Sensitivity Analysis for Drained Triaxial Element Tests Using PDMY and ManzariDafalias Constitutive Models

Learning Curve Approach

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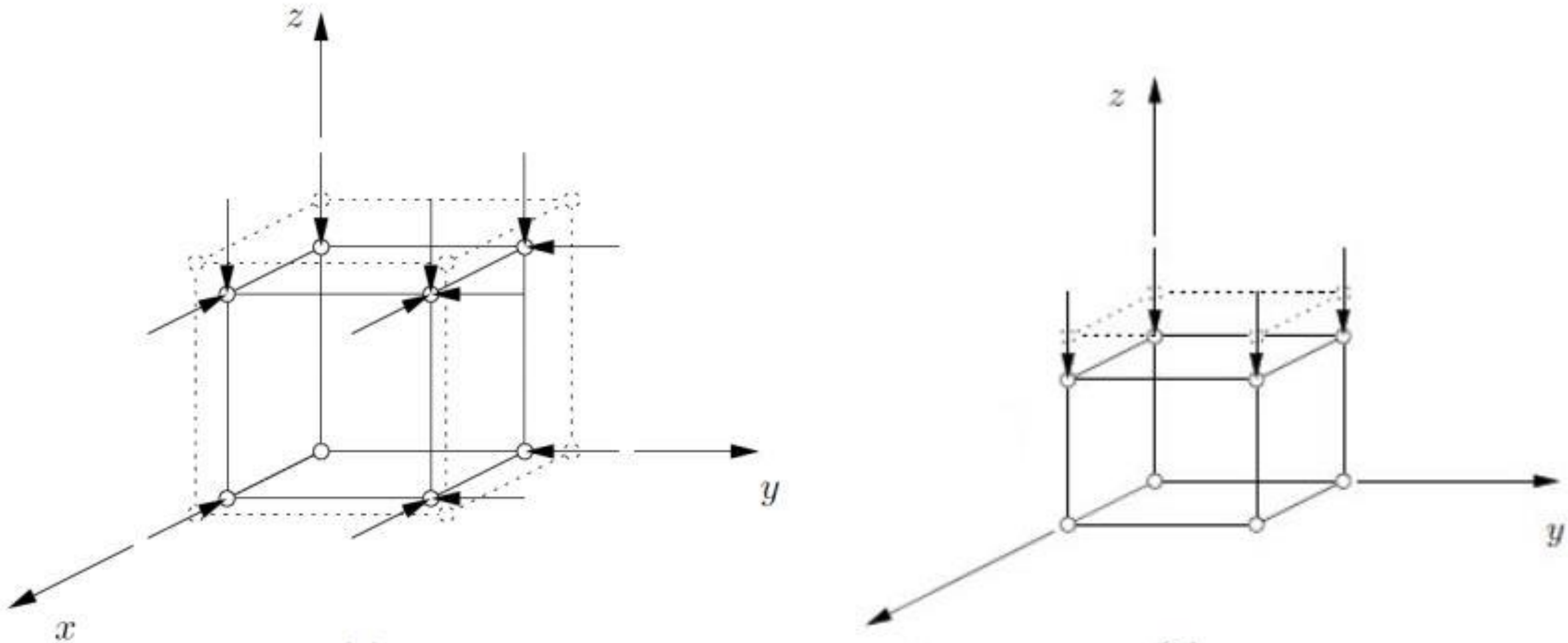
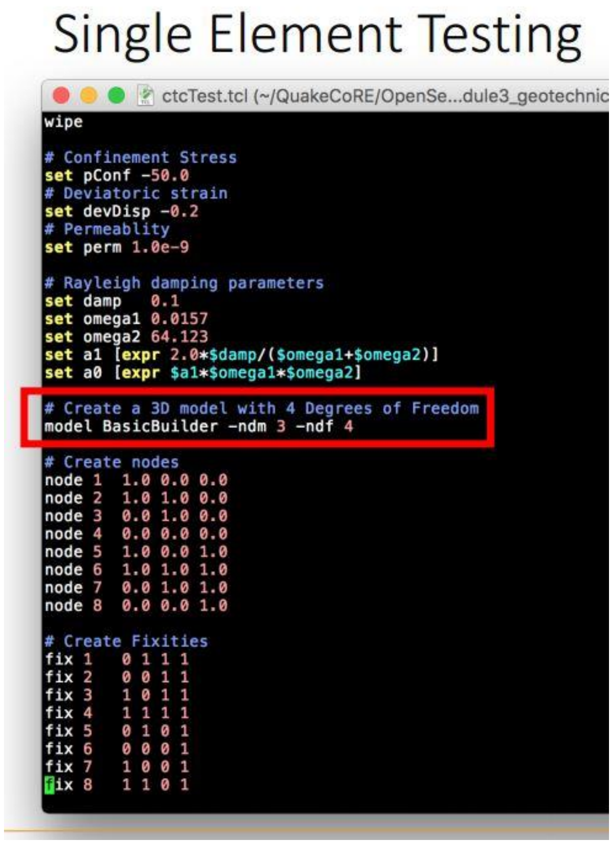
OpenSees Model



(a) (b)

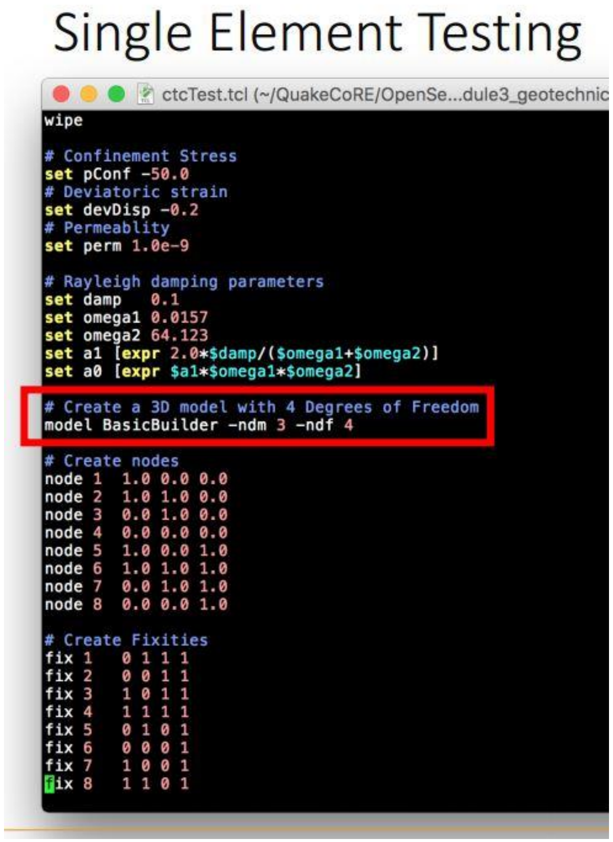
Script



Credits to Chris McGann

https://wiki.canterbury.ac.nz/display/QuakeCore/OpenSees+Training+Workshops+-+2017

Script



Single Element Testing

ctcTest.tcl (~/QuakeCoRE/OpenSe...dule3_geotechnic

```
wipe

# Confinement Stress
set pConf -50.0
# Deviatoric strain
set devDisp -0.2
# Permeablity
set perm 1.0e-9

# Rayleigh damping parameters
set damp   0.1
set omega1 0.0157
set omega2 64.123
set a1 [expr 2.0*$damp/($omega1+$omega2)]
set a0 [expr $a1*$omega1*$omega2]

# Create a 3D model with 4 Degrees of Freedom
model BasicBuilder -ndm 3 -ndf 4

# Create nodes
node 1  1.0 0.0 0.0
node 2  1.0 1.0 0.0
node 3  0.0 1.0 0.0
node 4  0.0 0.0 0.0
node 5  1.0 0.0 1.0
node 6  1.0 1.0 1.0
node 7  0.0 1.0 1.0
node 8  0.0 0.0 1.0

# Create Fixities
fix 1   0 1 1 1
fix 2   0 0 1 1
fix 3   1 0 1 1
fix 4   1 1 1 1
fix 5   0 1 0 1
fix 6   0 0 0 1
fix 7   1 0 0 1
fix 8   1 1 0 1
```

Single Element Testing

ctcTest.tcl (~/QuakeCoRE/OpenSe...dule3_geotechnicalExamples) - VIM

```
# Apply confinement pressure
set pNode [expr $pConf / 4.0]
pattern Plain 1 {Series -time {0 10000 1e10} -values {0 1 1} -factor 1} {
    load 1  $pNode  0.0     0.0     0.0
    load 2  $pNode  $pNode  0.0     0.0
    load 3  0.0     $pNode  0.0     0.0
    load 5  $pNode  0.0     $pNode  0.0
    load 6  $pNode  $pNode  $pNode  0.0
    load 7  0.0     $pNode  $pNode  0.0
    load 8  0.0     0.0     $pNode  0.0
}
analyze 100 100

# Let the model rest and waves damp out
analyze 10  1000

# Close ...age valves
for {se...
   remove sp...
}
analyze ...0.1

updateMaterialStage -material 1 -stage 1

analyze 5 0.1

# Read vertical displacement of top plane
set vertDisp [nodeDisp 5 3]
# Apply deviatoric strain
set eDisp [expr 1+$devDisp/$vertDisp]
eval "timeSeries Path 5 -time {0 20001 20301 1e10
pattern Plain 2 5 {
    sp 5  3 $vertDisp
    sp 6  3 $vertDisp
    sp 7  3 $vertDisp
    sp 8  3 $vertDisp
}
```

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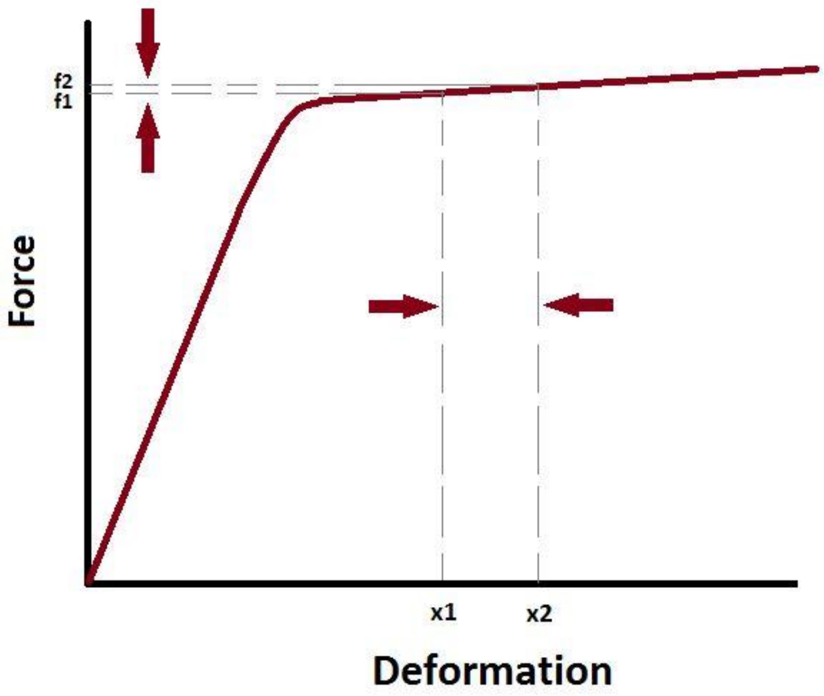
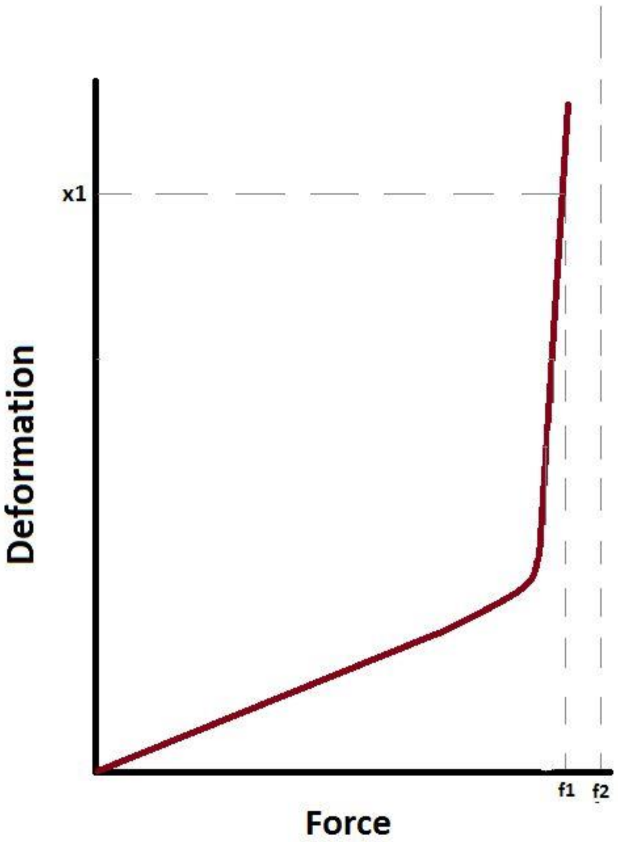
Applying Deviatoric Stress vs Strain





Variation of PDMY Material Parameters

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- **Deviatoric Stress ($q=\sigma_1-\sigma_3$)**

- **Mobilized Shear Angle**

- **Volumetric Change (Strain)**

Variation of PDMY Material Parameters

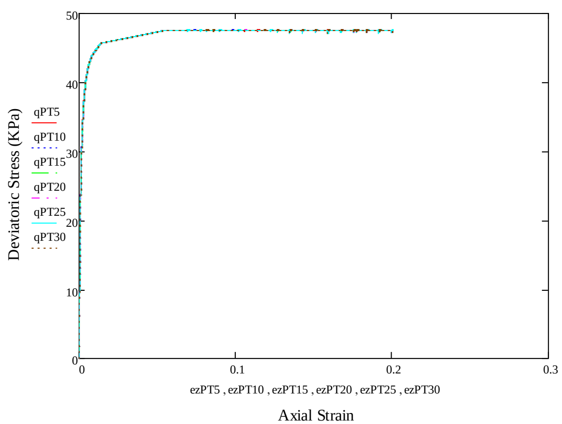
	Loose	Medium	Dense
Deviatoric Displacement (m)	0.2~0.4	0.2~0.4	0.2~0.4
Density (tonne/m^3)	1.7	1.95	2.1
Shear Modulus G_0 (MPa)	55	87.5	130
Shear Modulus K_0 (MPa)	150	250	390
Poisson Ratio v	0.34	0.343	0.35
Young Modulus E_0 (MPa)	147.4	235	351
Friction Angle	29	35	40
Phase Transformation Angle	29	27	27
Contraction Constant	0.21	0.06	0.03
Dilatancy Constant 1	0	0.5	0.8
Dilatancy Constant 2	0	2.5	5
Liquefaction Factor 1 (KPa)	10	7.5	0
Liquefaction Factor 2	0	0.0065	0
Liquefaction Factor 3	0	1.0	0
Initial Void Ratio (e)	0.85	0.625	0.45

Confining Pressure	Values (KPa)
P_{c1}	50
P_{c2}	1000
P_{c3}	4000

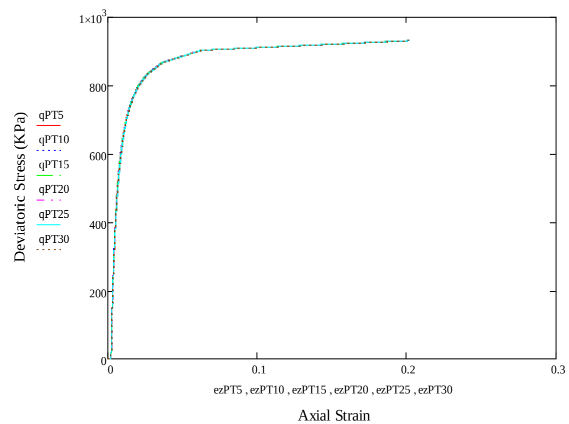
Loose PDMY
Phase Transformation Angle

Phase Transformation Angle (Degrees)
5
10
15
20
25
30

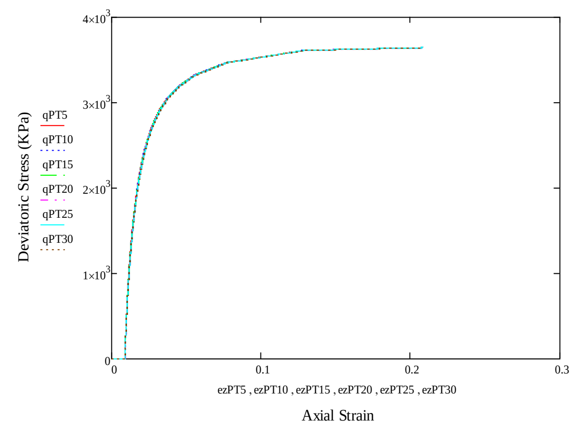
50 KPa



1000 KPa



4000 KPa



Loose PDMY Phase Transformation Angle

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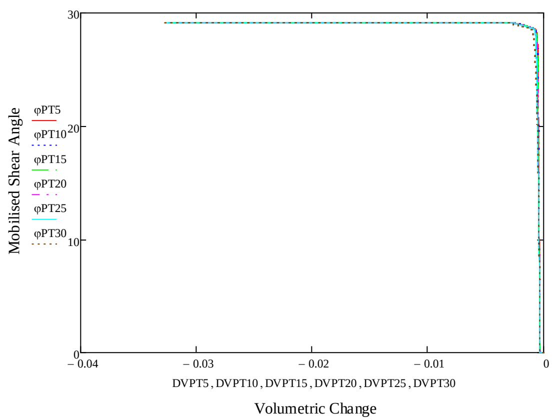
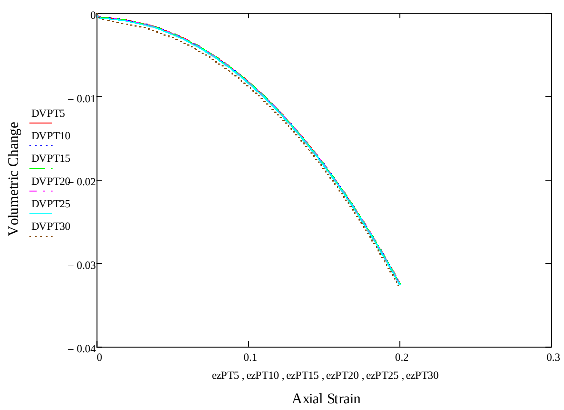
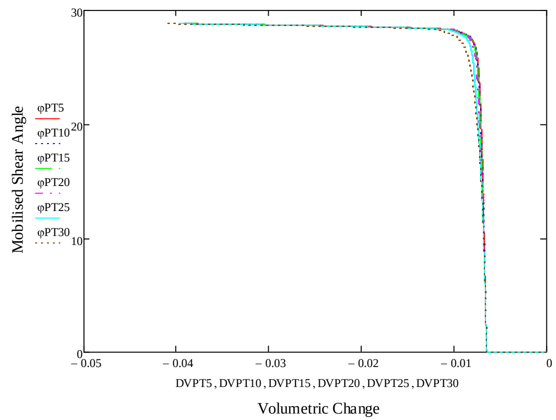
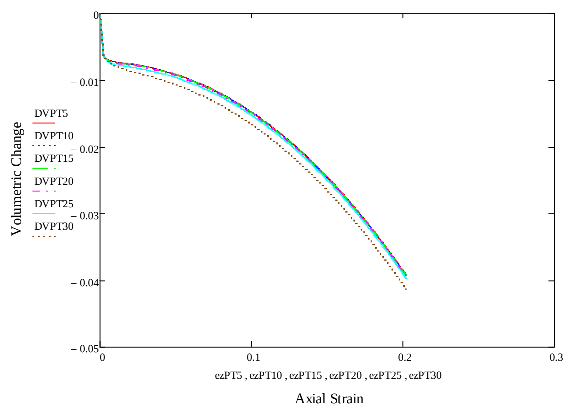
50 KPa



