yield} + 780 / \sigma_{Yield}^{0.73}$$

$$\varepsilon_{critical} = 0.02 + 86 / \sigma_{Yield}^{1.62}$$

Tubular string collapsing processes are different between fluid pressure loading and geotectonic loading.

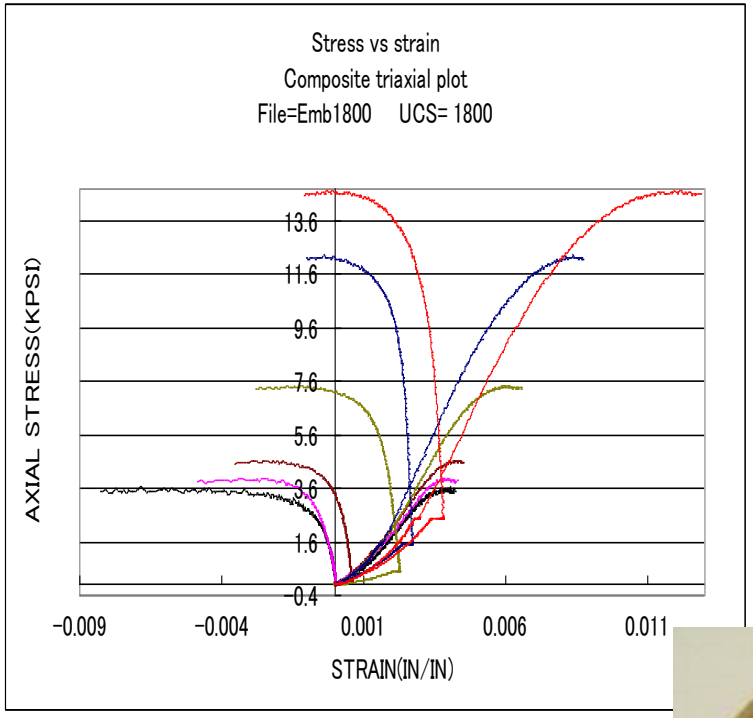
Steel alloy is approximately a perfect plastic material



Hydrostatic loading



Geotechnical loading





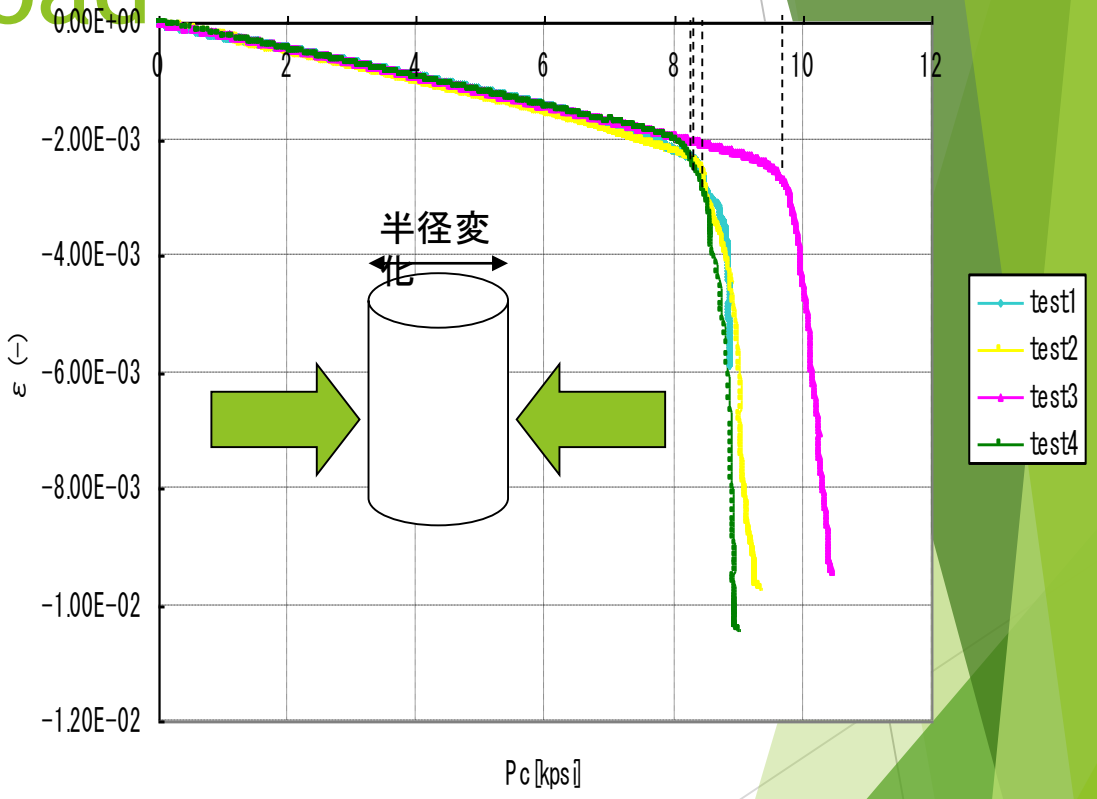




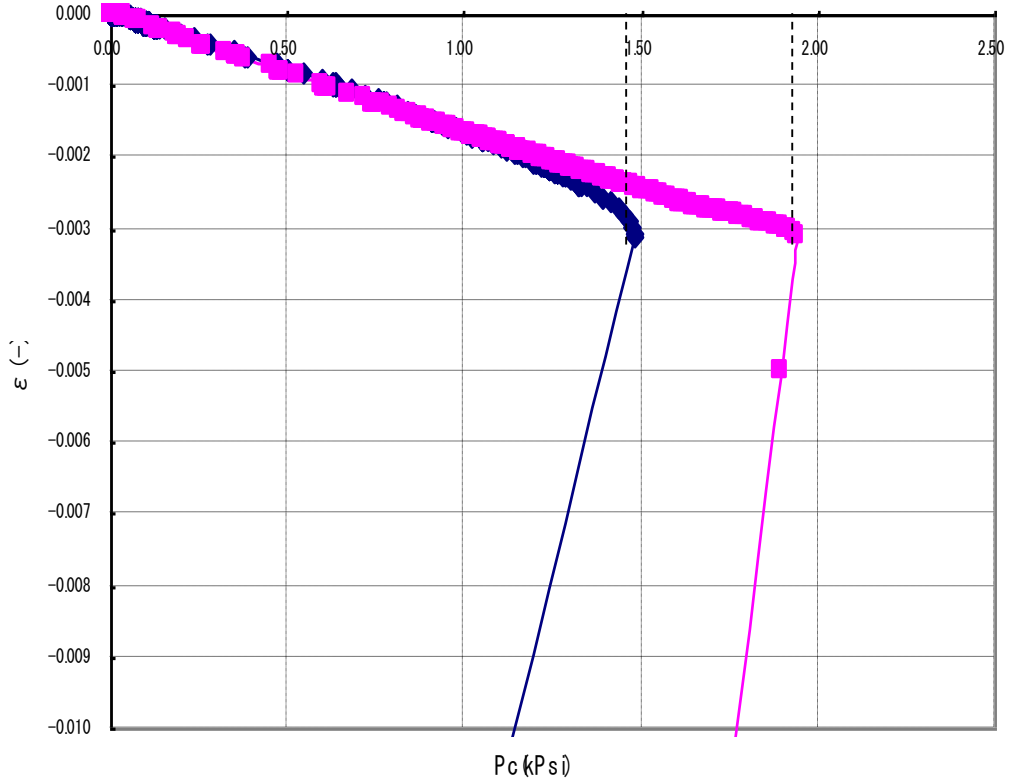


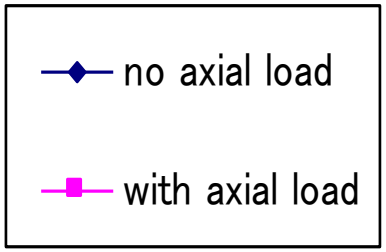
Laboratory observations
Hydrostatic load