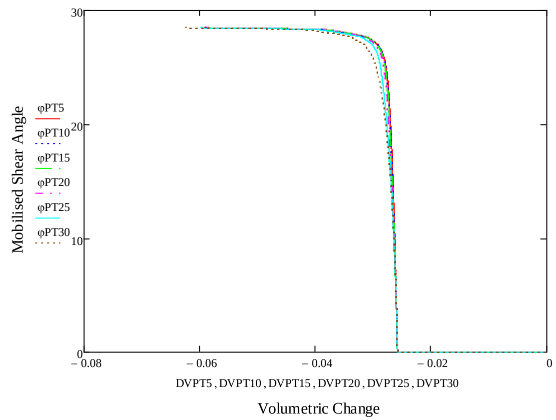


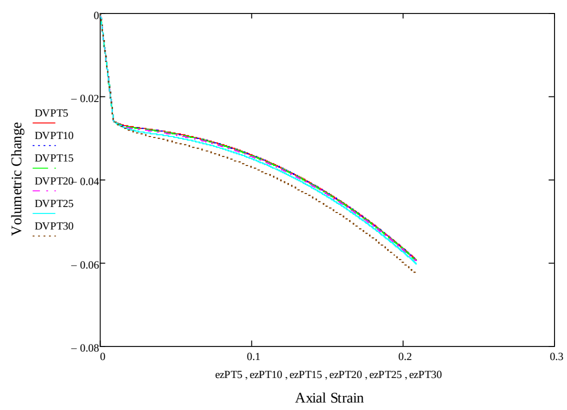
1000 KPa





4000 KPa

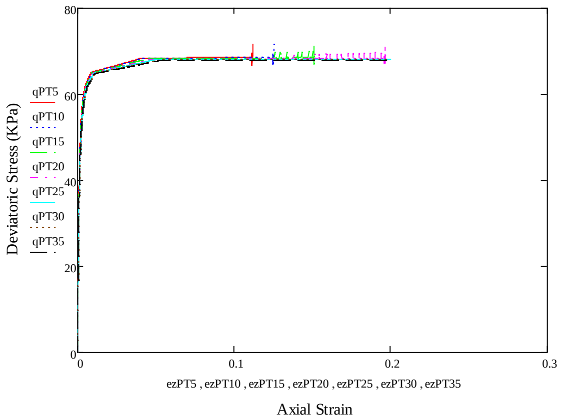




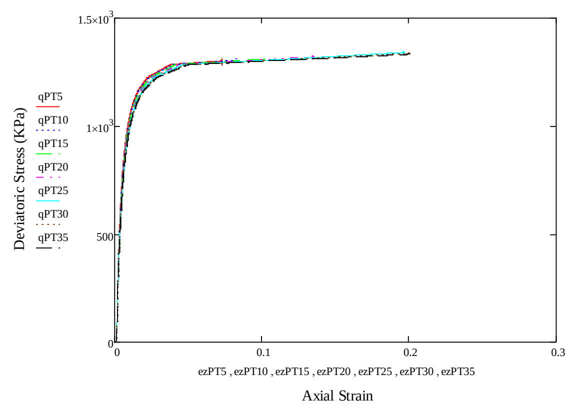
Medium PDMY
Phase Transformation Angle

Phase Transformation Angle (Degrees)
5
10
15
20
25
30
35

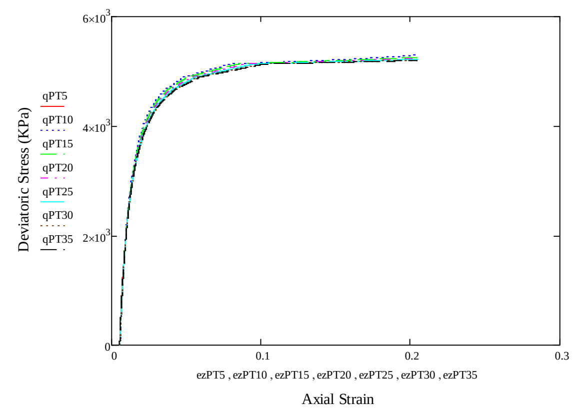
50 KPa



1000 KPa

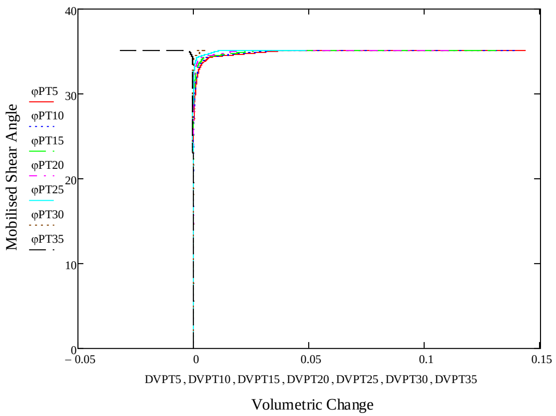


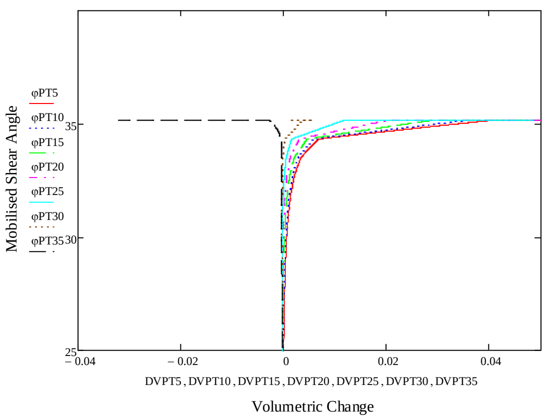
4000 KPa



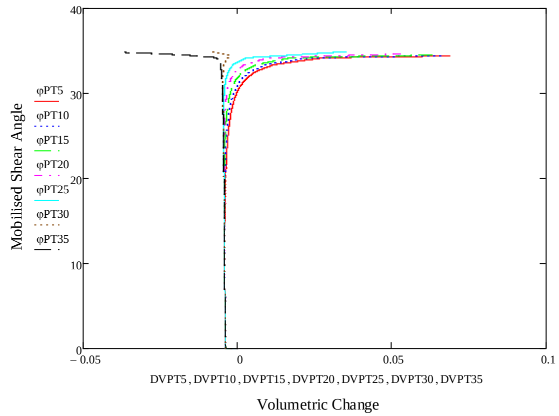
Medium PDMY
Phase Transformation Angle

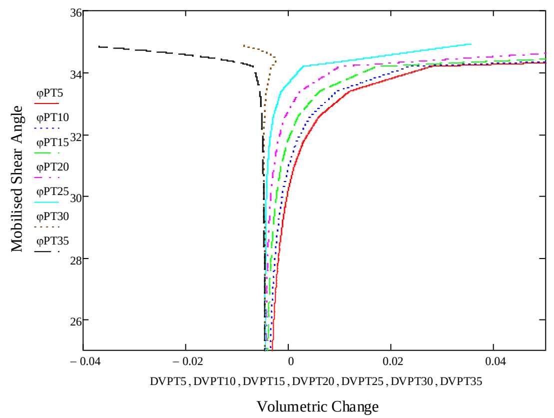
50 KPa



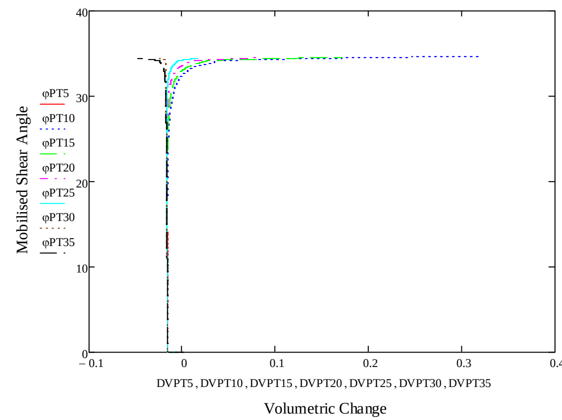


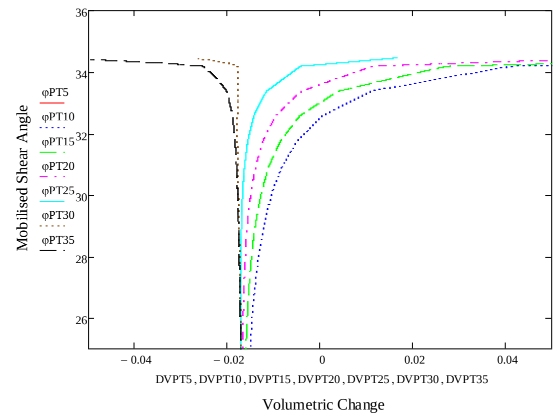
1000 KPa





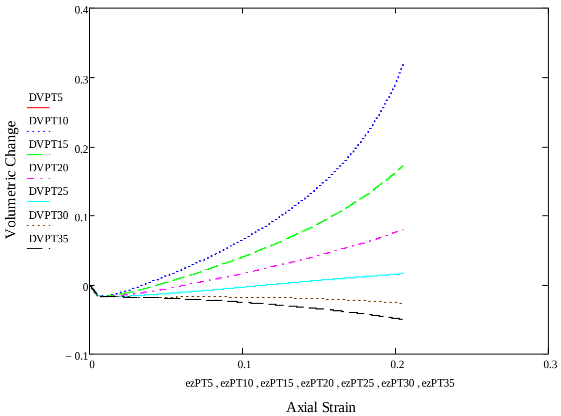
4000 KPa



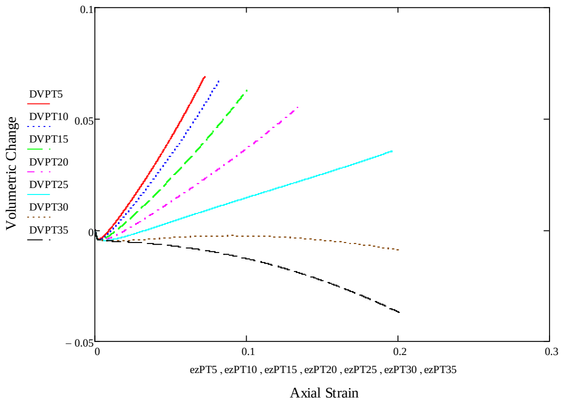


Medium PDMY
Phase Transformation Angle

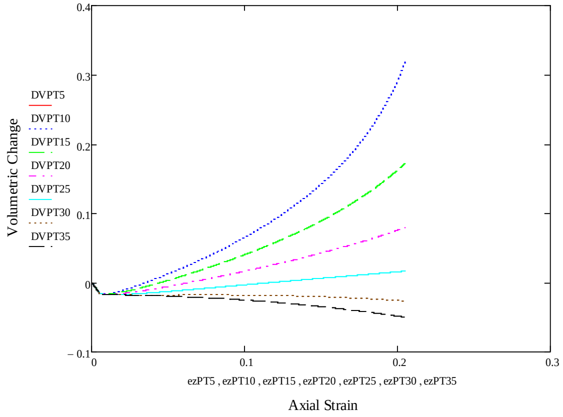
50 KPa



1000 KPa



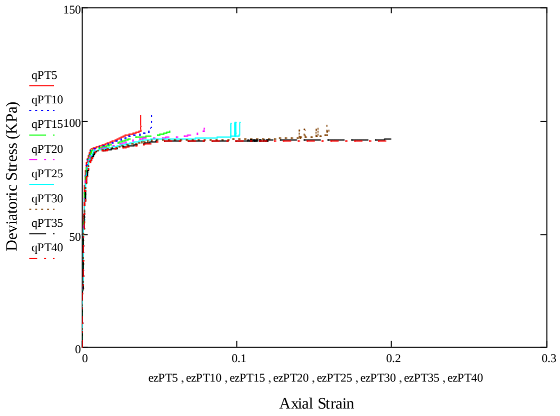
4000 KPa



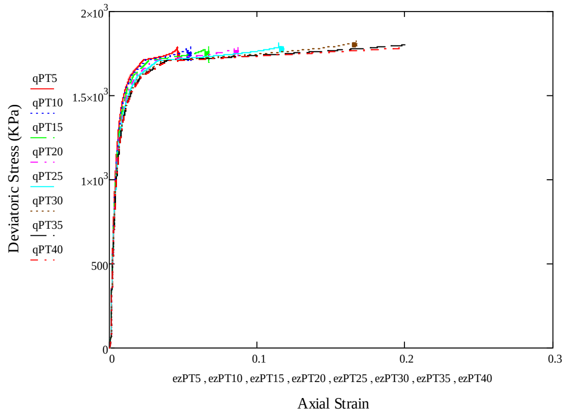
Dense PDMY
Phase Transformation Angle

Phase Transformation Angle (Degrees)
5
10
15
20
25
30
35
40

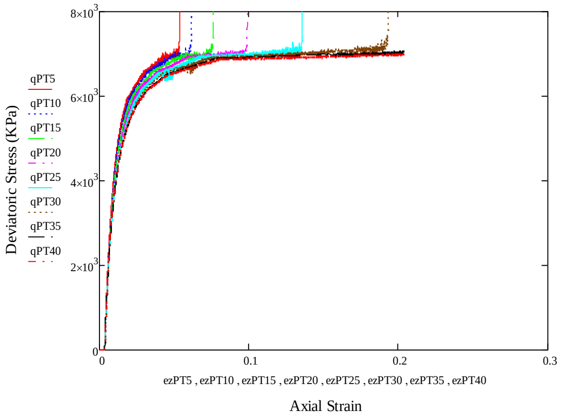
50 KPa



1000 KPa



4000 KPa



Dense PDMY
Phase Transformation Angle

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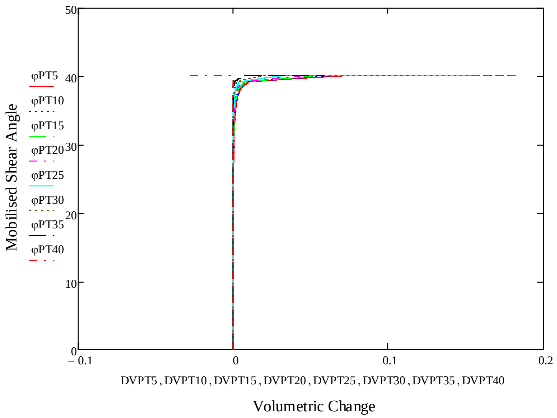
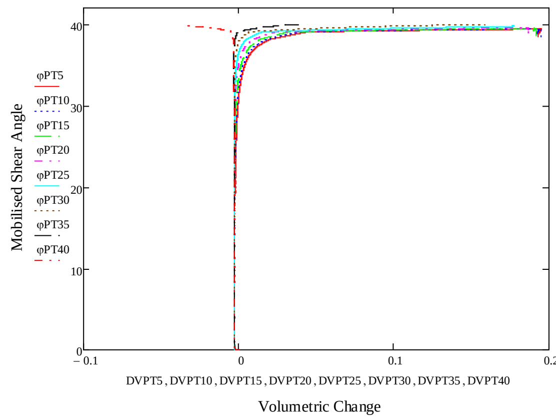
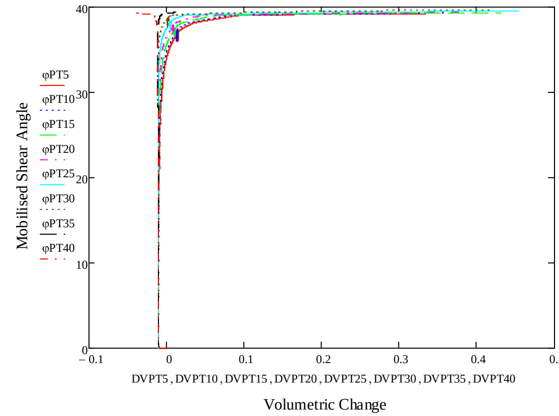
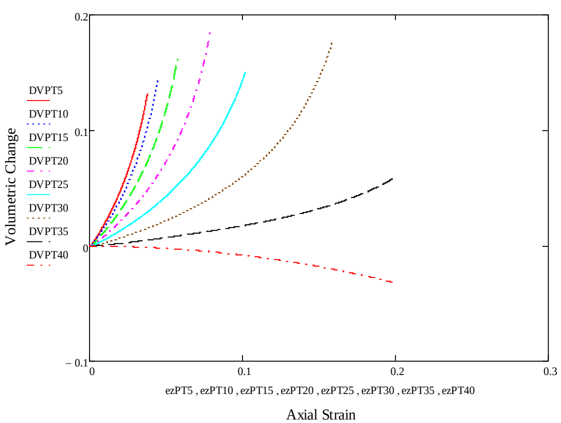
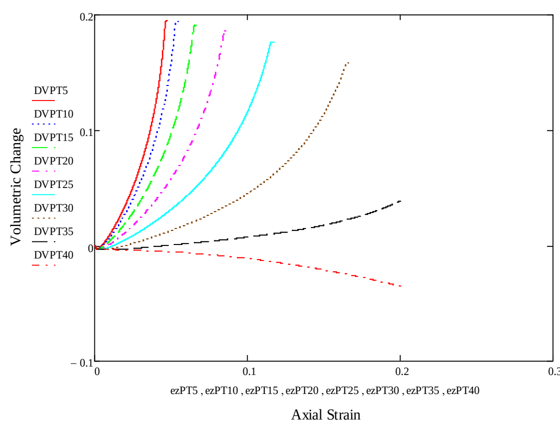
50 KPa	1000 KPa	4000 KPa

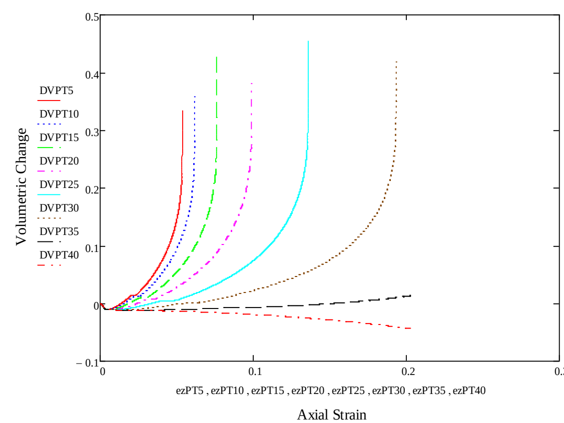








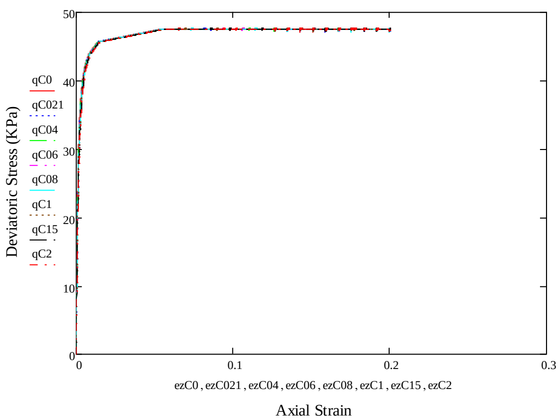




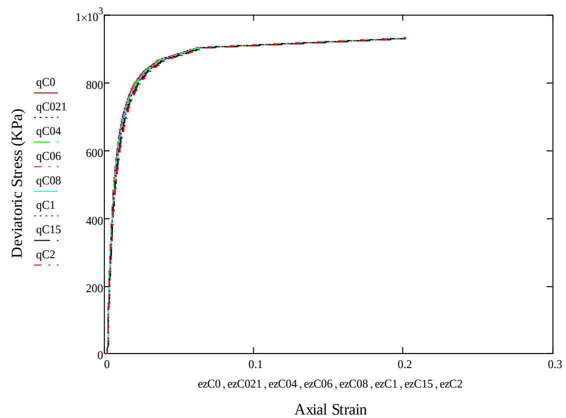
Loose PDMY Contraction Constant

Contraction Constant c_1
0
0.21
0.4
0.6
0.8
1.0
1.5
2.0

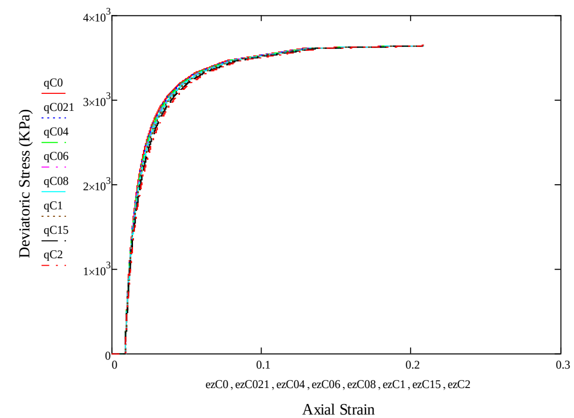
50 KPa



1000 KPa

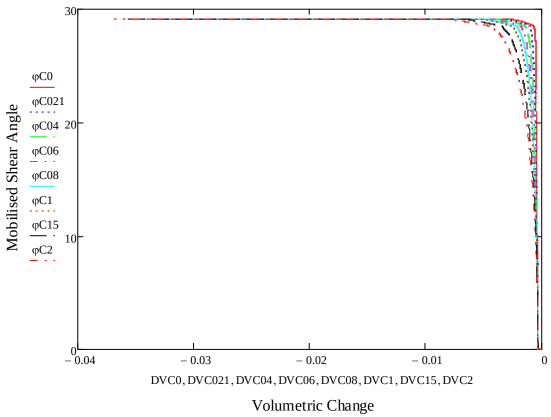


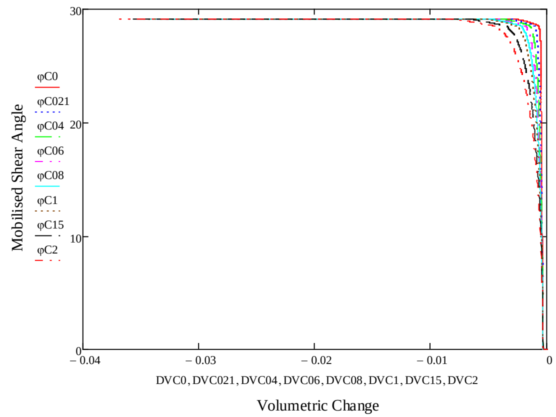
4000 KPa

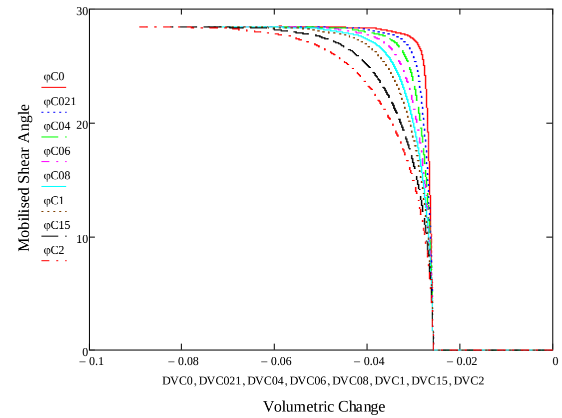


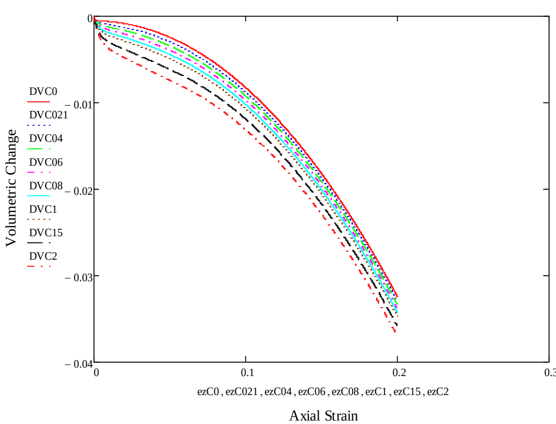
Loose PDMY Contraction Constant

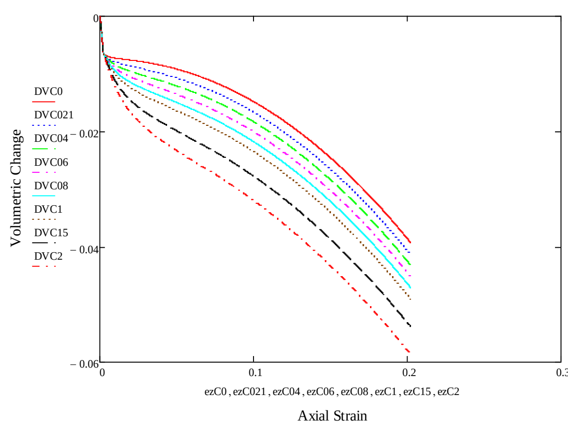
50 KPa	1000 KPa	4000 KPa

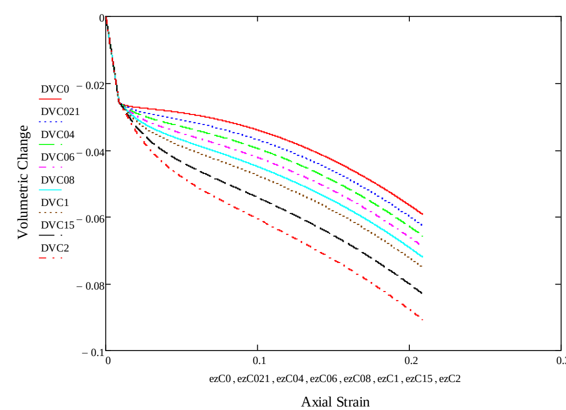








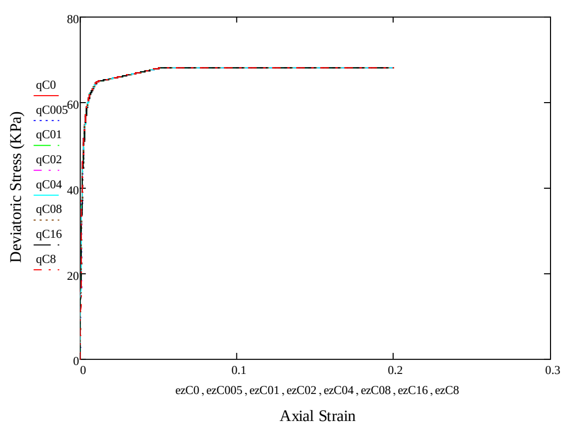




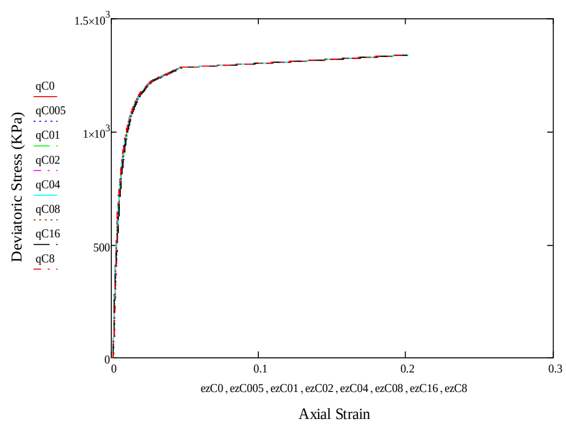
Medium PDMY Contraction Constant

Contraction Constant c_1
0
0.05
0.1
0.2
0.4
0.8
1.6
8

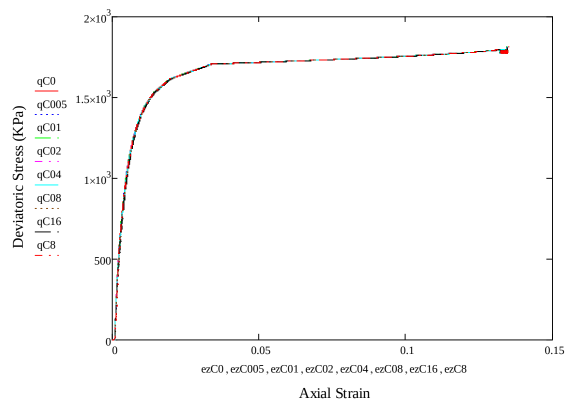
50 KPa



1000 KPa

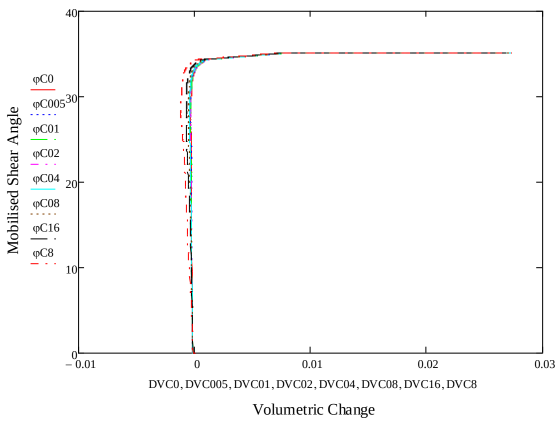


4000 KPa

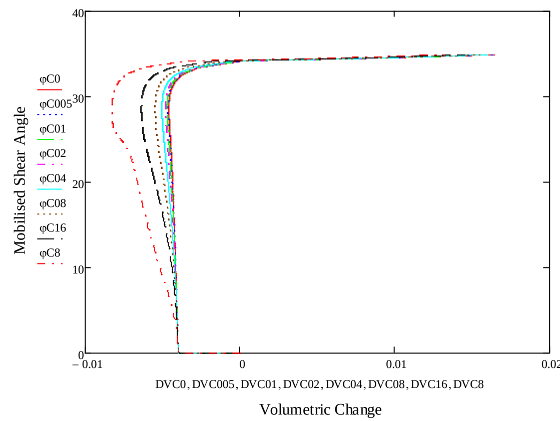


Medium PDMY Contraction Constant

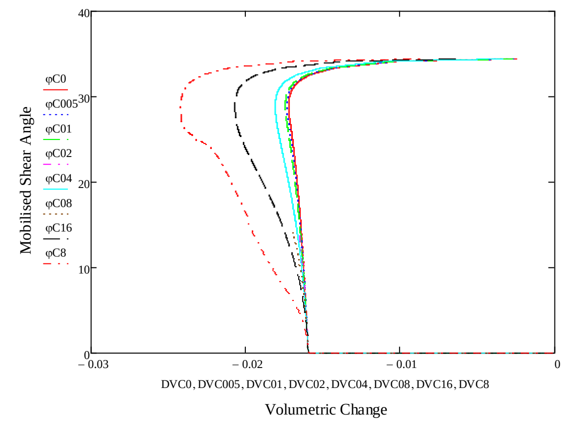
50 KPa

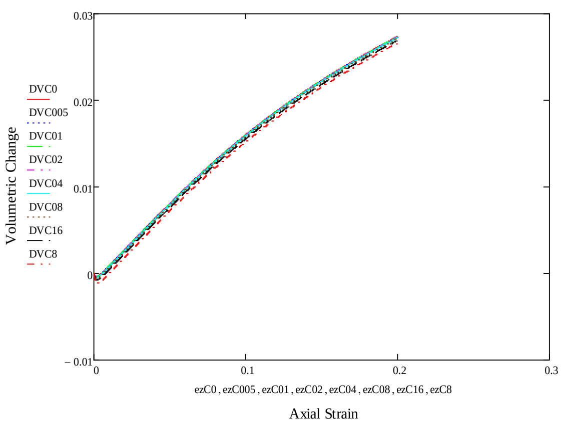


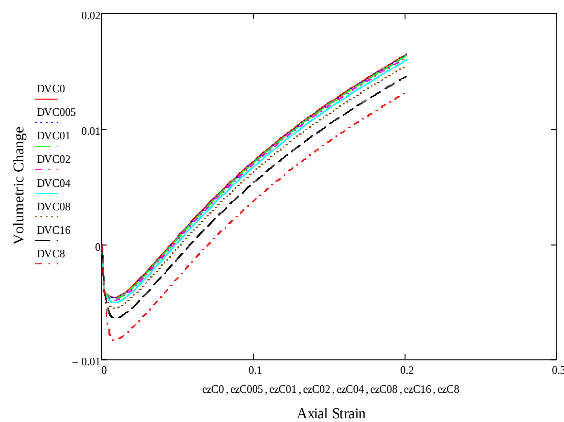
1000 KPa

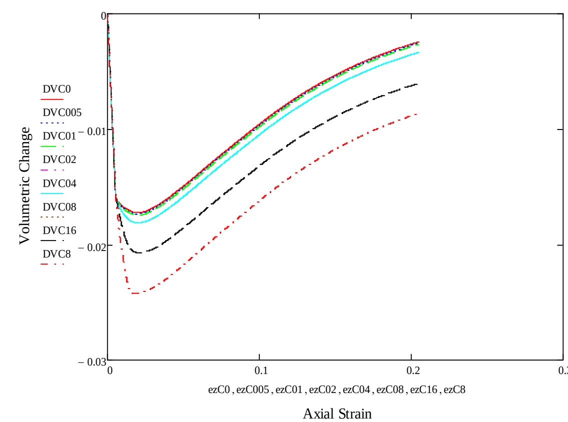


4000 KPa





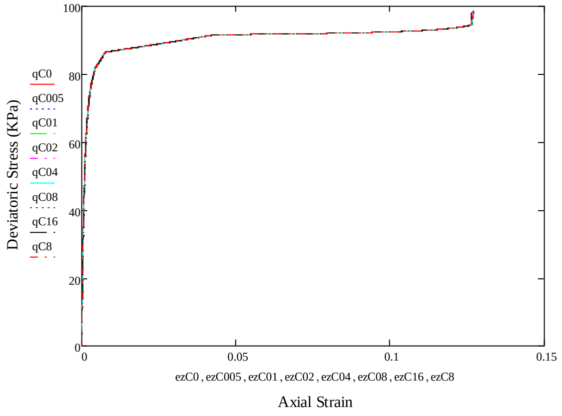




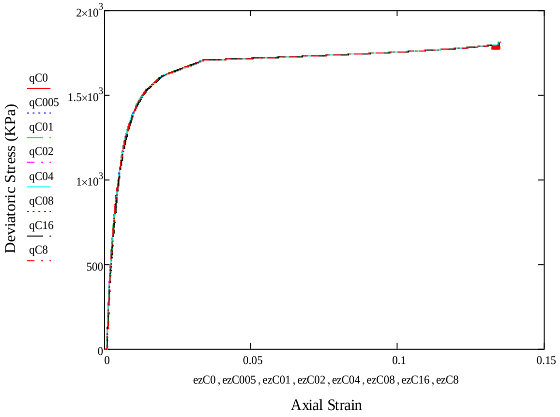
Dense PDMY Contraction Constant

Contraction Constant c_1
0
0.05
0.1
0.2
0.4
0.8
1.6
8

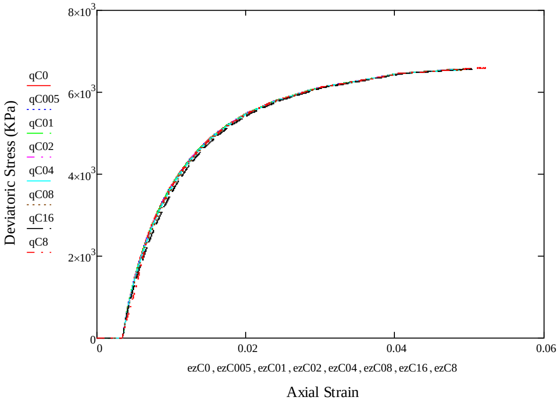
50 KPa



1000 KPa



4000 KPa



Dense PDMY Contraction Constant

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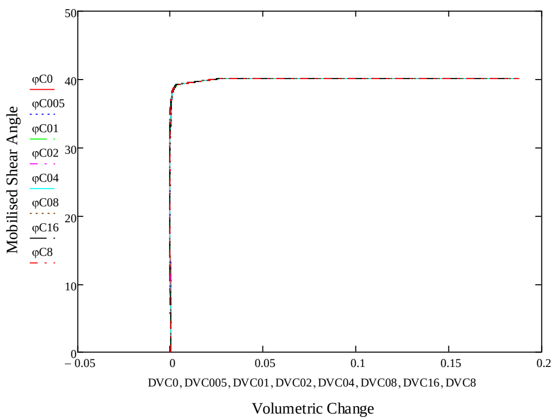
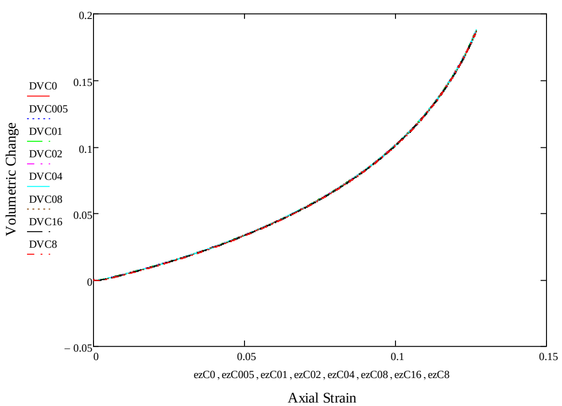
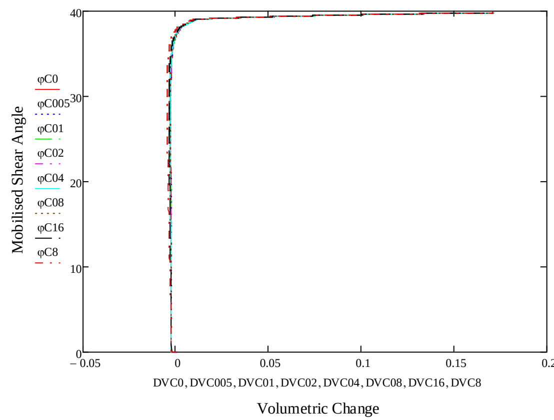
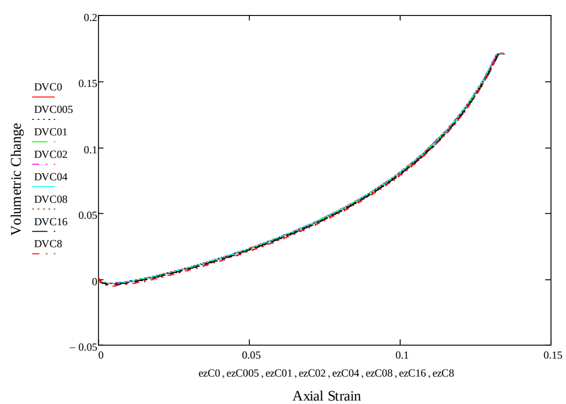
50 KPa



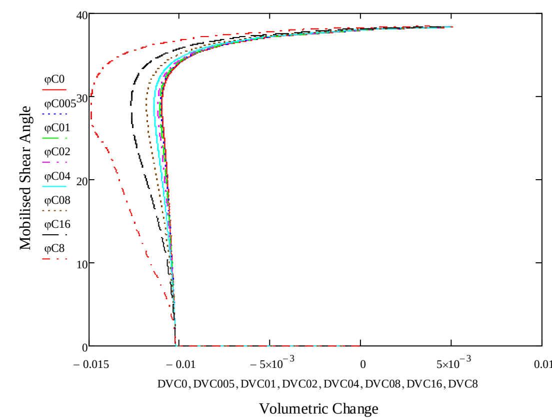


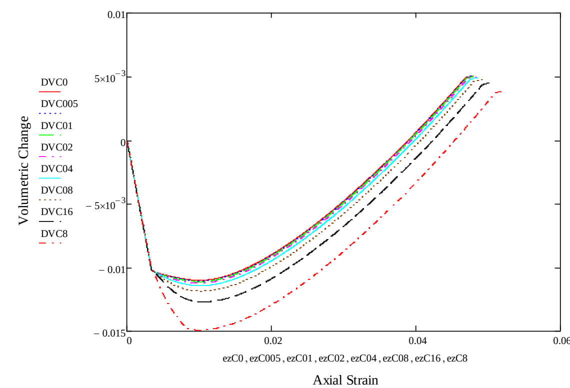
1000 KPa





4000 KPa

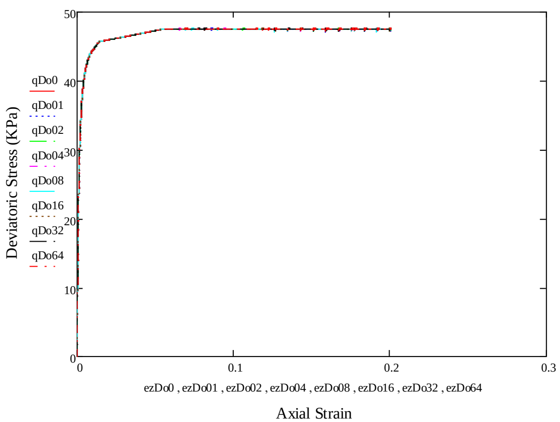




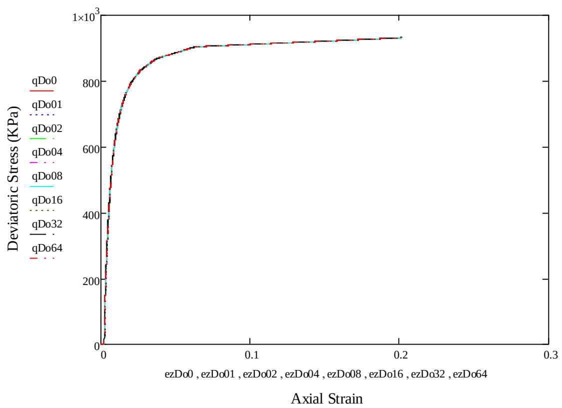
Loose PDMY
Dilatancy1 Constant

Dilatancy1 Constant d_1
0
0.1
0.2
0.4
0.8
1.6
3.2
6.4

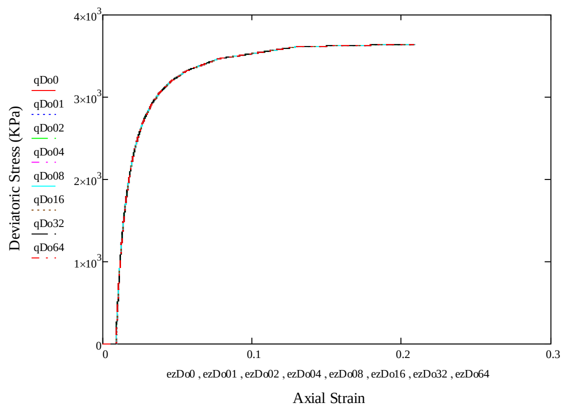
50 KPa



1000 KPa



4000 KPa



Loose PDMY Dilatancy1 Constant

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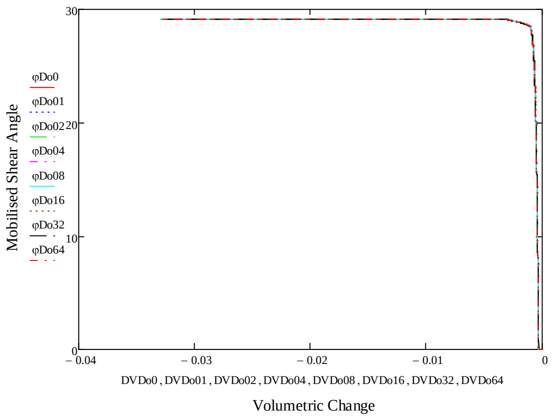
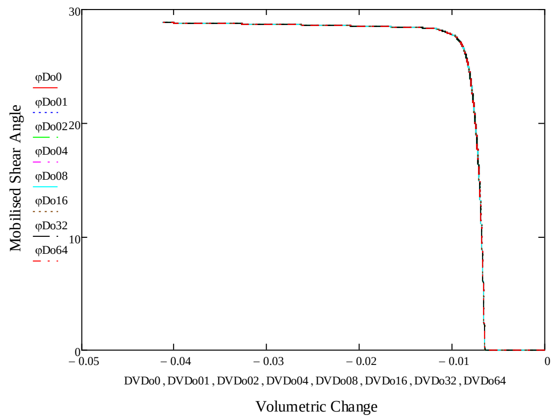
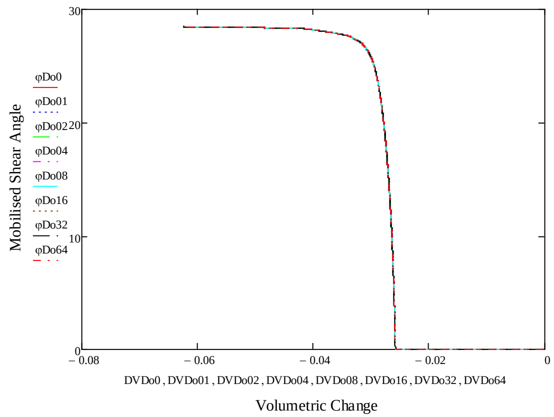
50 KPa