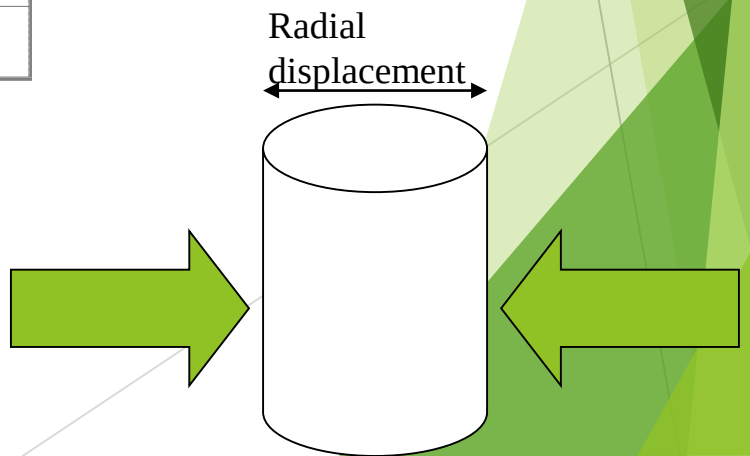




Thin casing stability test

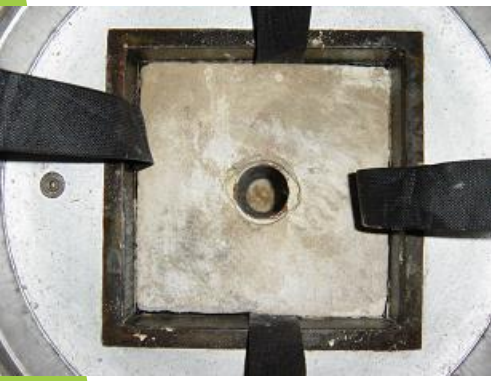


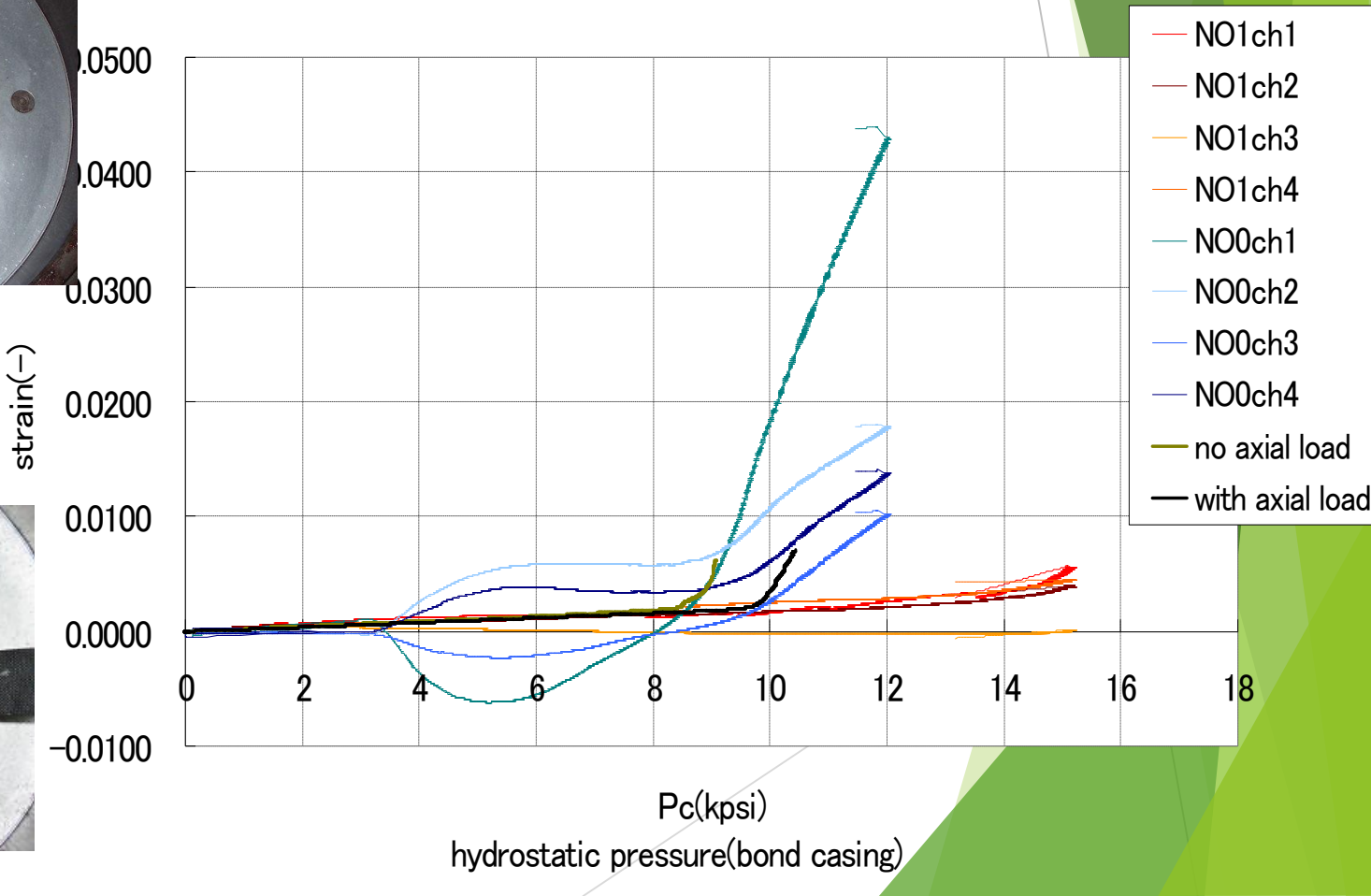




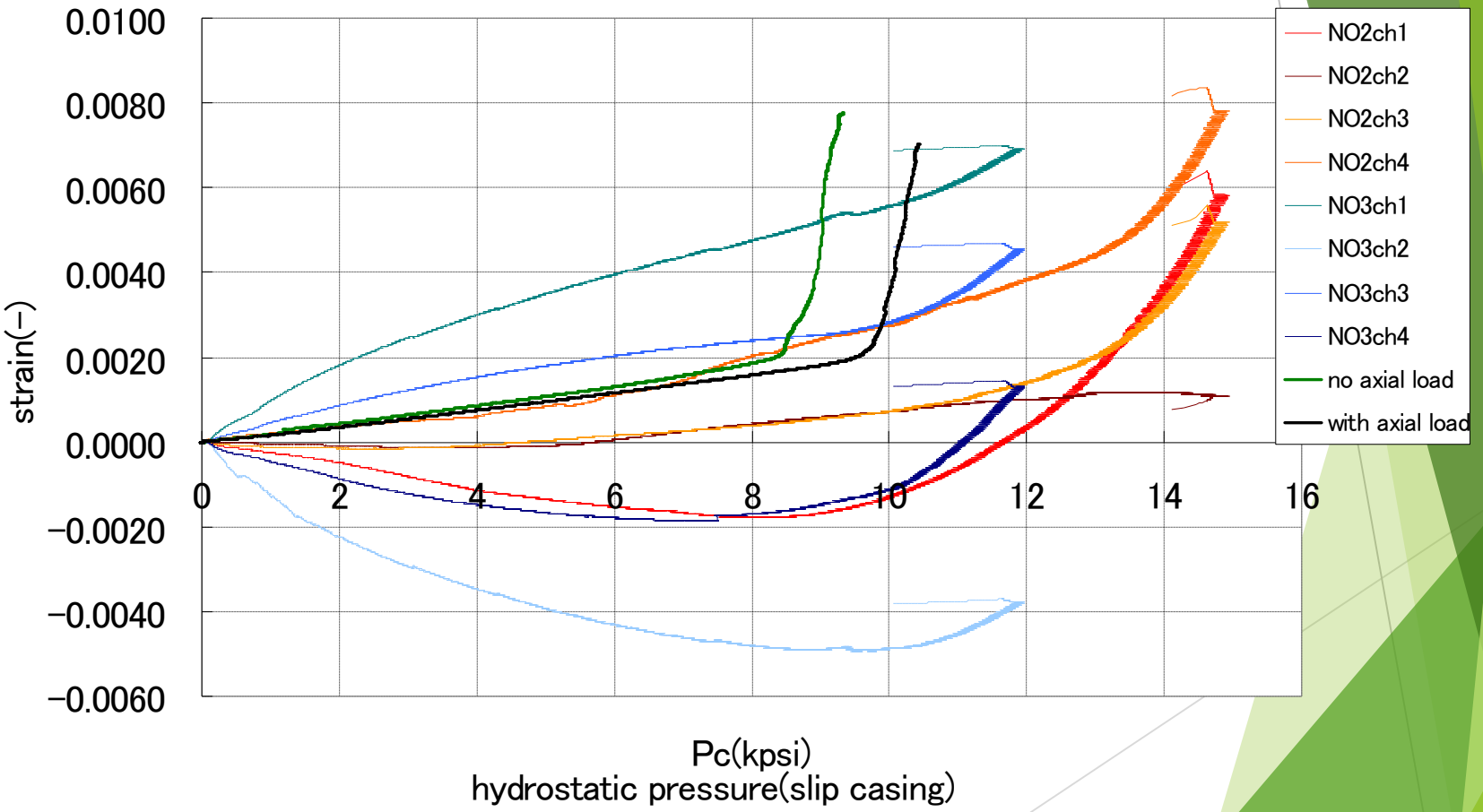
Geotectonic・ h ydrostatic pressure(bond casing)