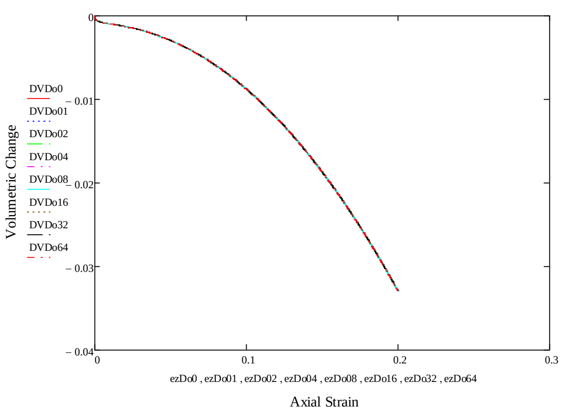
1000 KPa

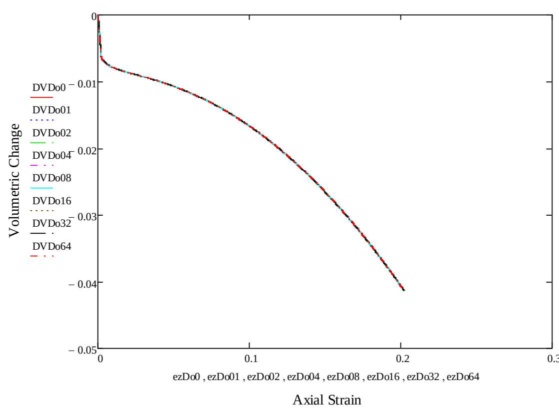
4000 KPa

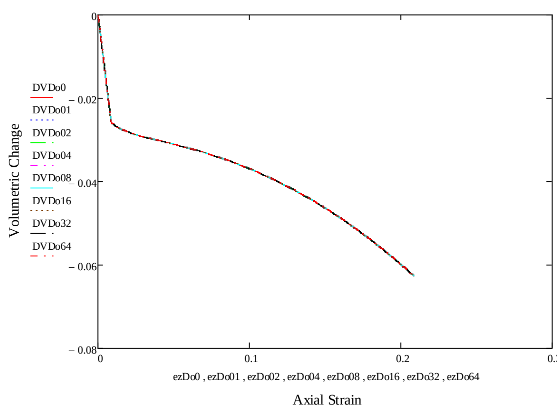








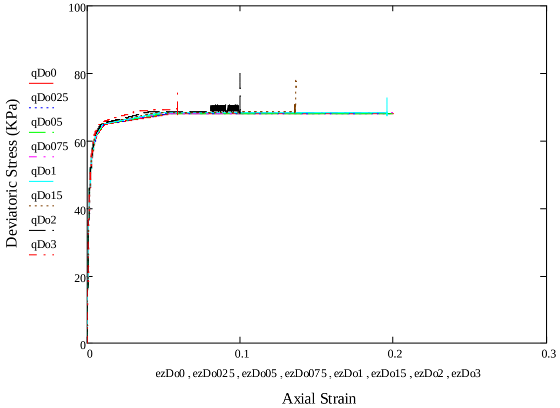




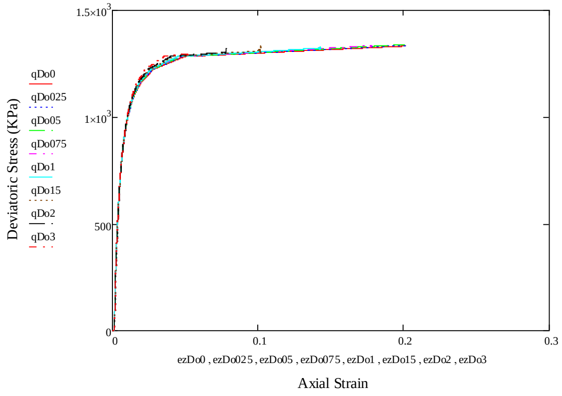
Medium PDMY
Dilatancy1 Constant

Dilatancy1 Constant d_1
0
0.25
0.5
0.75
1.0
1.5
2.0
3.0

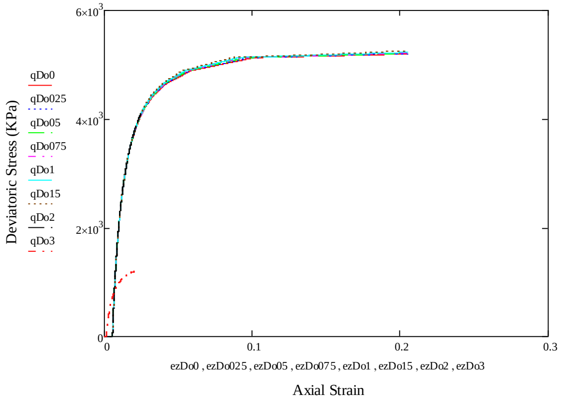
50 KPa



1000 KPa



4000 KPa

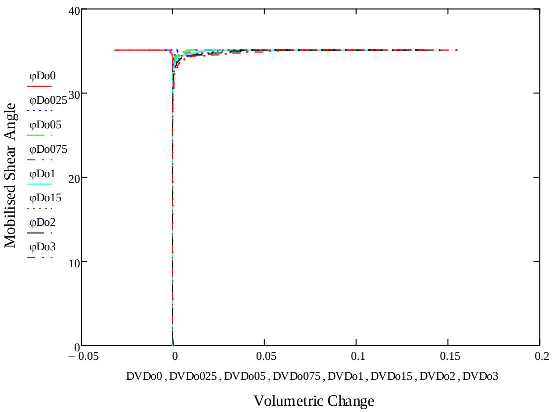


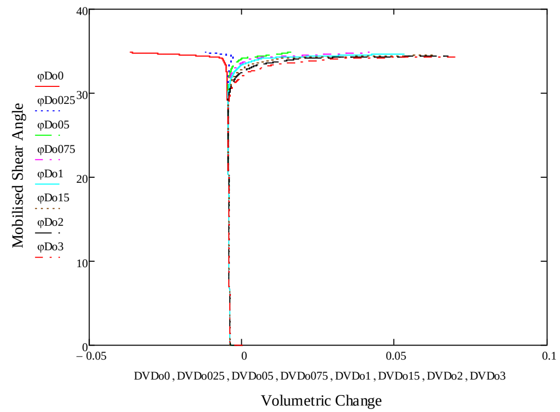
Medium PDMY Dilatancy1 Constant

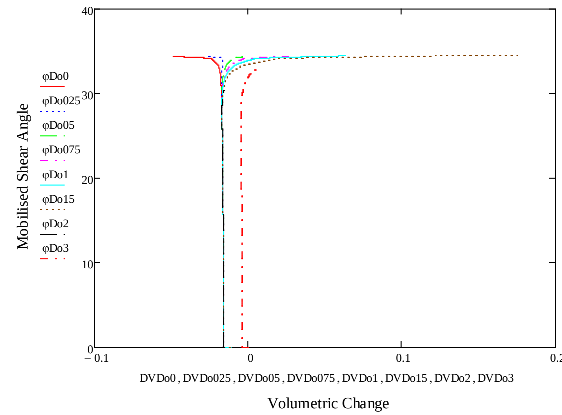
50 KPa

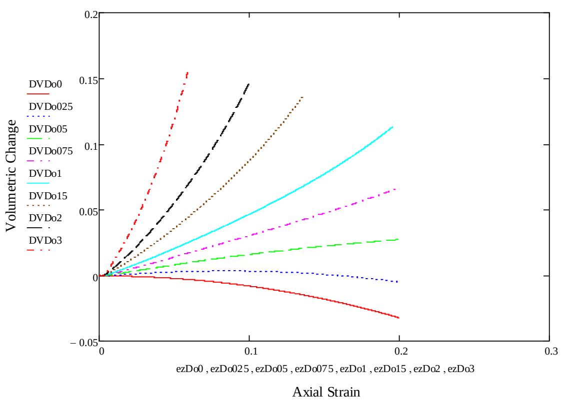
1000 KPa

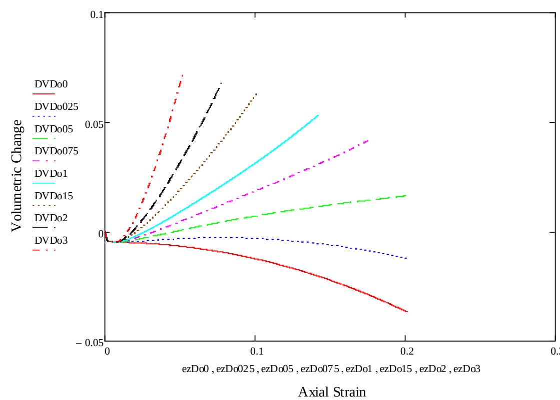
4000 KPa

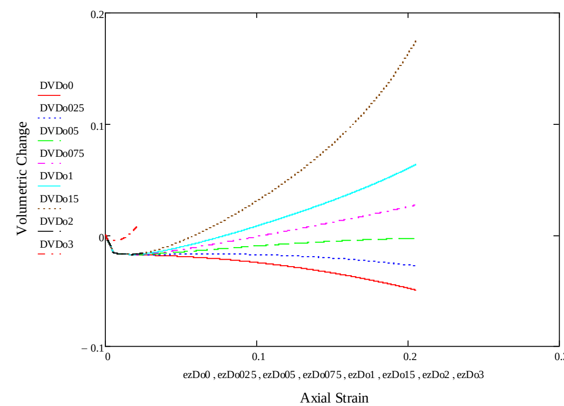








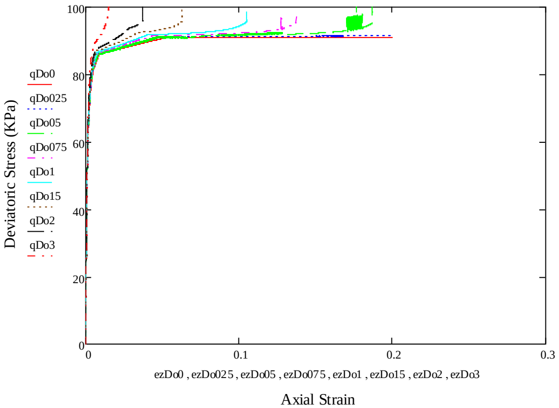




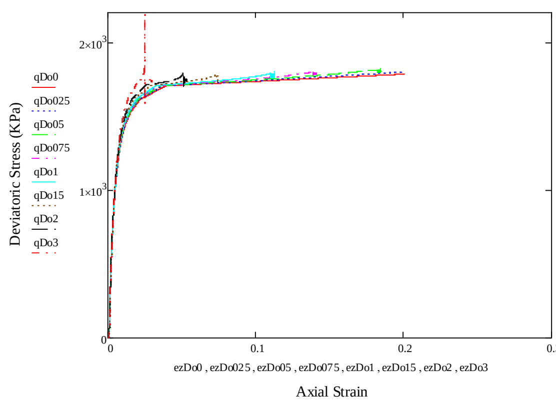
Dense PDMY
Dilatancy1 Constant

Dilatancy1 Constant d_1
0
0.25
0.5
0.75
1.0
1.5
2.0
3.0

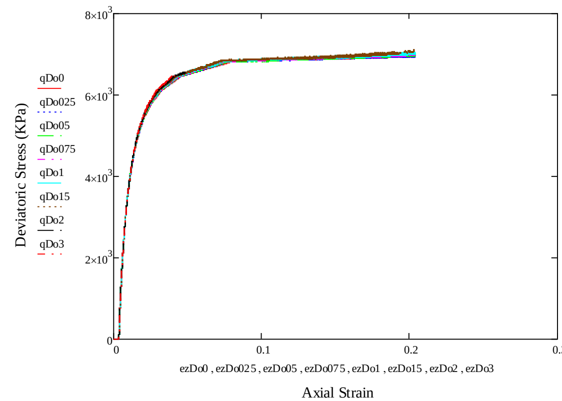
50 KPa



1000 KPa

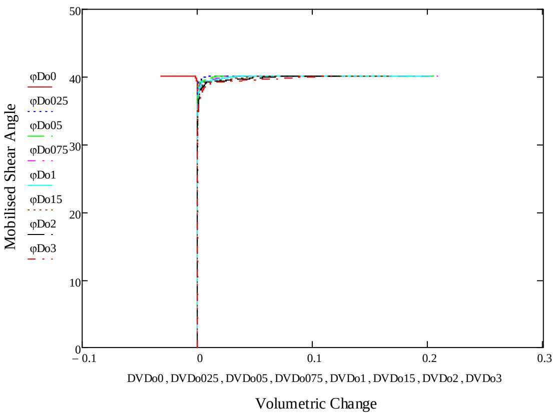


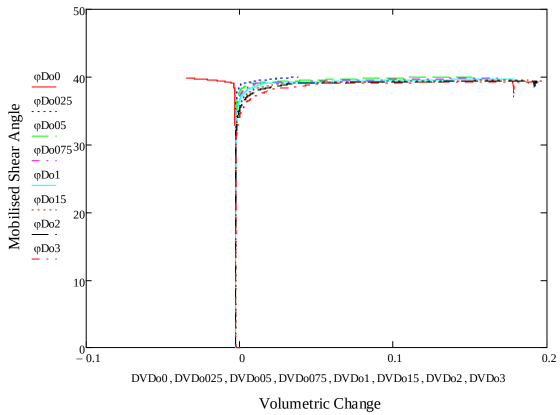
4000 KPa

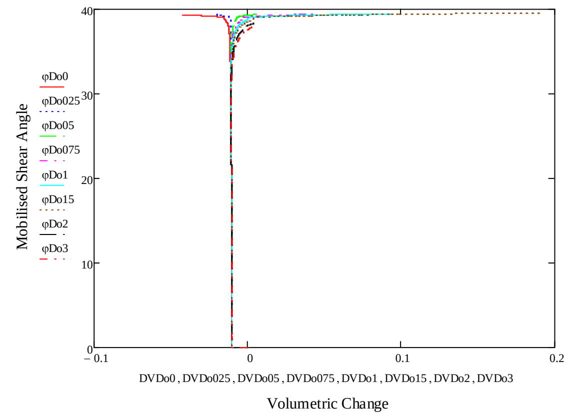


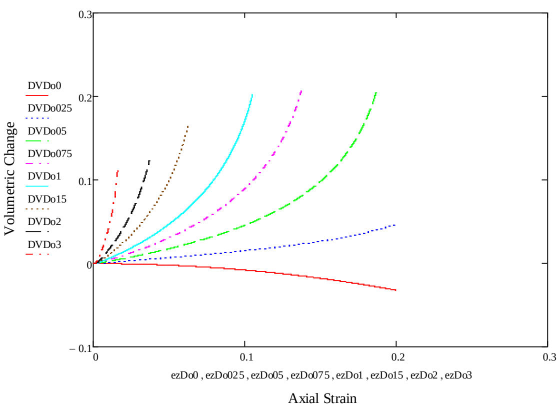
Dense PDMY Dilatancy1 Constant

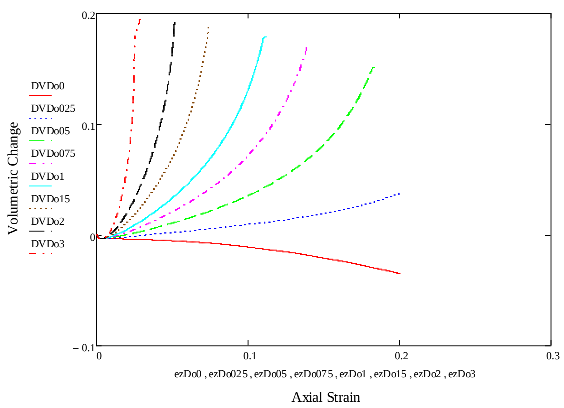
50 KPa	1000 KPa	4000 KPa

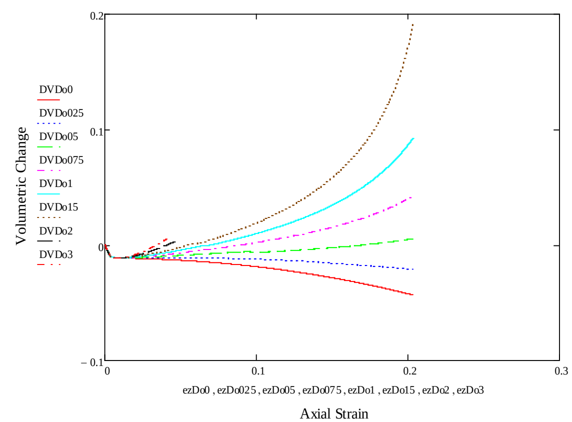












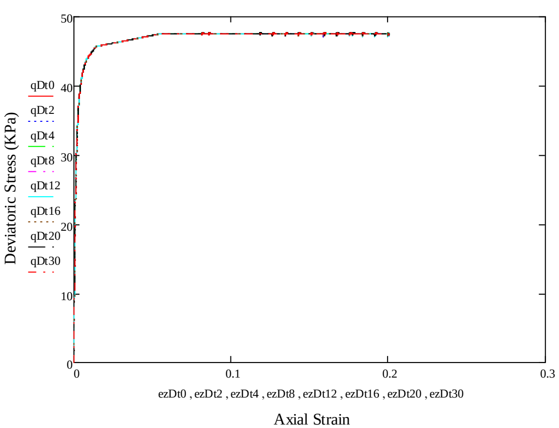
Loose PDMY Dilatancy2 Constant

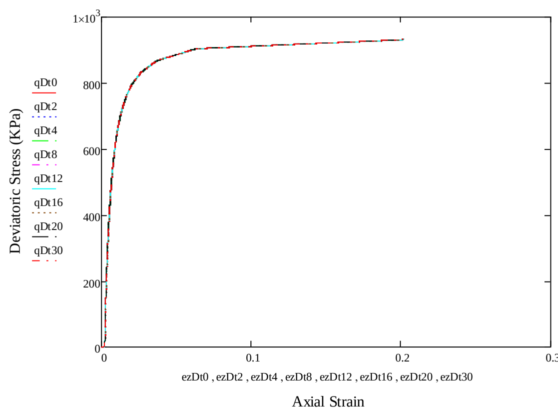
Dilatancy2 Constant d_2
0
2.0
4.0
8.0
12.0
16.0
20.0
30.0

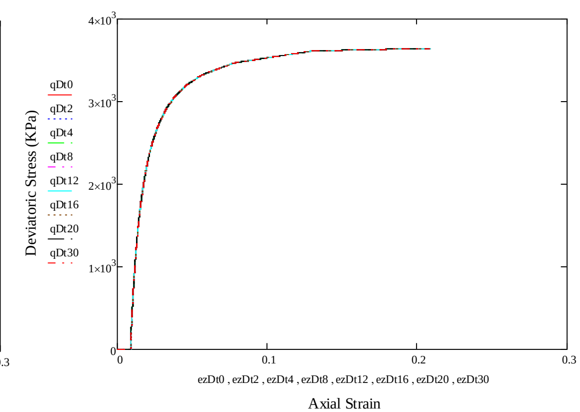
50 KPa

1000 KPa

4000 KPa







Loose PDMY
Dilatancy2 Constant

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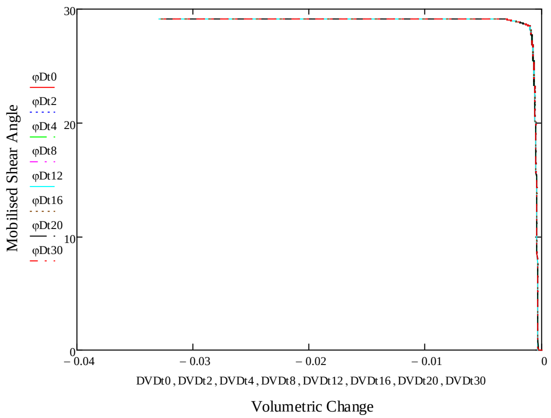
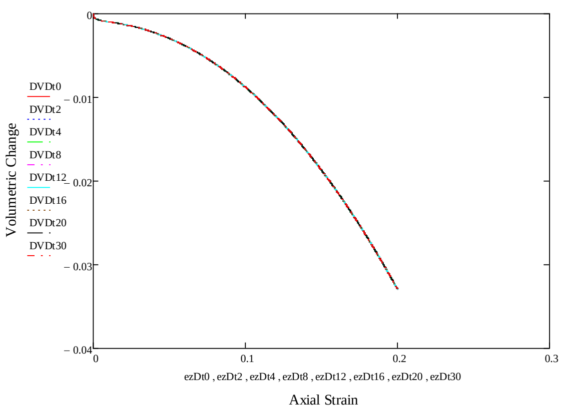
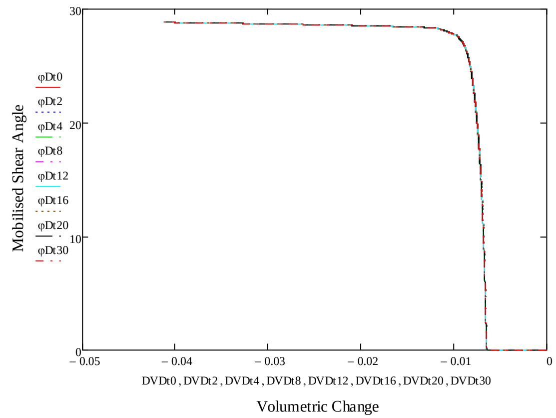
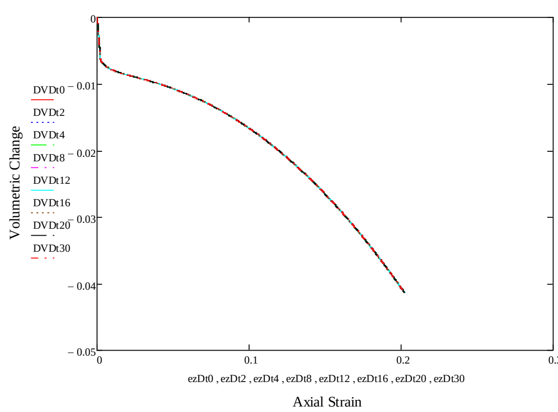
50 KPa



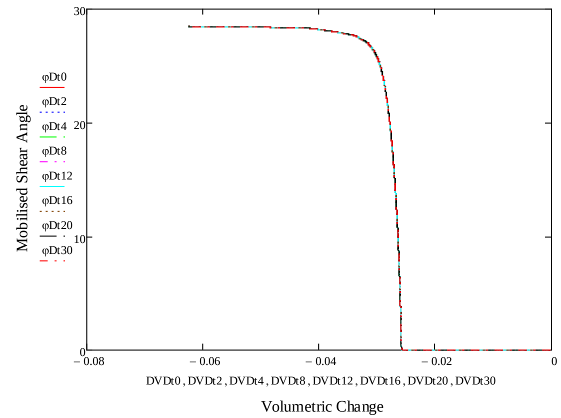


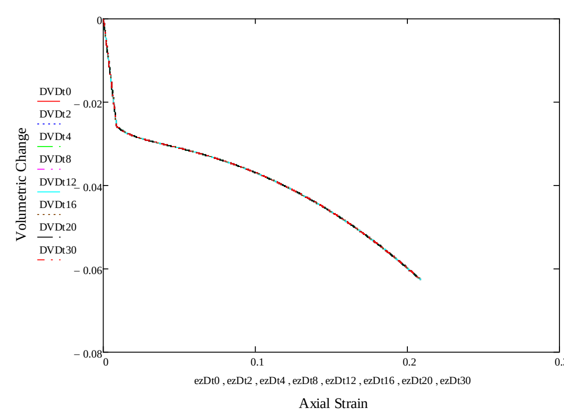
1000 KPa





4000 KPa

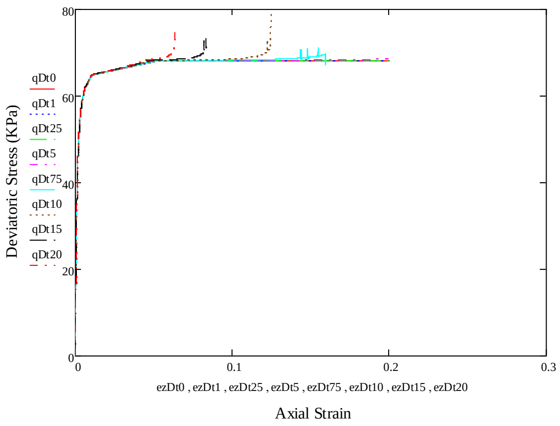




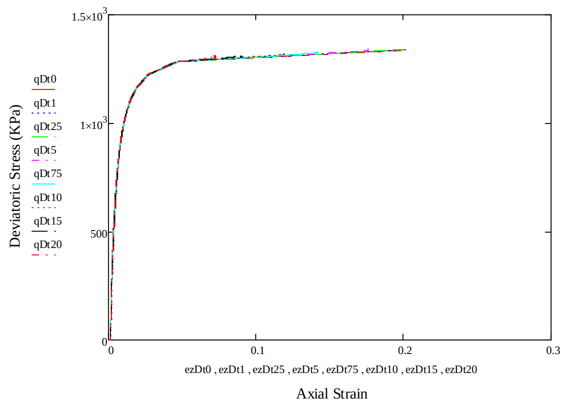
Medium PDMY Dilatancy2 Constant

Dilatancy2 Constant d_2
0
1.0
2.5
5.0
7.5
10.0
15.0
20.0

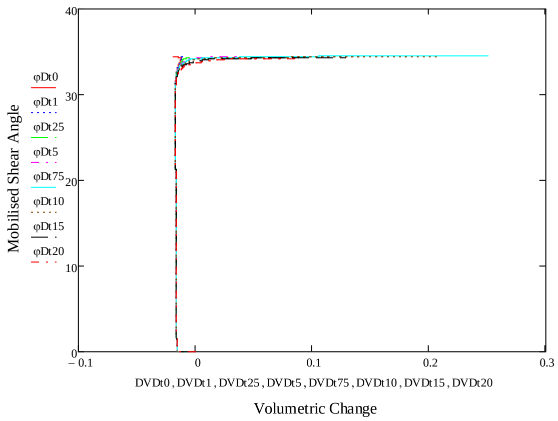
50 KPa



1000 KPa



4000 KPa



Medium PDMY Dilatancy2 Constant

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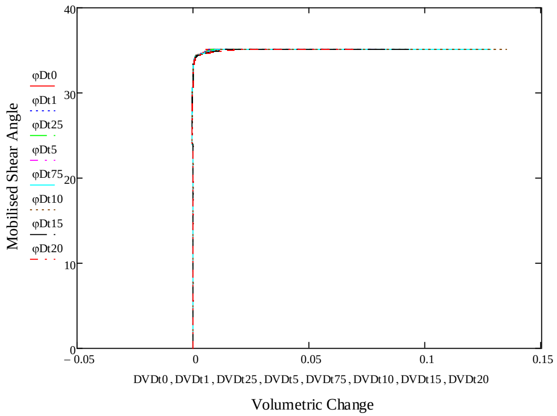
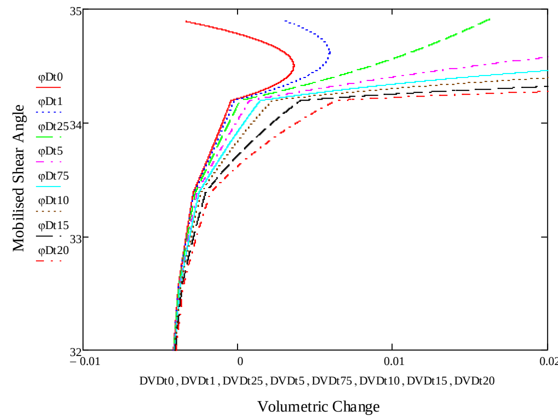
NEW ZEALAND