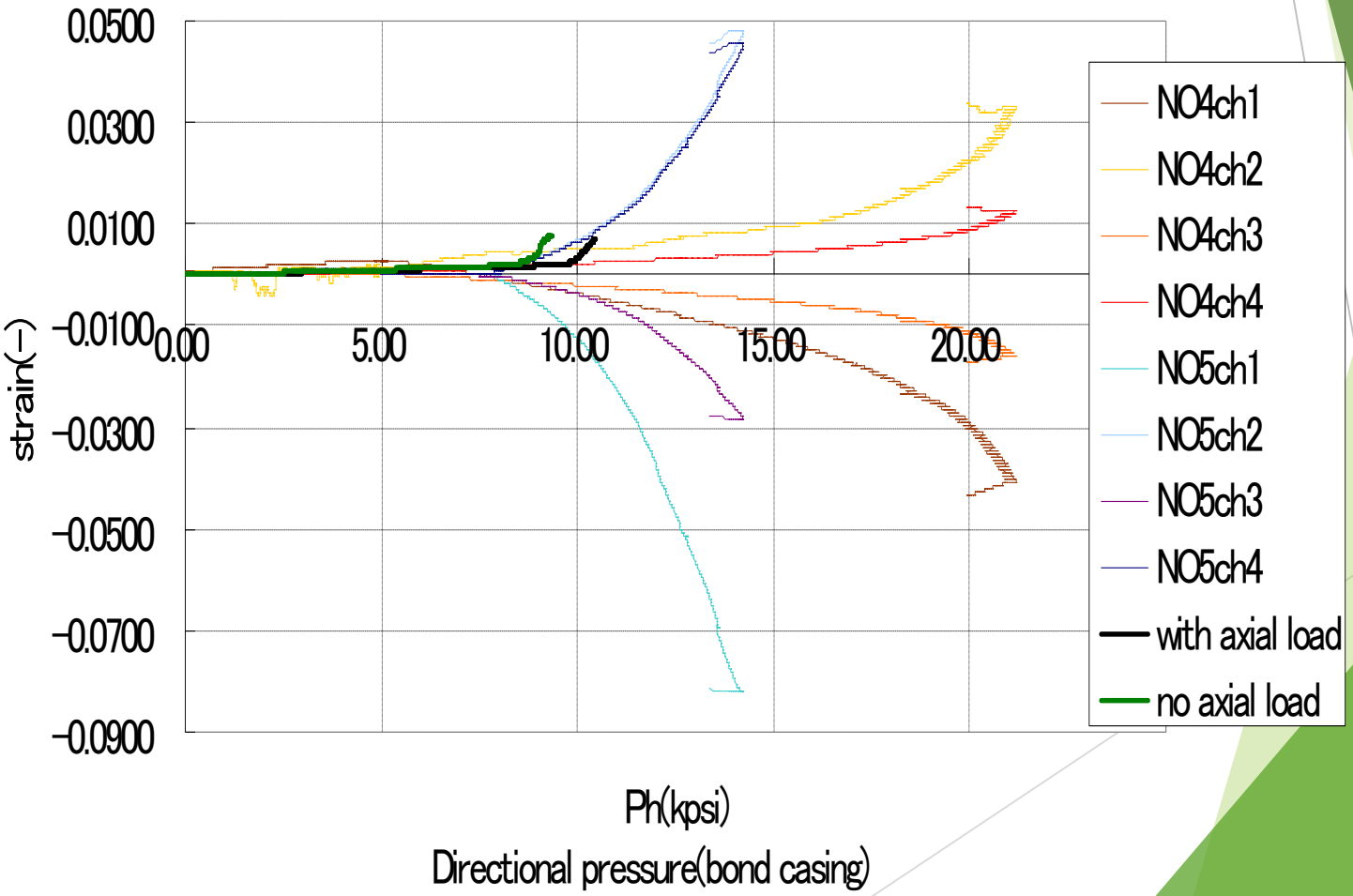




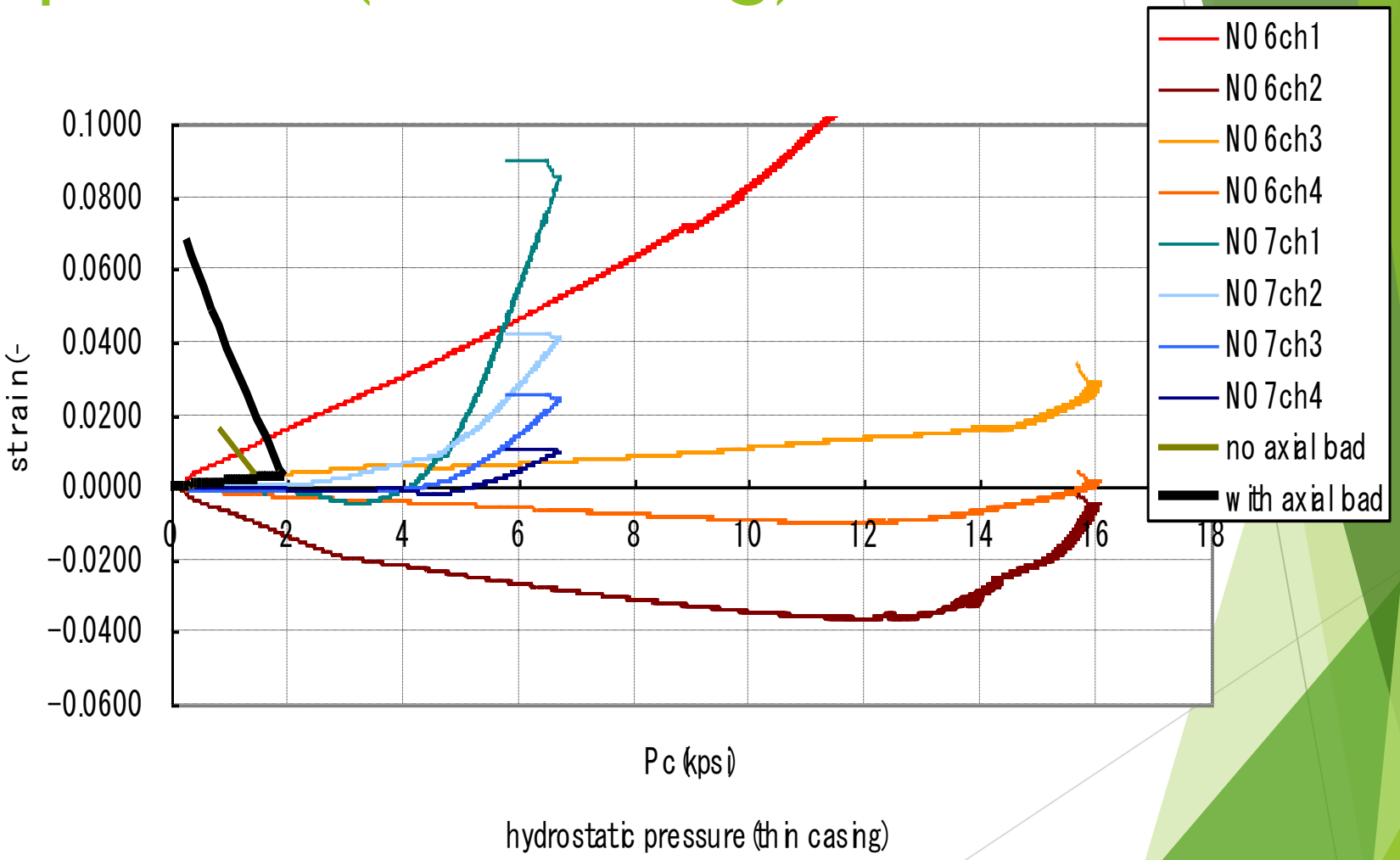
Hydrostatic pressure(slip casing)



Directional pressure (bond casing)



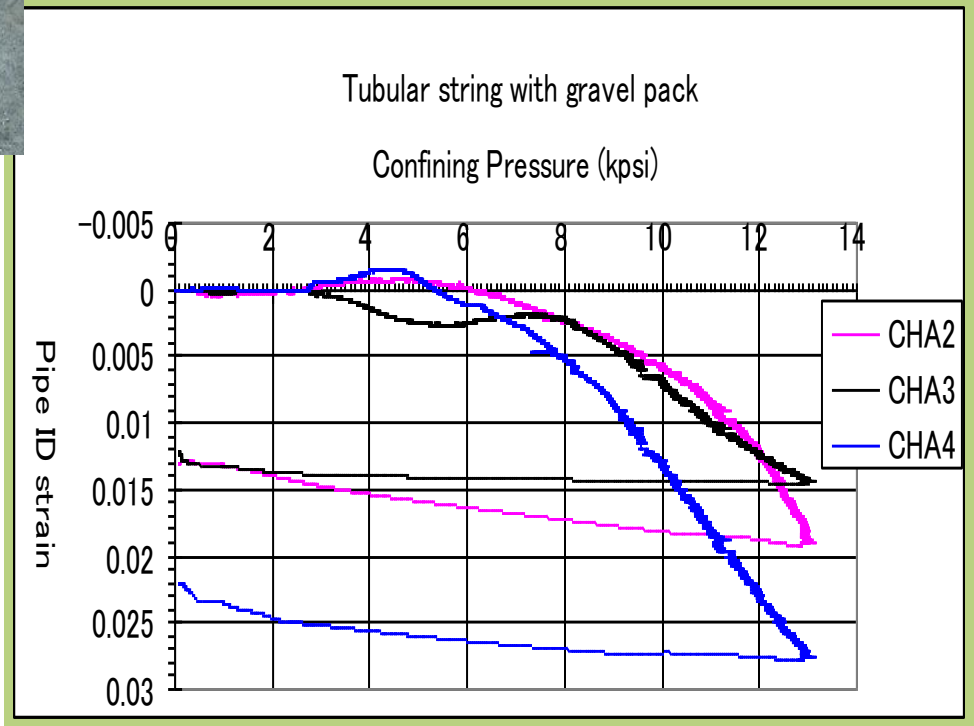
Geotectonic__ h ydrostatic pressure(thin casing)