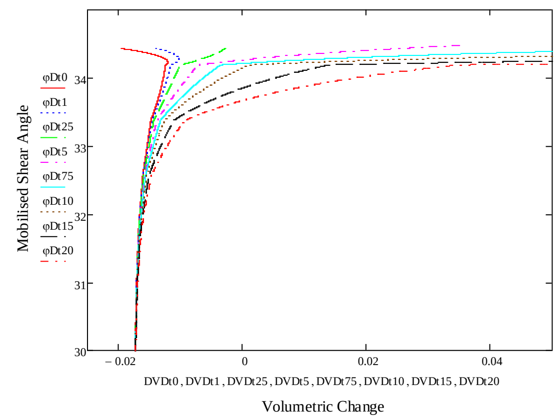
50 KPa

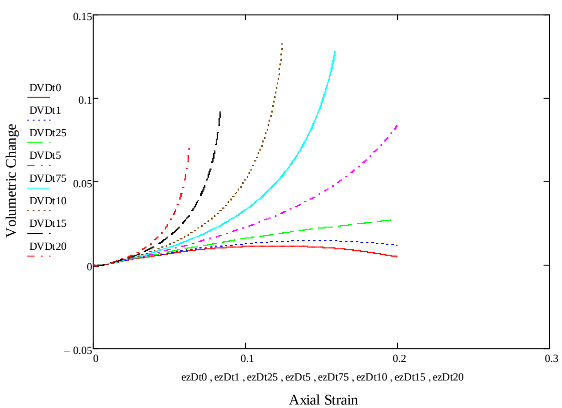
1000 KPa

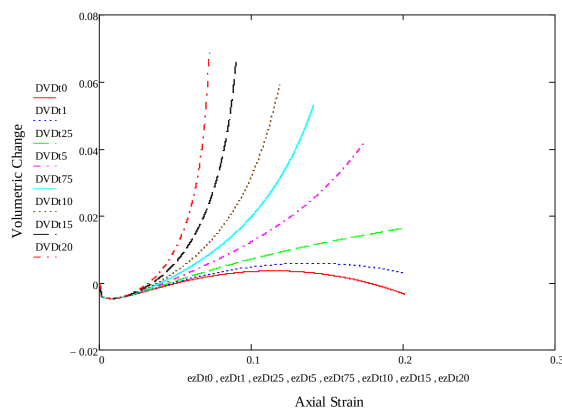
4000 KPa

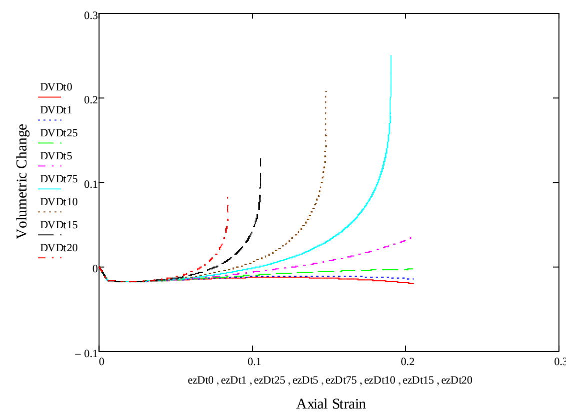








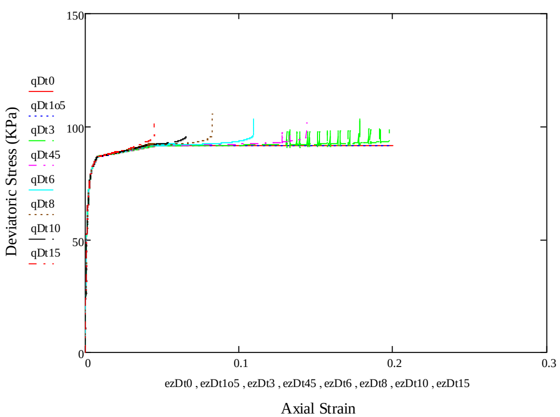




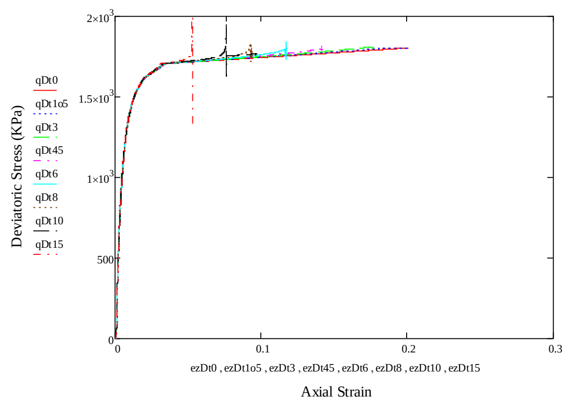
Dense PDMY Dilatancy2 Constant

Dilatancy2 Constant d_2
0
1.5
3.0
4.5
6.0
8.0
10.0
15.0

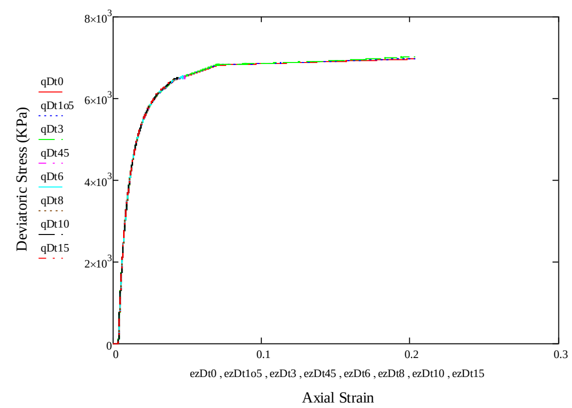
50 KPa



1000 KPa



4000 KPa



Dense PDMY Dilatancy2 Constant

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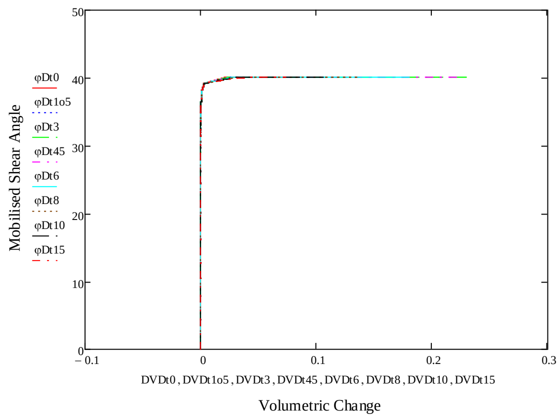
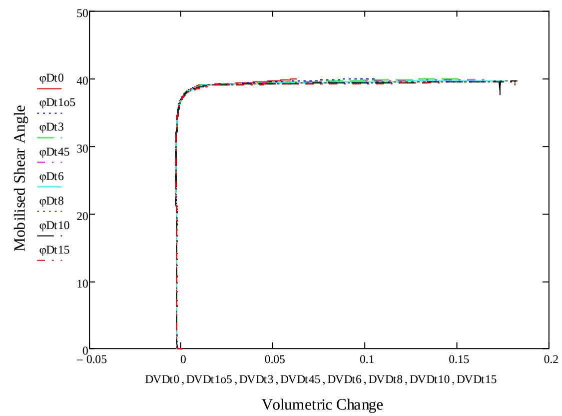
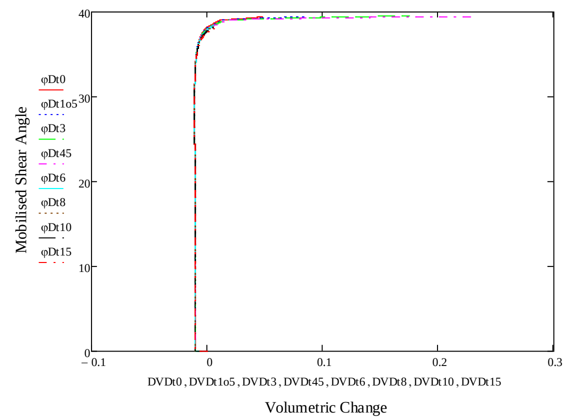
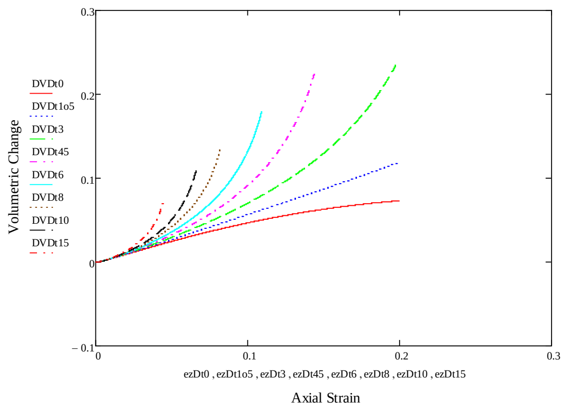
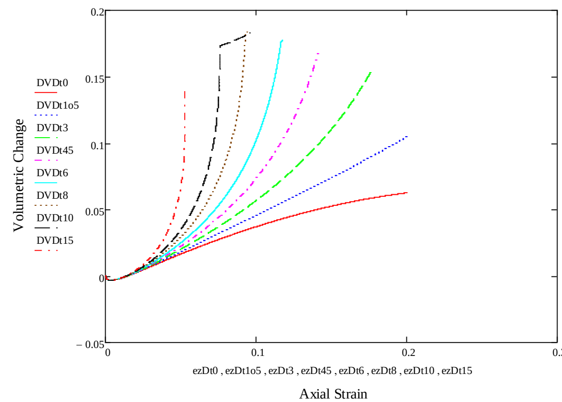
50 KPa	1000 KPa	4000 KPa

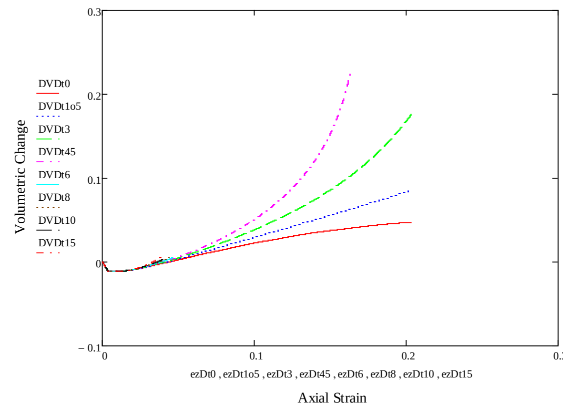












PDMY Conclusion

- Because of contraction of confining phase, phase transformation angle has more effect on samples that tends to dilate in the next phase (medium and dense).
- Contraction constant has more effect on the samples has more tendency to contract. This effect is more on volumetric change.
- Dilatancy1 Constant (d_1) cause the medium and dense sand to be more dilatant. There is no effect on loose sand. The influence of this constant on volumetric change is recognizable from initial steps of applied deviatoric strains and the behavior is different at low strains.
- Dilatancy2 Constant (d_2) cause the medium and dense sand to be more dilatant. There is no effect on loose sand. The volumetric change behavior starts the same but the rate of volumetric change vs axial strain graph differs.
- There were no or negligible effects on deviatoric stress (q) for variation of these four parameters.
- The effect of these four parameters is not at the ultimate magnitude of mobilized shear angle but on the corresponding volumetric change that the ultimate mobilized shear angle occurs.

Confining Pressure
PDMY and Manzari-Dafalias

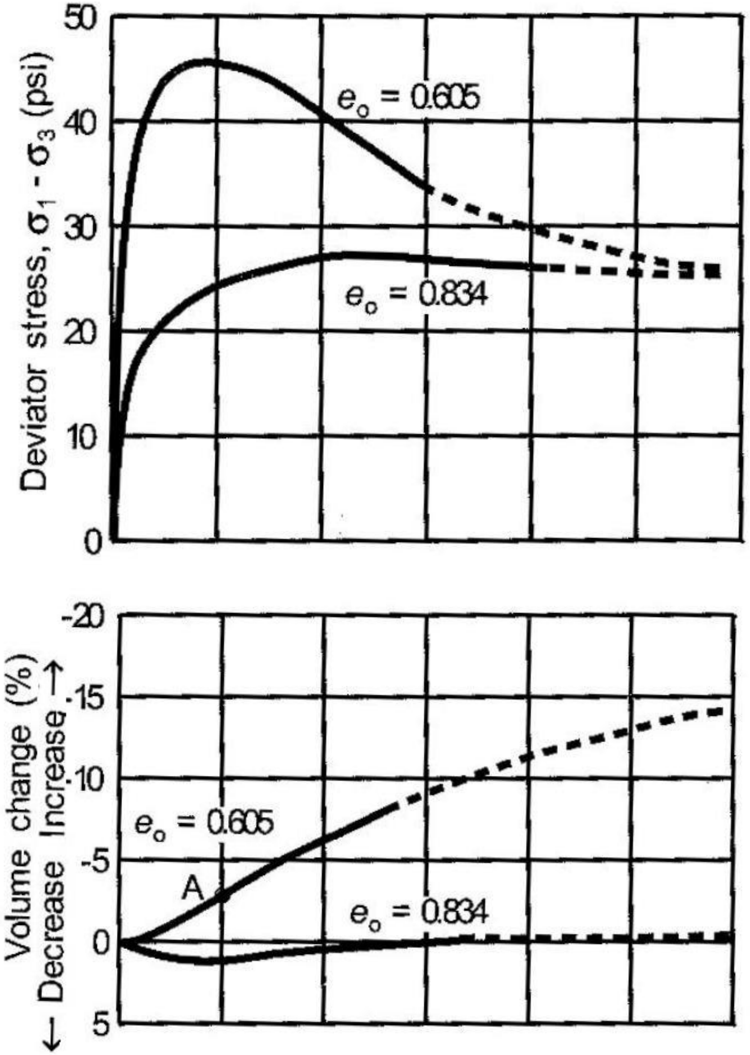
	Loose	Medium	Dense
Deviatoric Displacement (m)	0.2~0.4	0.2~0.4	0.2~0.4
Density (tonne/m^3)	1.7	1.95	2.1
Shear Modulus G_0 (MPa)	55	87.5	130
Shear Modulus K_0 (MPa)	150	250	390
Poisson Ratio ν	0.34	0.343	0.35
Young Modulus E_0 (MPa)	147.4	235	351
Friction Angle	29	35	40
Phase Transformation Angle	29	27	27
Contraction Constant	0.21	0.06	0.03
Dilatancy Constant 1	0	0.5	0.8
Dilatancy Constant 2	0	2.5	5
Liquefaction Factor 1 (KPa)	10	7.5	0
Liquefaction Factor 2	0	0.0065	0
Liquefaction Factor 3	0	1.0	0
Initial Void Ratio (e)	0.85	0.625	0.45

Confining Pressure
PDMY and Manzari-Dafalias

Constant	Variable	Tayoura Sand Manzari & Dafalias (2004)	Nevada Sand Shahir et al. (2012)	Babolsar Sand Zahmatkesh & Janalizadeh (2016)
Elasticity	G_0	125.0	150.0	100.0
	ν	0.05	0.05	0.05
Critical state	M	1.25	1.14	1.45
	C	0.712	0.78	0.682
	λ_c	0.019	0.027	0.018
	e_0	0.934	0.83	0.781
	ξ	0.7	0.45	0.7
Plastic Modulus	h_0	7.05	9.7	50.99
	c_h	0.968	1.02	1.248
	n^b	1.1	2.56	1.51
Dilatancy	A_0	0.704	0.81	0.48
	n^d	3.5	1.05	7.51
Dilatancy-fabric	z_{max}	4	5	35
	c_z	600	800	700
Yield Surface	m	0.01	0.02	0.01

Confining Pressure (KPa)	Confining Pressure (KPa)
50	1000
200	2500
400	4000
700	8000