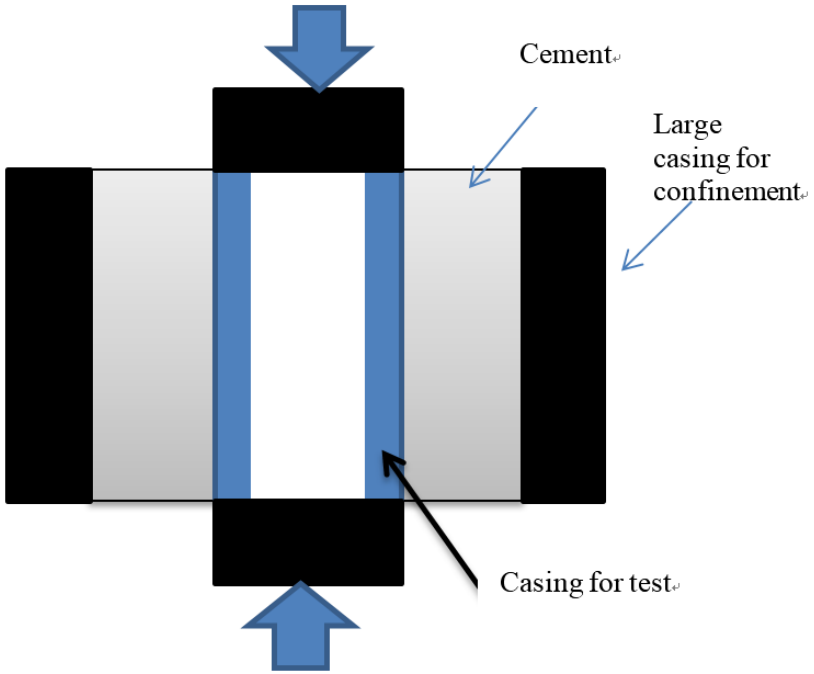
Geotectonic__ h ydrostatic pressure (gravel packed)







Compression test with confinement

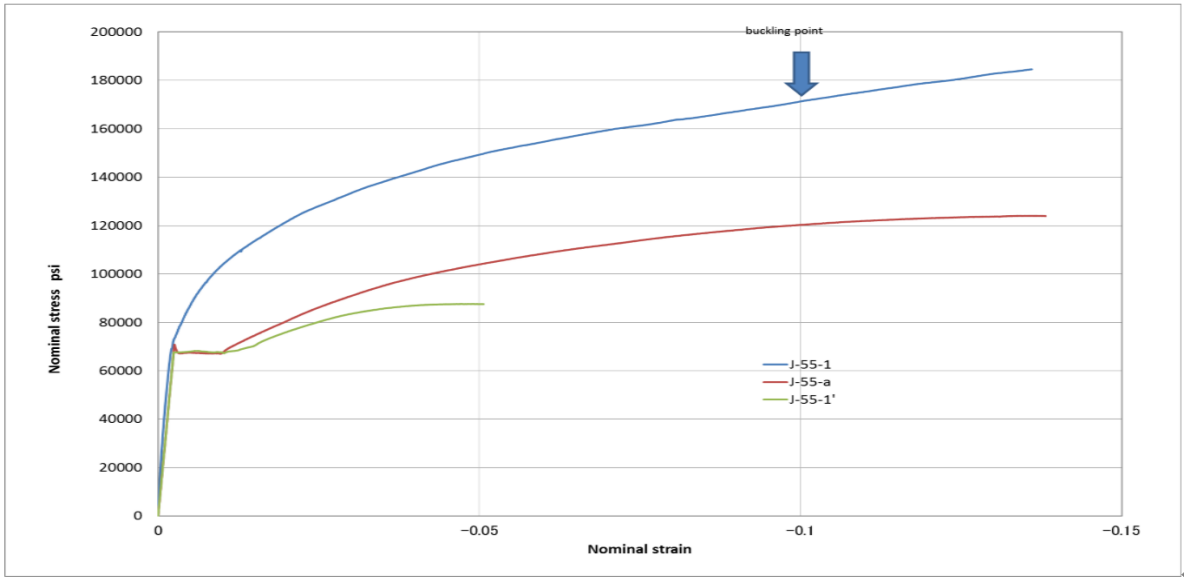


Compression test surrounded by cement simulating a tight formation



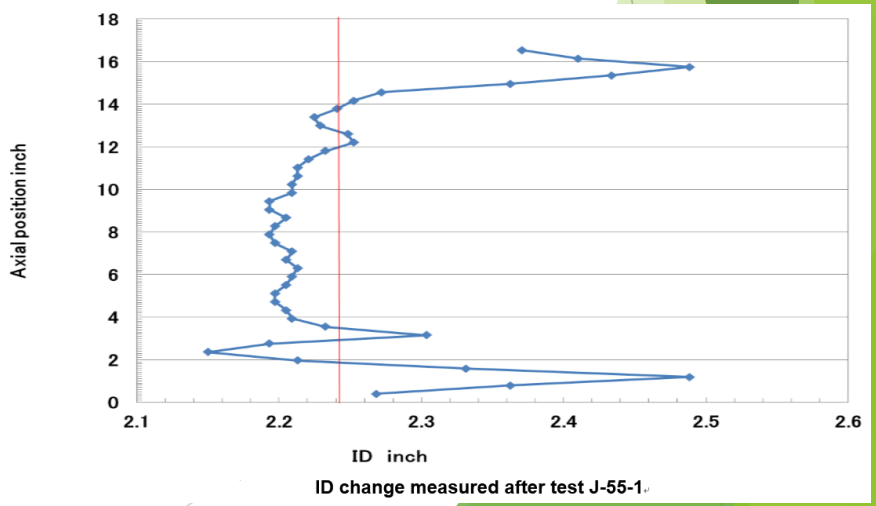
Deformed casing J-55-1 with cement confinement (top and bottom views)

Deformation vs. load for J-55 with confinements



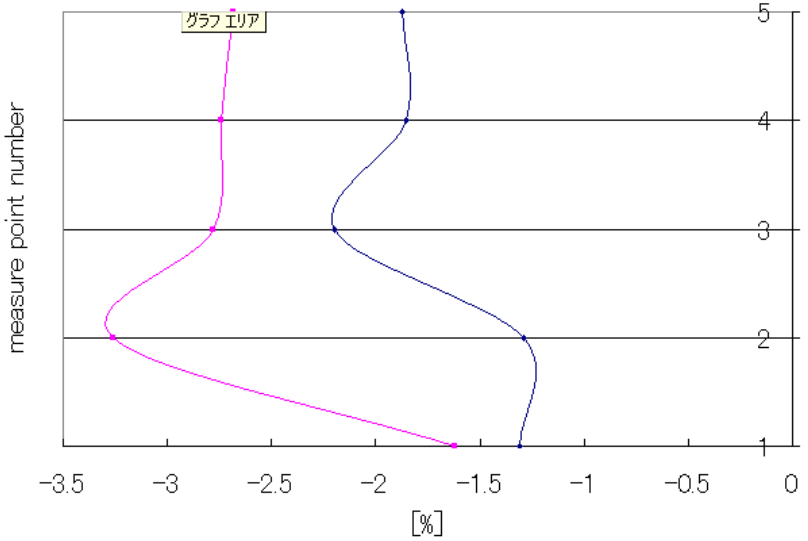
Casing deformations J-55-1

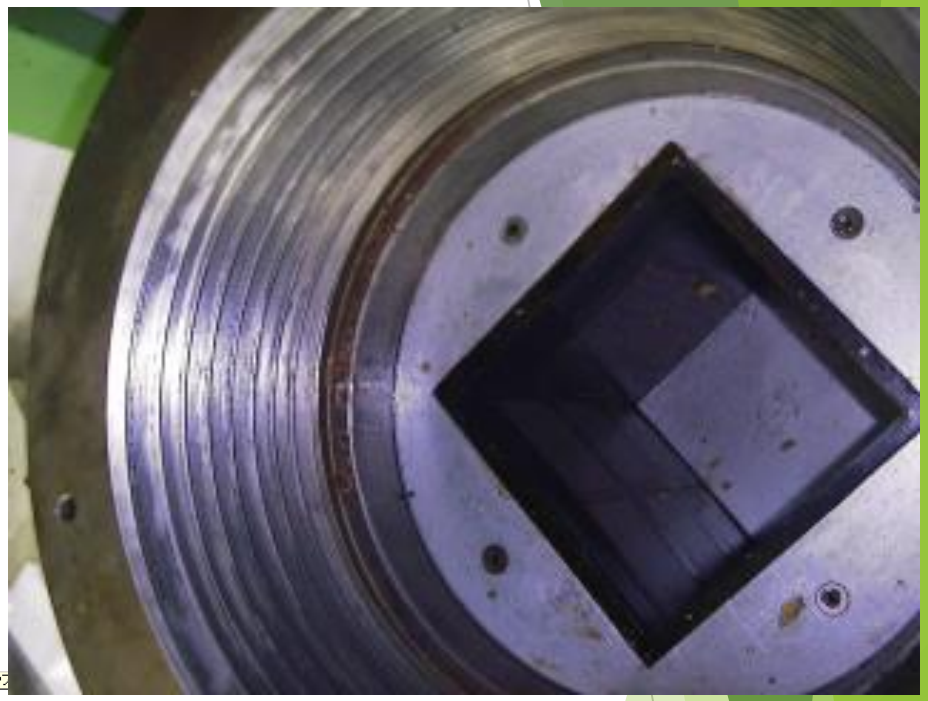
(blue: cemented casing, red: short casing without confinement, green: a long casing without confinement)

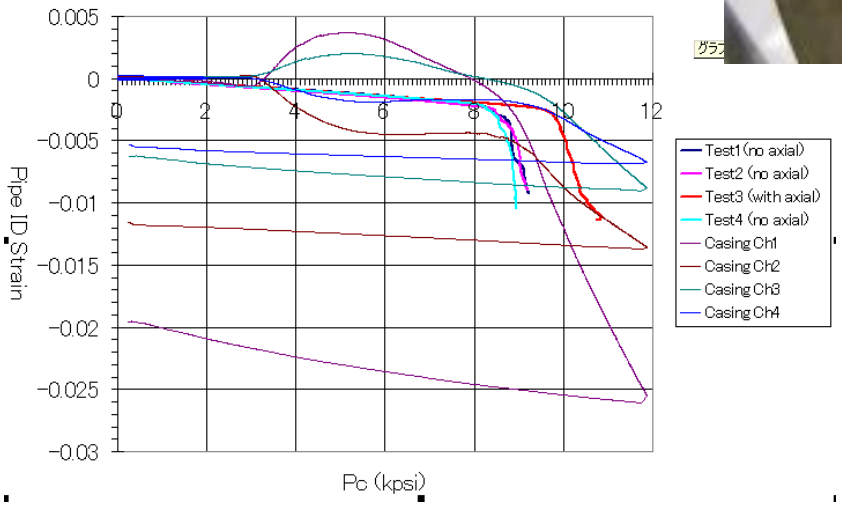


ID change measured after test J-55-1

Collapse tests with confinement

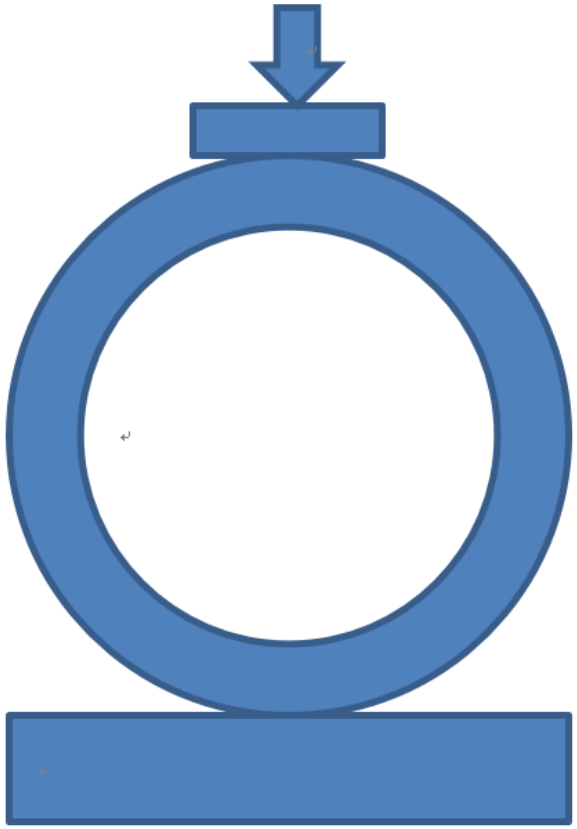








Casing deformation with a line load

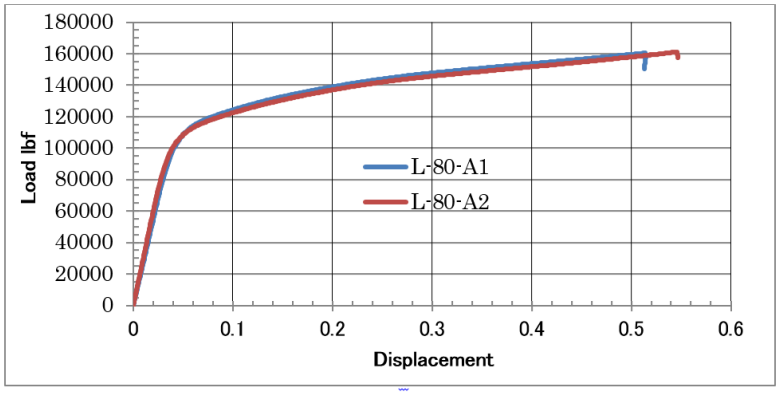


Test for casing deformation with a line load

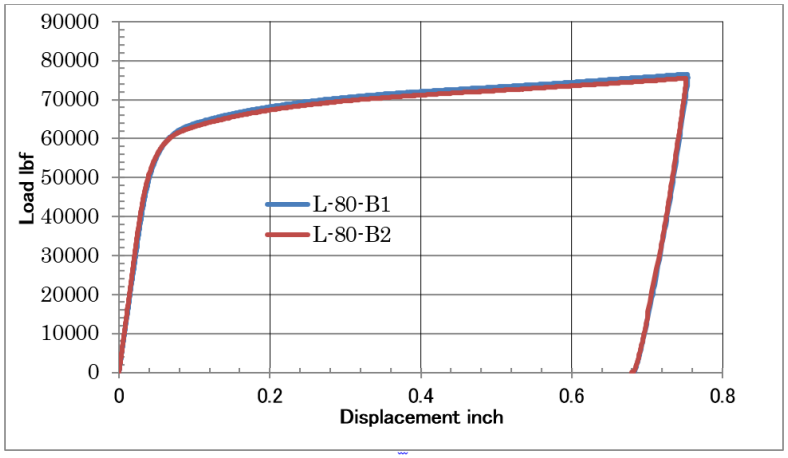
Casing dimensions used for the compression tests

Grade	OD	ID	t in.	L in.
	in.	in.		
H-40	3.5	2.91	0.295	3.937
J-55	3.06	2.24	0.409	3.937
	3.67	2.73	0.468	3.937
L-80	2.87	1.79	0.539	3.937
	3.67	2.73	0.468	3.937
P-110	3.06	2.24	0.409	3.937