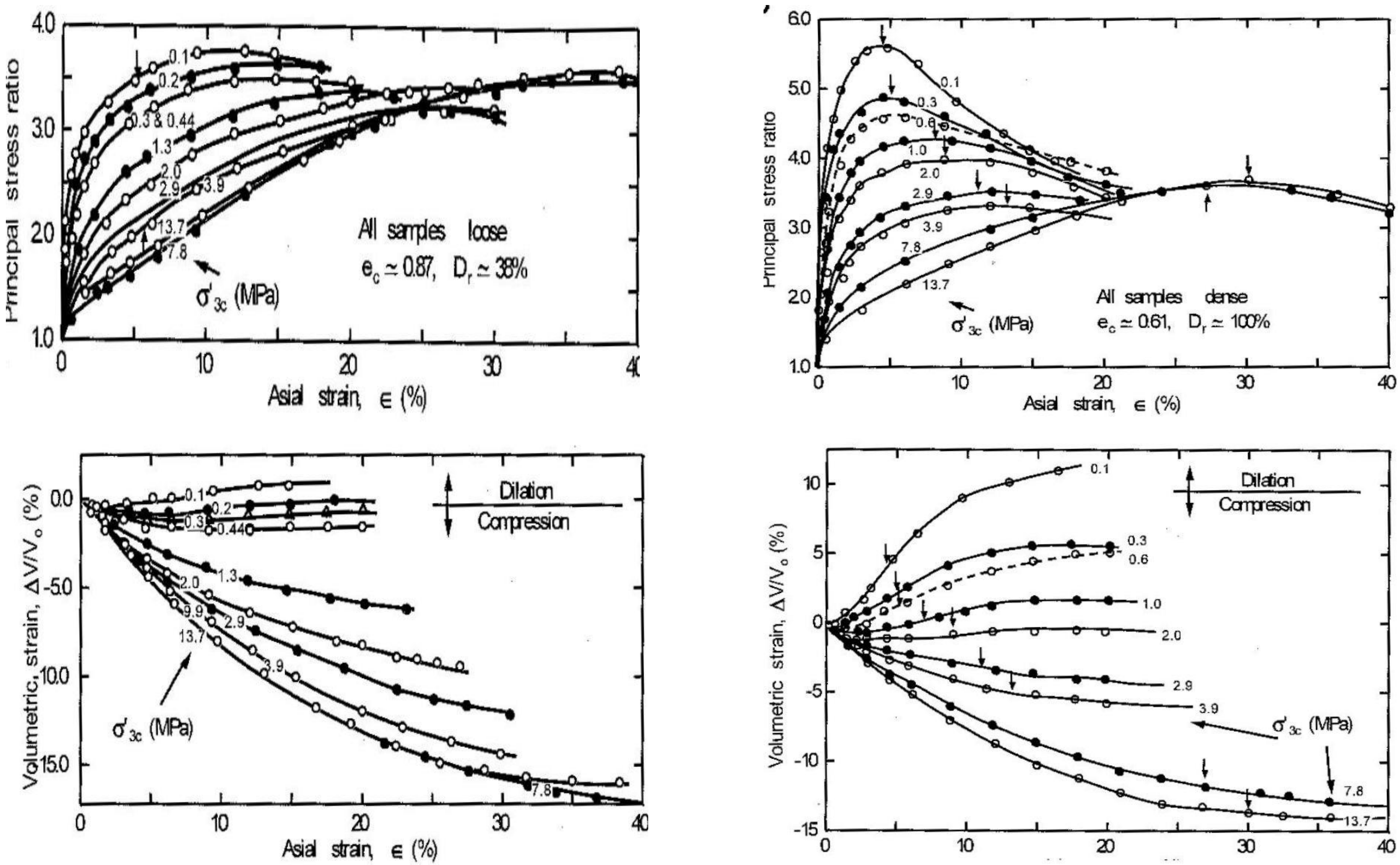
Confining Pressure
PDMY and Manzari-Dafalias



Axial Strain

Taylor (1948)

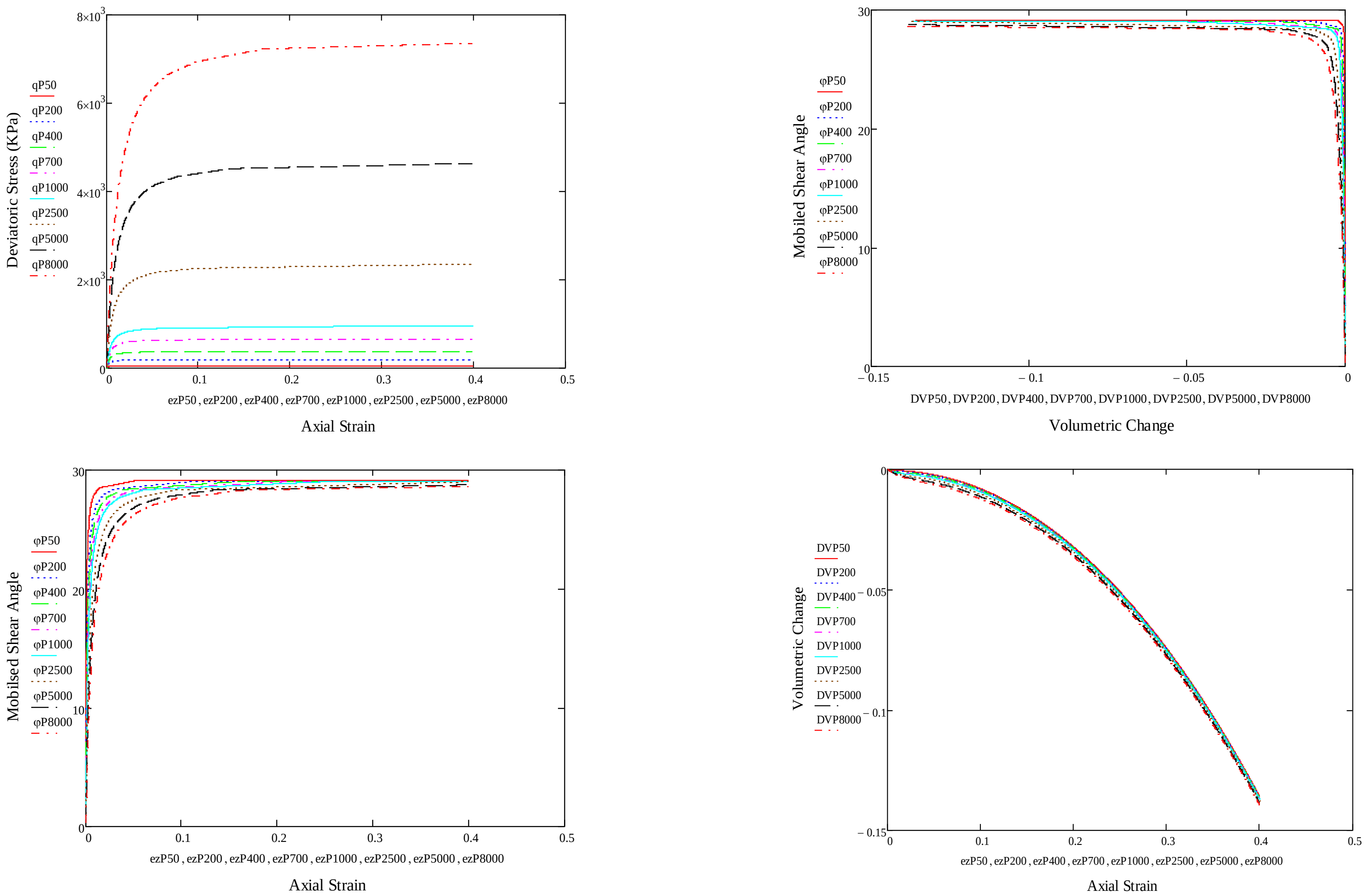
Confining Pressure
PDMY and Manzari-Dafalias



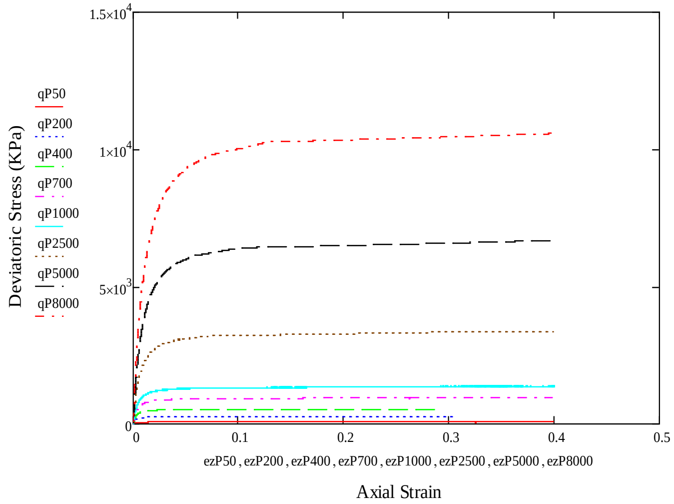
Loose Sand **Dense Sand**

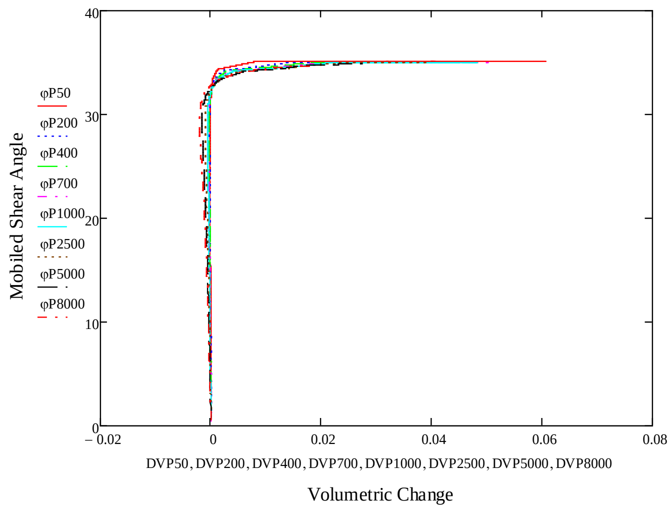
Lee (1965)

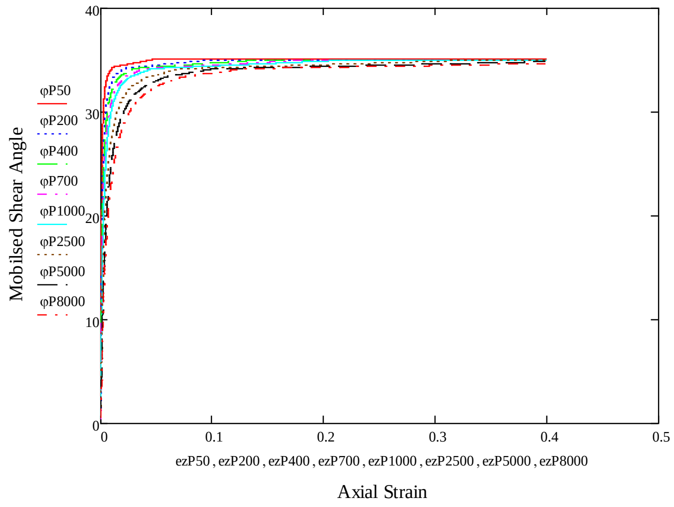
Confining Pressure
Loose PDMY

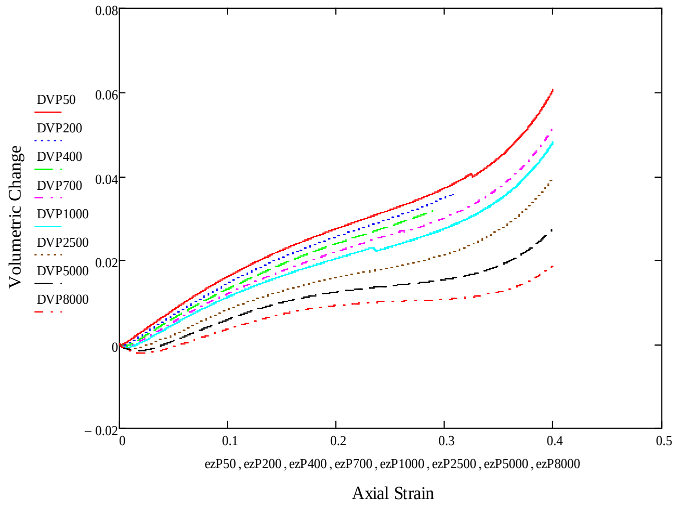


Confining Pressure Medium PDMY

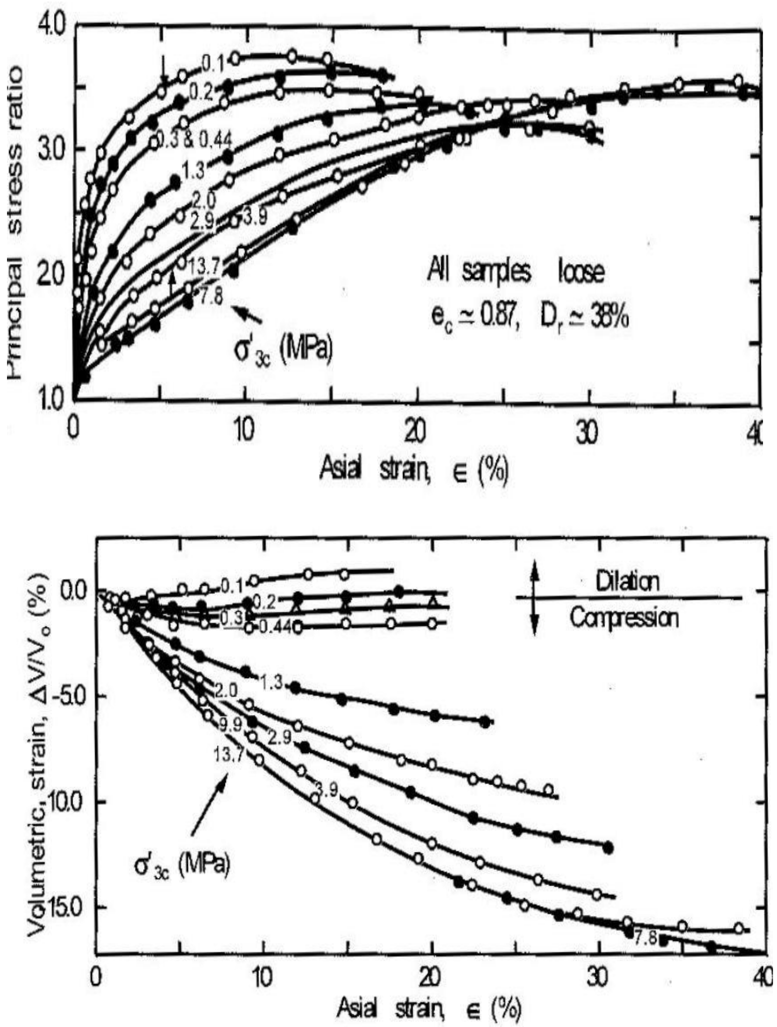




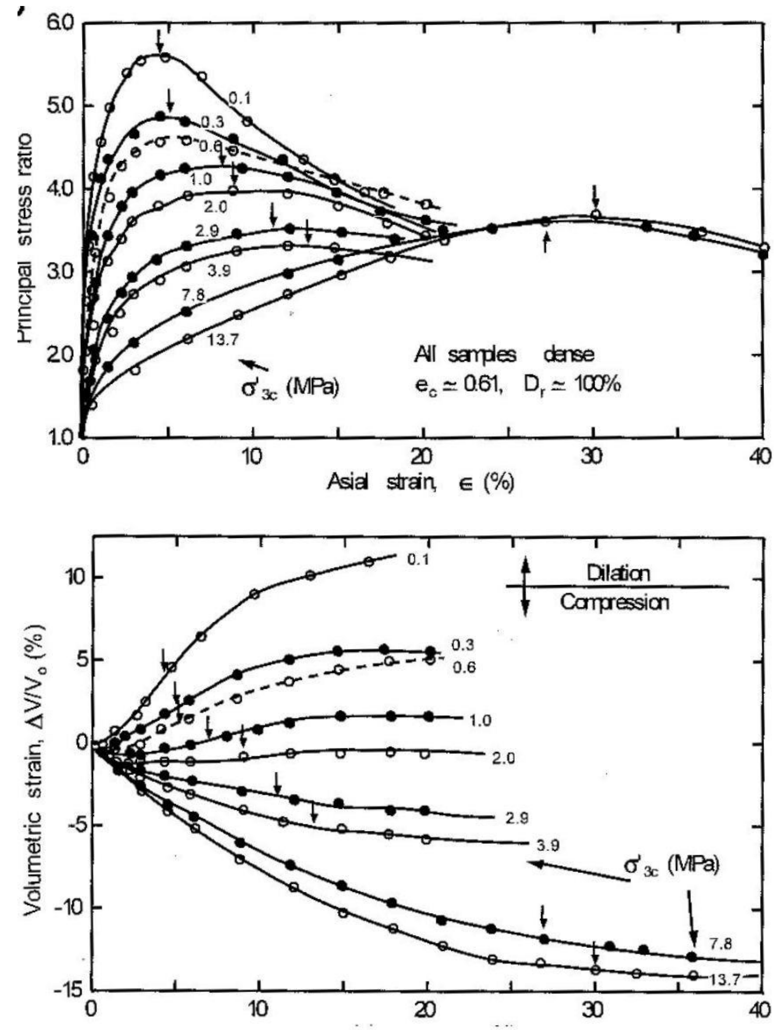




Confining Pressure
PDMY and Manzari-Dafalias



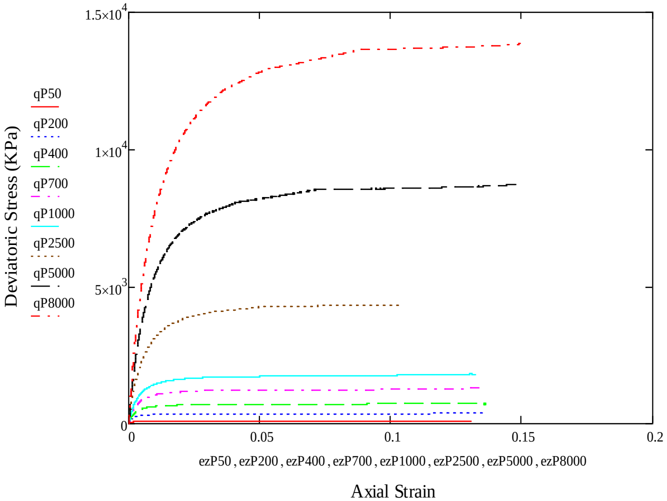
Loose Sand

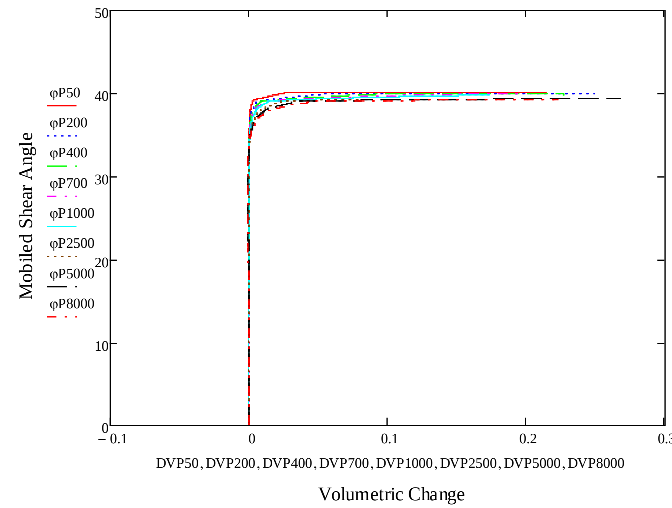


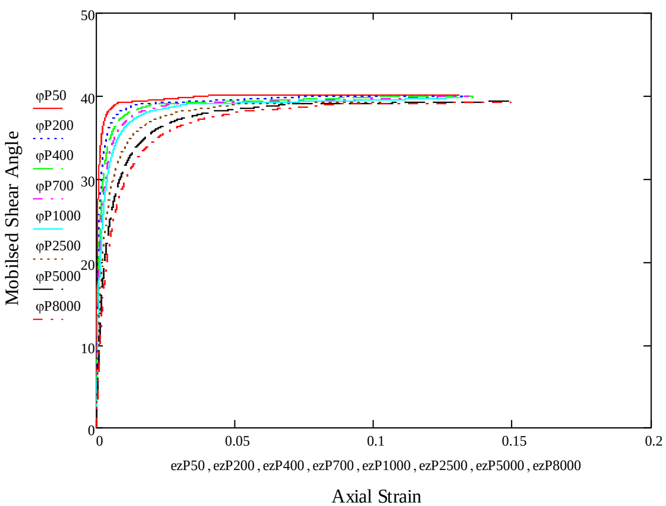
Dense Sand

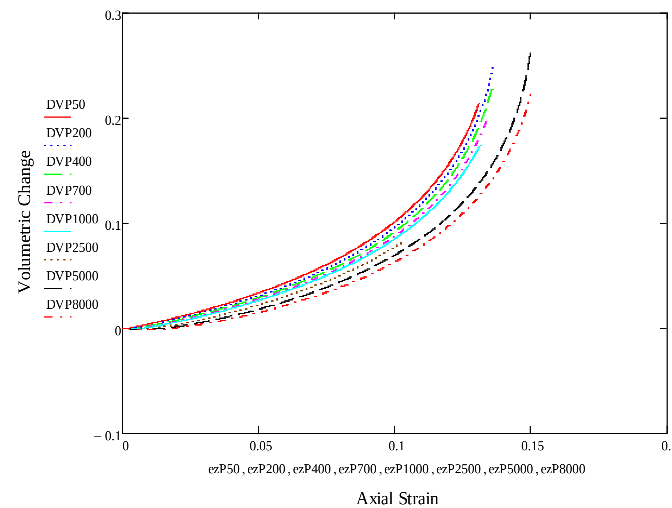
Lee (1965)