L-80



Empirical load-displacement curves for a L-80-A casings



Empirical load-displacement curves for a L-80-B casings

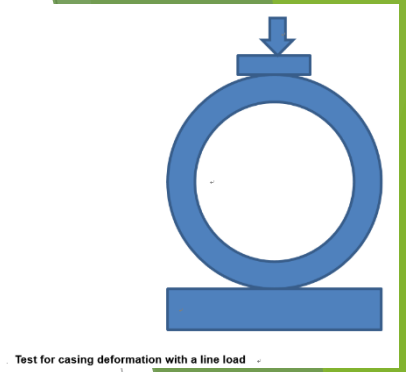


-80-B1

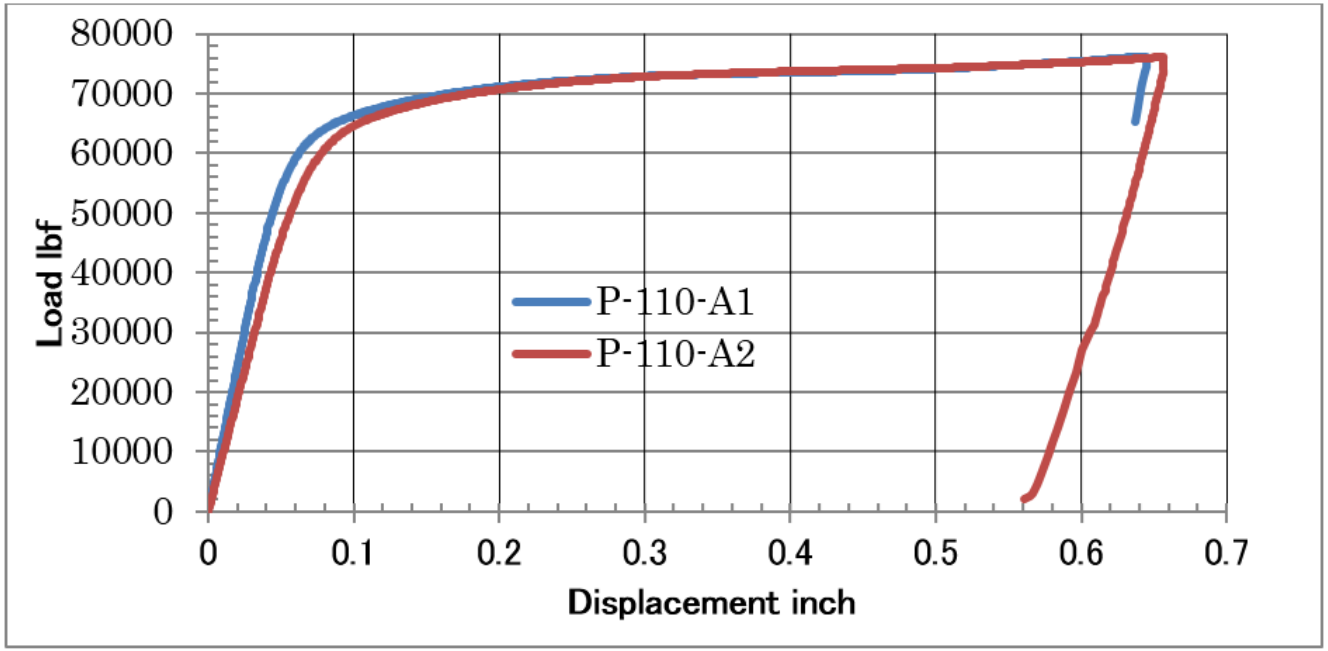


Test for casing deformation with a line load

P-110

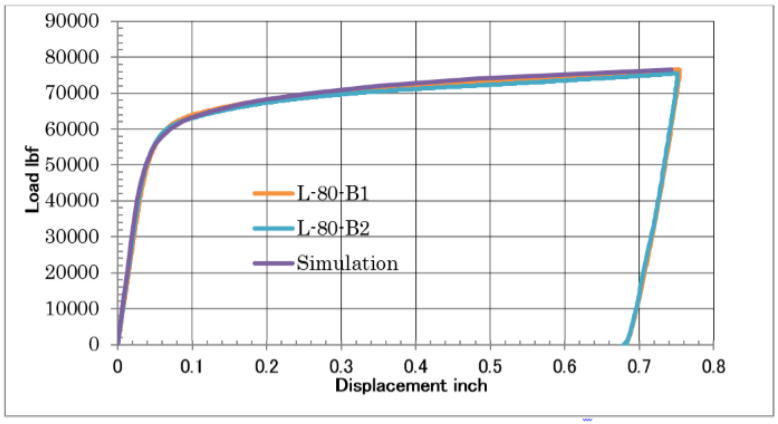


Test for casing deformation with a line load

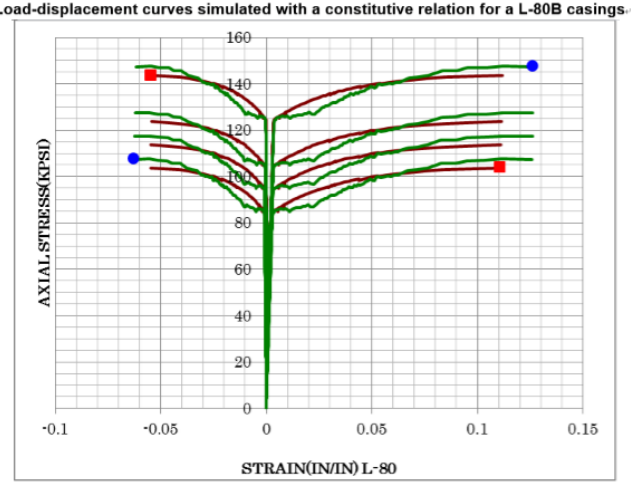


Empirical load-displacement curves for a P-110-A casings

L-80 simulation



Load-displacement curves simulated with a constitutive relation for a L-80B casings



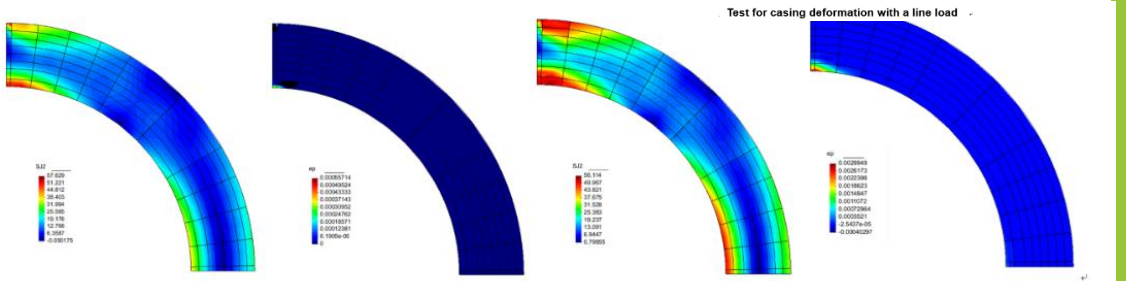


Fig.20B- SQRT(J2) and plastic strain for a L-80-B casings, load= 30 Klb and 40 Klb

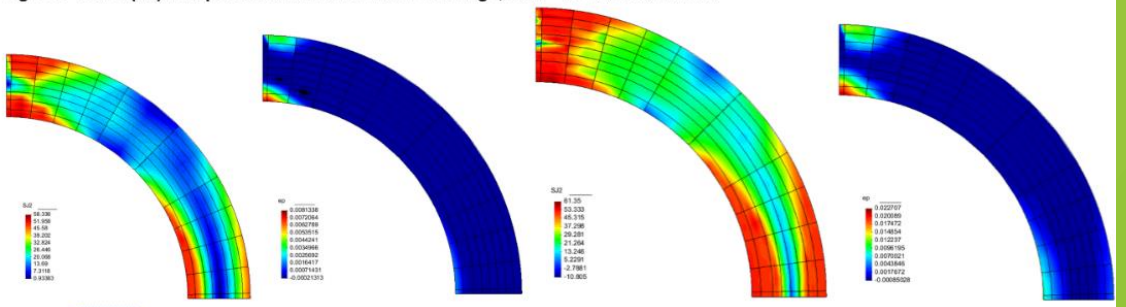


Fig.20C- SQRT(J2) and plastic strain for a L-80-B casings, load= 50 Klb and 60 Klb

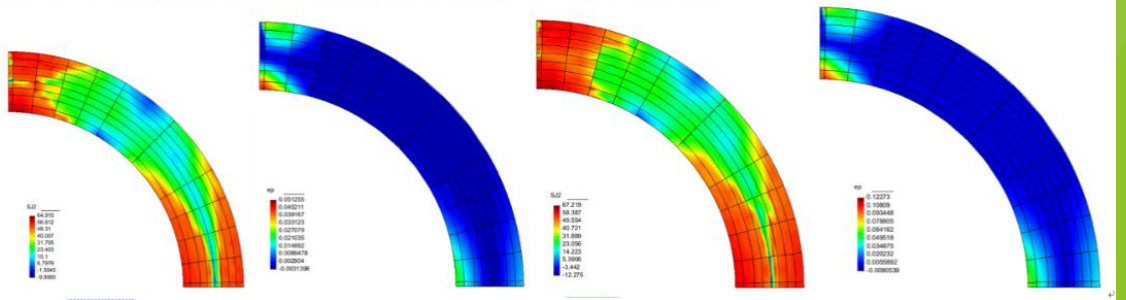
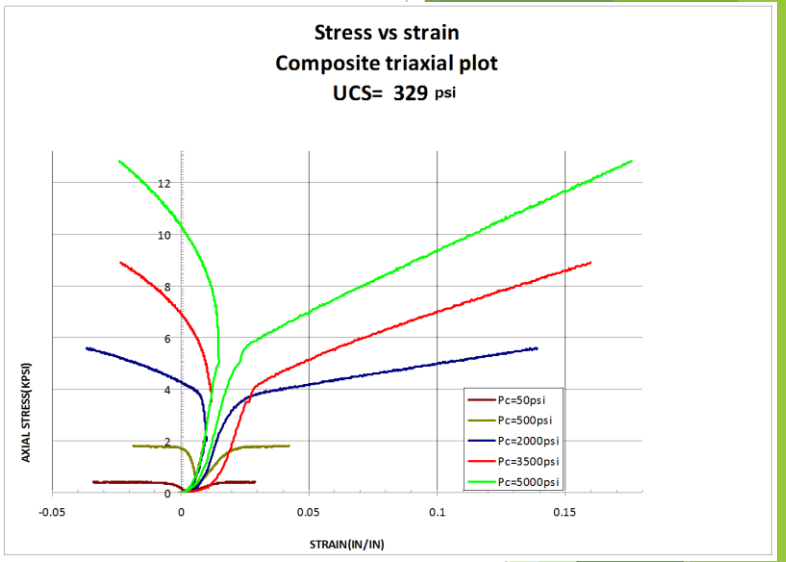
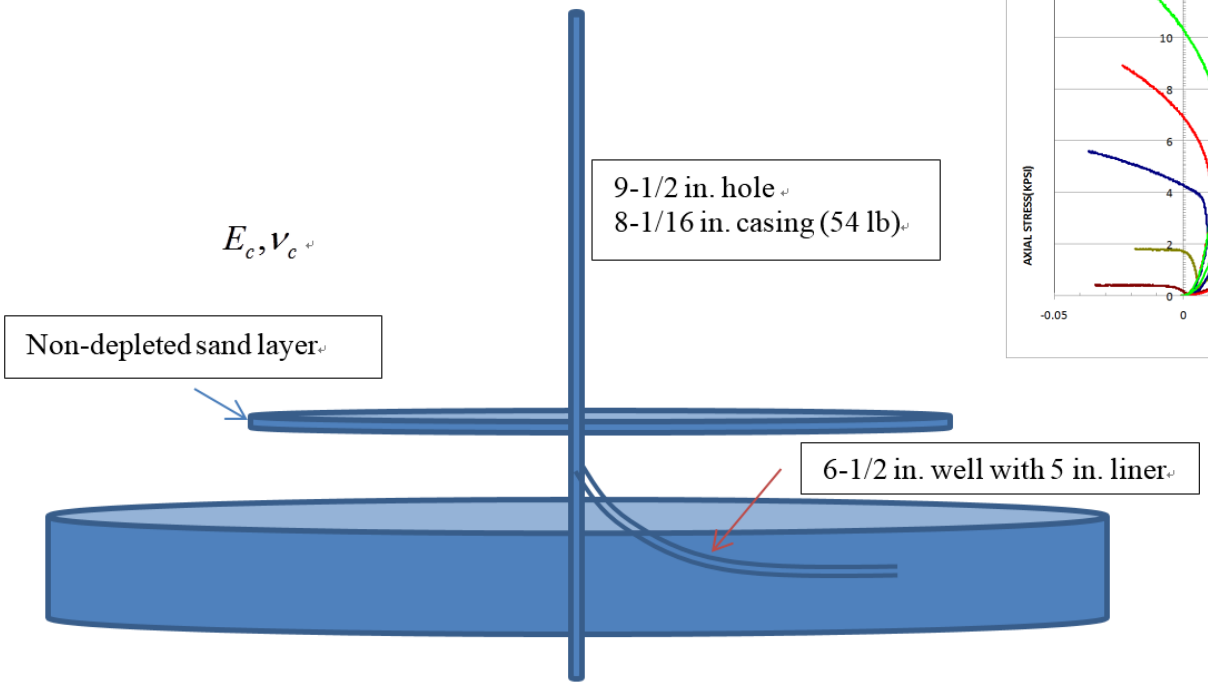


Fig.20D- SQRT(J2) and plastic strain for a L-80-B casings, load= 65 Klb and 70 Klb

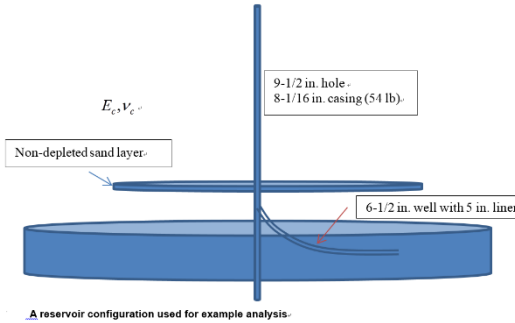
Field applications



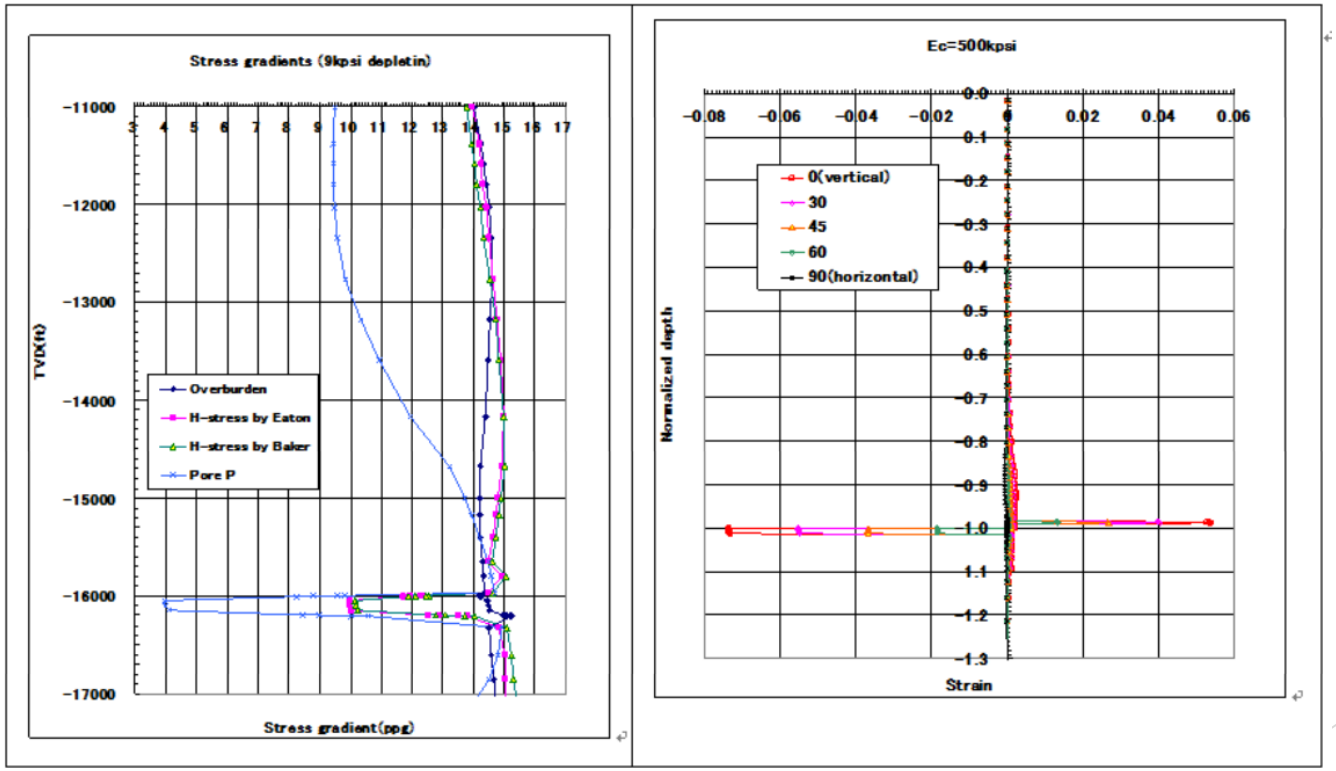


A reservoir configuration used for example analysis

well

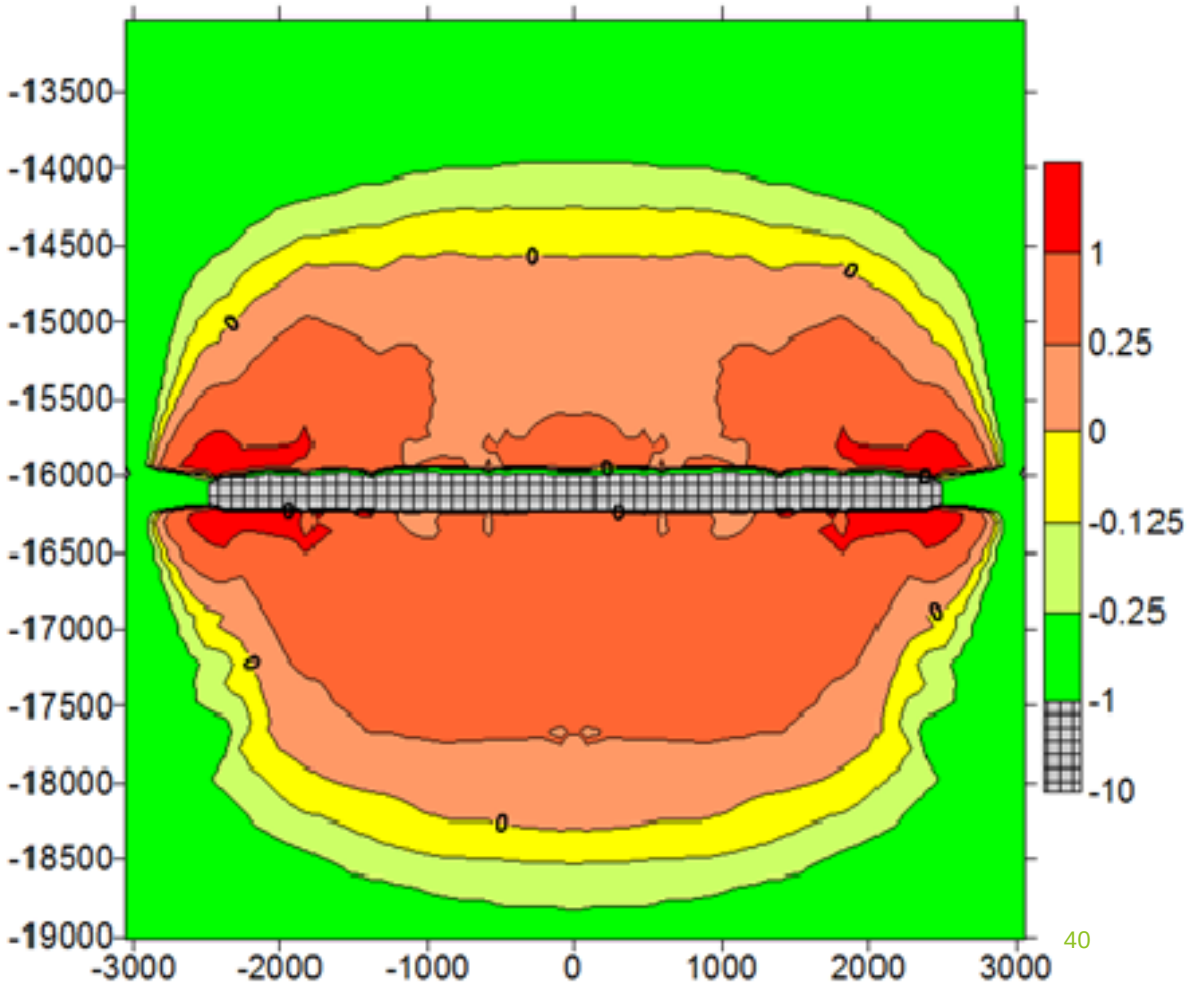


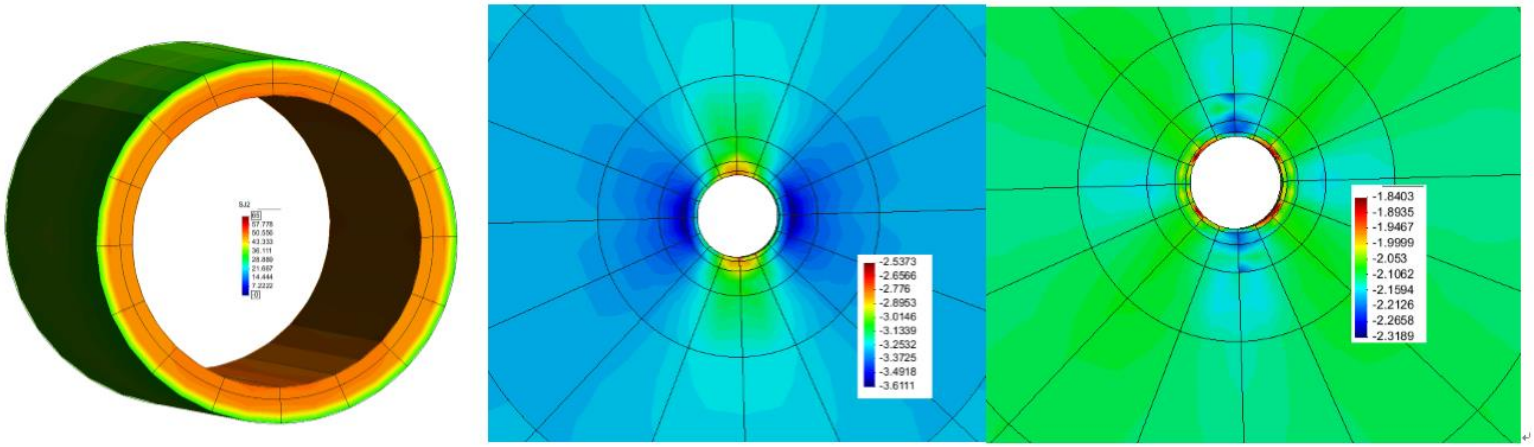
A reservoir configuration used for example analysis.



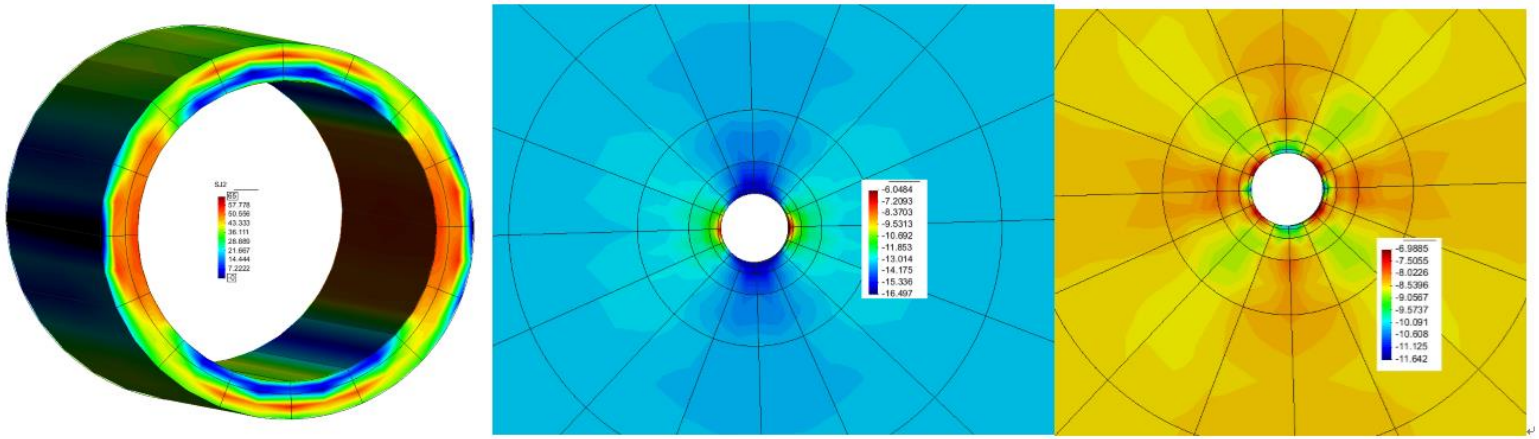
The stress state and the formation strain after 8 kpsi pore pressure depletion.

Side view of the tensile region

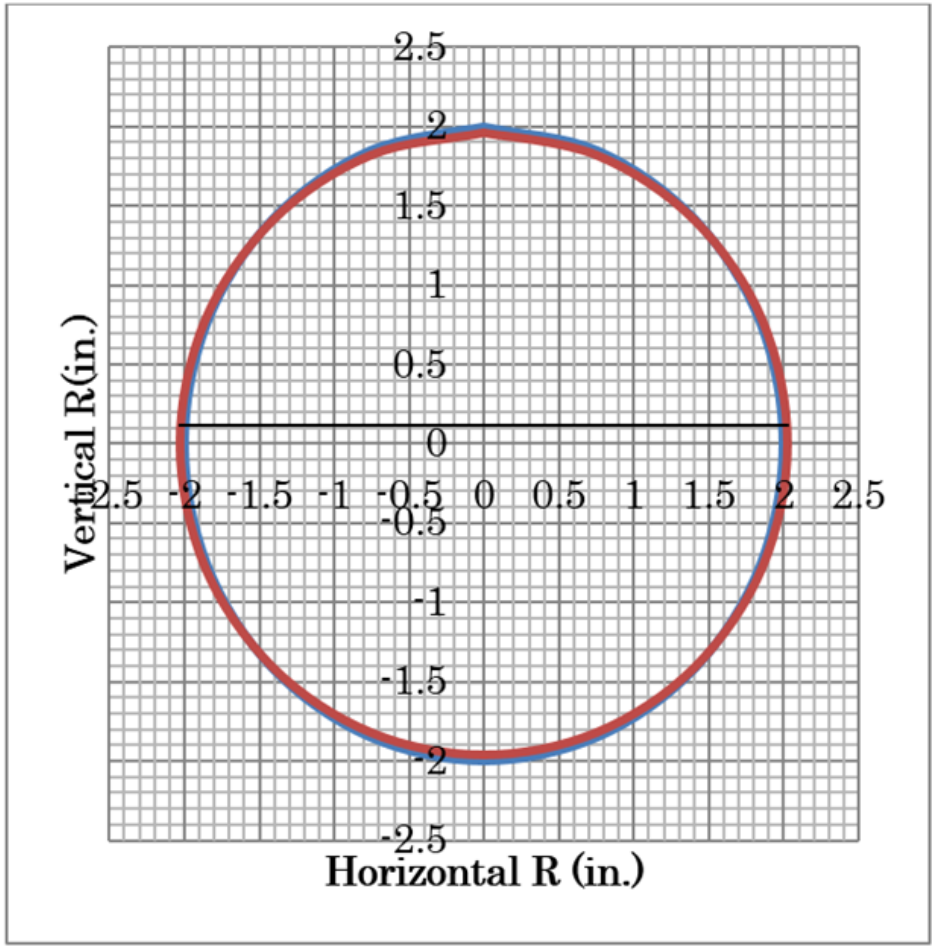




SQRT(J2) in the casing and vertical and horizontal effective stress after 2000 psi depletion in the formation (right figures not including the cement and casing) at the reservoir center(16250ft)



SQRT(J2) in the casing and vertical and horizontal effective stress after 12000 psi depletion in the formation (right figures not including the cement and casing)



Oval deformation of the casing inner radius (brown: after deformation)

Conclusions

1. Under extension tests, the casings were uniformly deformed after exceeding the yield strength. The uniform deformation continued while the casings were stretched by 4 to 25% until non-uniform deformation was induced.

2. The strain up to the peak strength was as large as 25% for H-40 casings while it was as small as 4% for P-110 and higher grade casings.

3. For compression tests, uniform compression continued exceeding the yield point. The uniform deformation continued up to the peak strength which varied from 3% to 12% from V-150 to H-40 casings. Both the cemented casings and short casings induced axisymmetric wrinkles (local buckling) after uniform deformation.

Conclusions(continued)

4. A field example shows that a casing can stand far beyond the yield stress if the lateral confining pressure is not large.

5. The higher grade casings did not significantly increase the maximum strength after yielding while lower grade casings increased the strength while being stretched or compressed uniformly after yielding. Hence, if the formation compaction or stretch is the cause of casing failure, reducing the casing grade with a heavy duty casing ($D/t<10$) may solve the problem.

Standard casing design

API recommendation: Collapse, Burst, Extension within Elastic limit
Assuming internal and external of casings are filled with liquid



Our proposition

Standard casing design

API recommendation: Collapse, Burst, Extension within Elastic limit
Assuming internal and external of casings are filled with liquid

Plus

Stable Yield or Buckling Limit Design

For geomechanicsl loading
assuming casing loaded with solid formation and cement

Casing grade and D/t selections are significantly different.