Confining Pressure
Dense PDMY







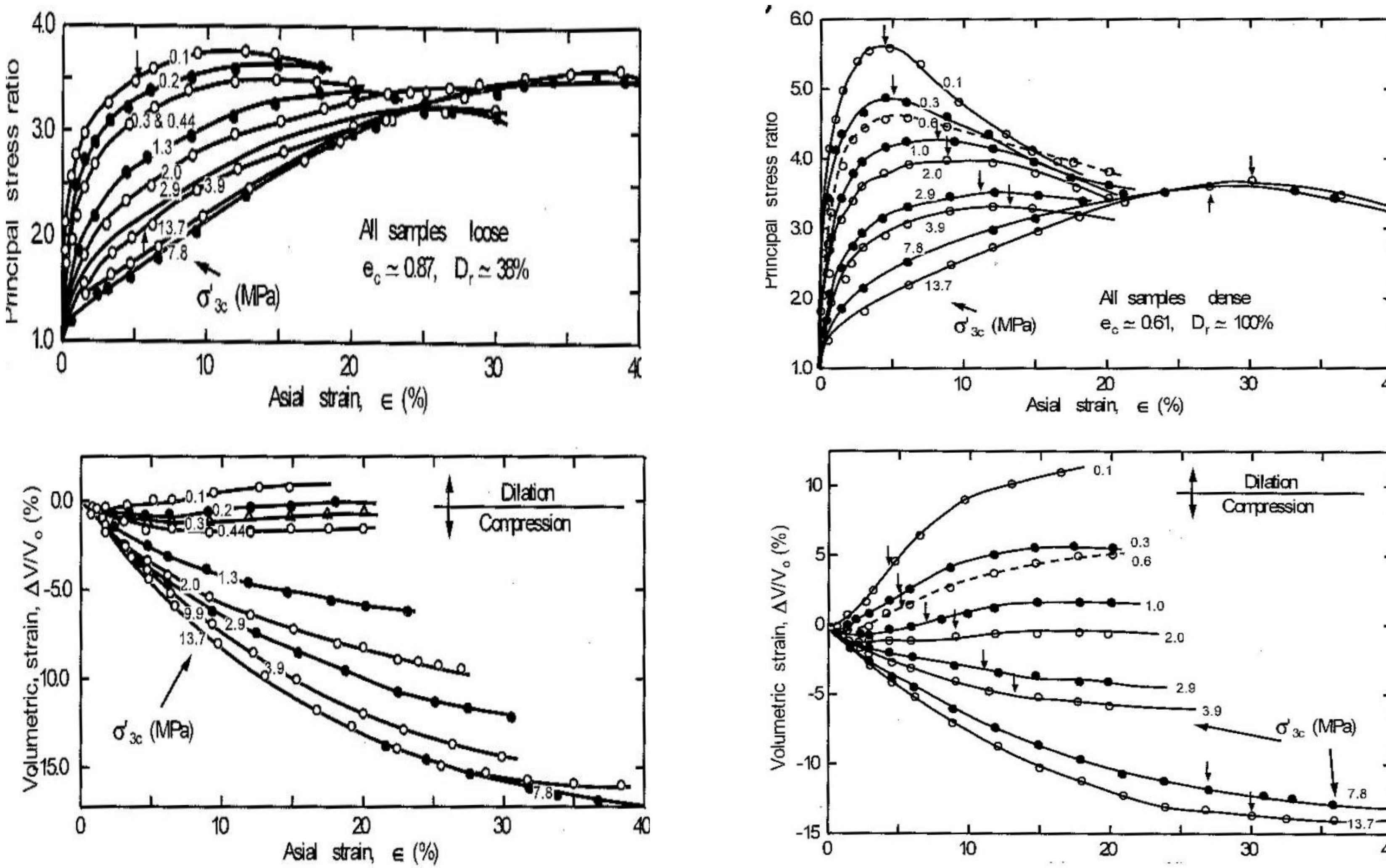


Confining Pressure
PDMY and Manzari-Dafalias

Constant	Variable	Tayoura Sand Manzari & Dafalias (2004)	Nevada Sand Shahir et al. (2012)	Babolsar Sand Zahmatkesh & Janalizadeh (2016)
Elasticity	G_0	125.0	150.0	100.0
	v	0.05	0.05	0.05
Critical state	M	1.25	1.14	1.45
	C	0.712	0.78	0.682
	λ_c	0.019	0.027	0.018
	e_0	0.934	0.83	0.781
	ξ	0.7	0.45	0.7
Plastic Modulus	h_0	7.05	9.7	50.99
	c_h	0.968	1.02	1.248
	n^b	1.1	2.56	1.51
Dilatancy	A_0	0.704	0.81	0.48
	n^d	3.5	1.05	7.51
Dilatancy-fabric	z_{max}	4	5	35
	c_z	600	800	700
Yield Surface	m	0.01	0.02	0.01

Confining Pressure (KPa)	Confining Pressure (KPa)
50	1000
200	2500
400	4000
700	8000

Confining Pressure
PDMY and Manzari-Dafalias

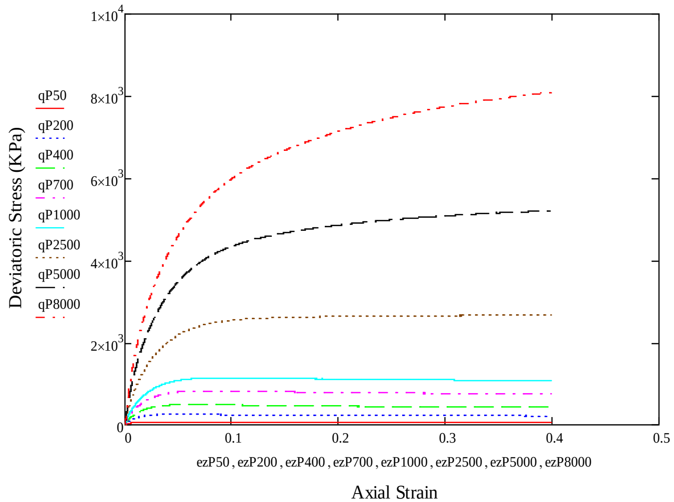


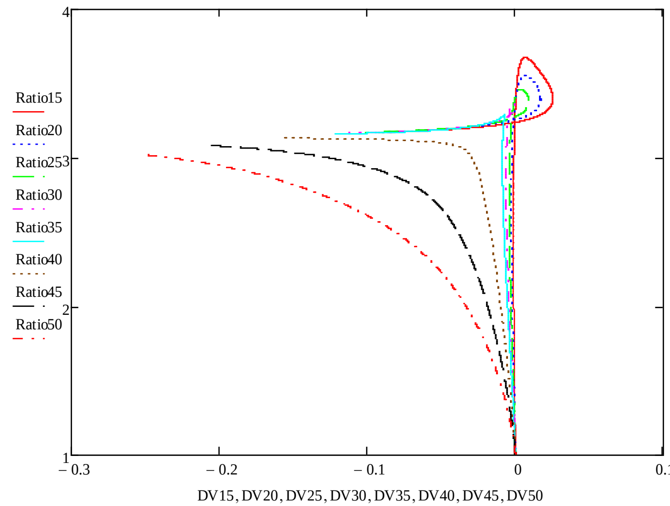
Loose Sand

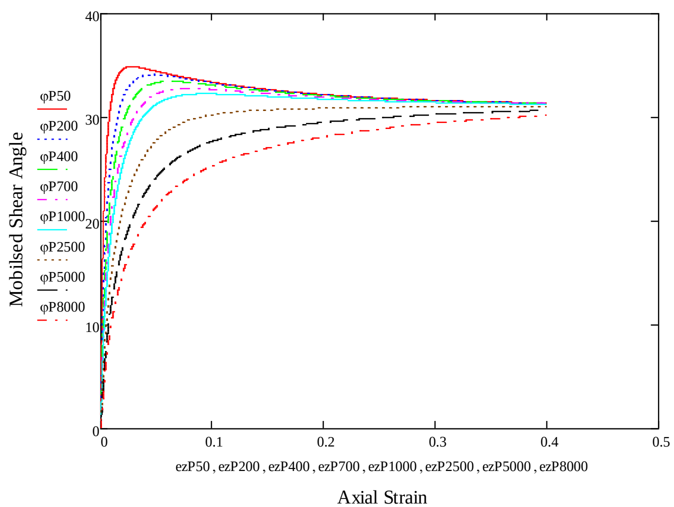
Dense Sand

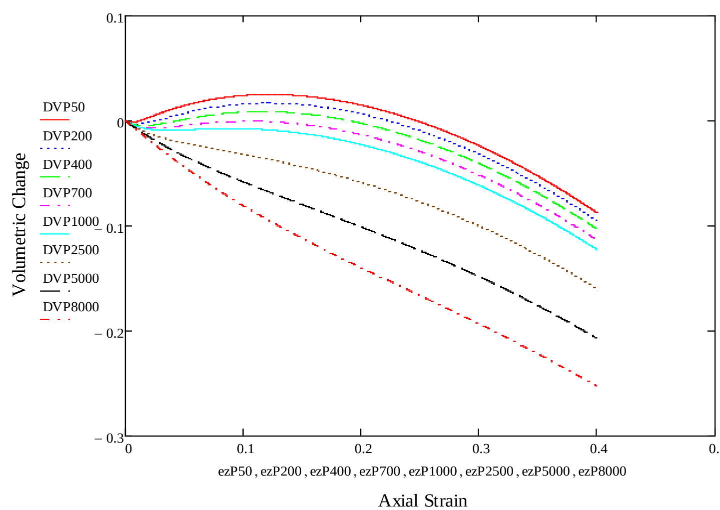
Lee (1965)

Confining Pressure
Tayoura MD Sand e_o=0.934

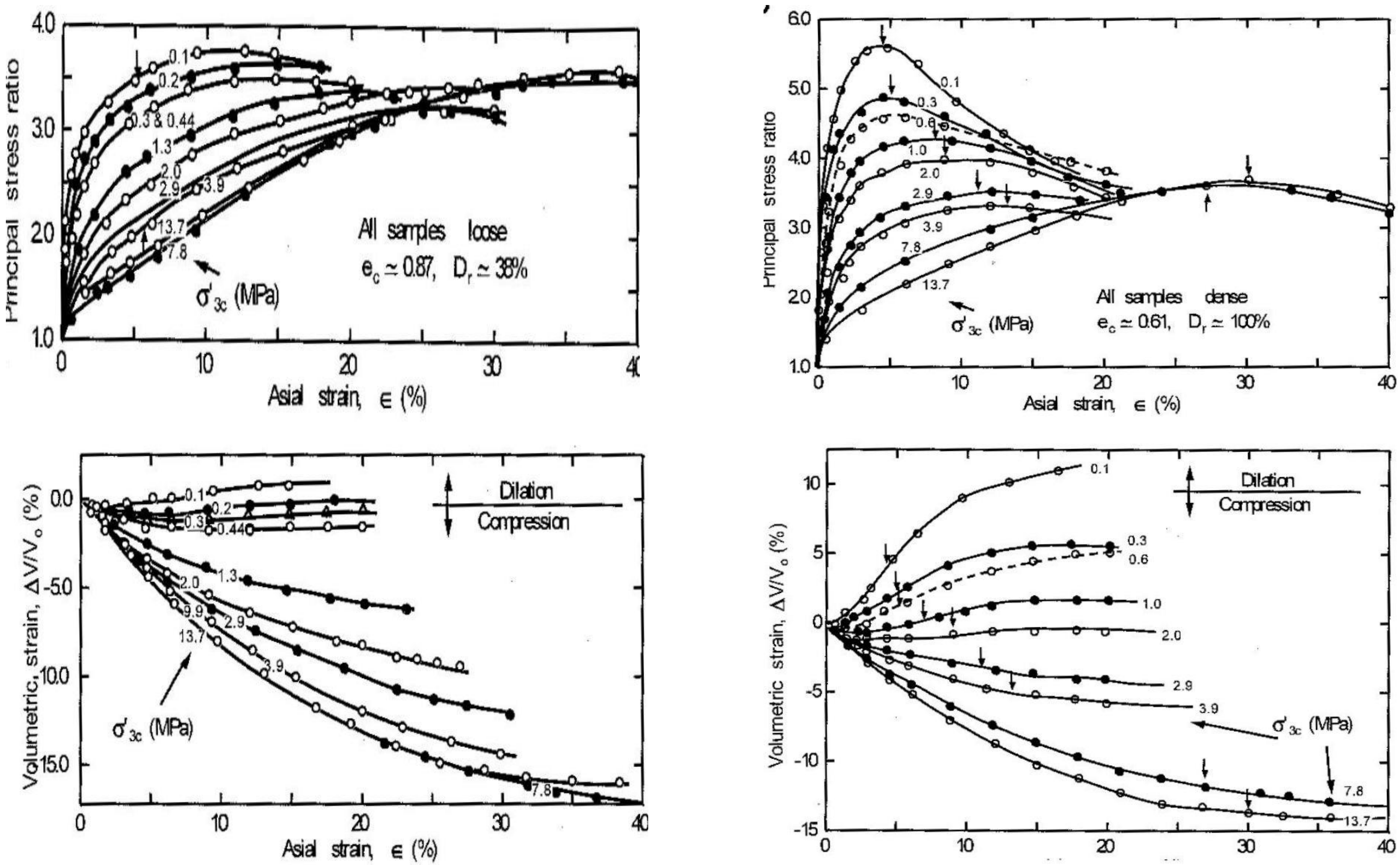








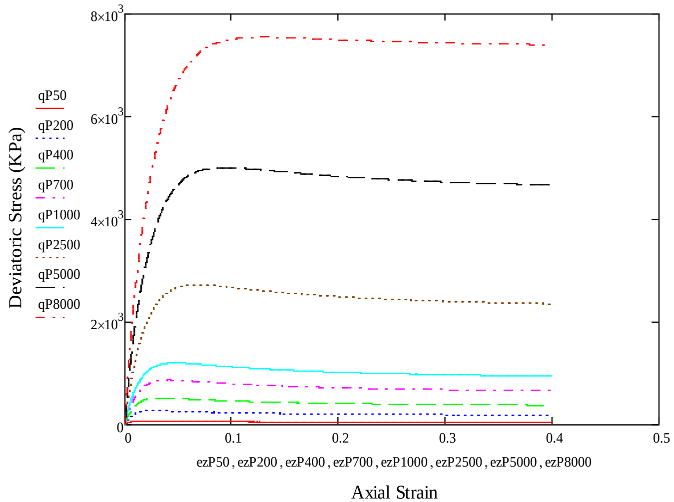
Confining Pressure
PDMY and Manzari-Dafalias

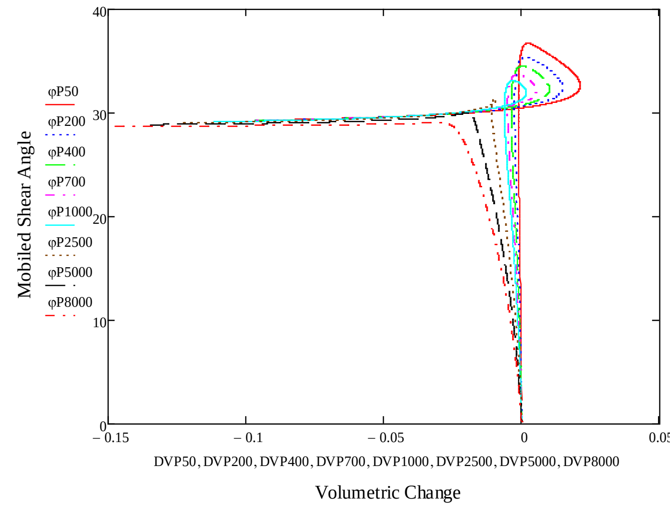


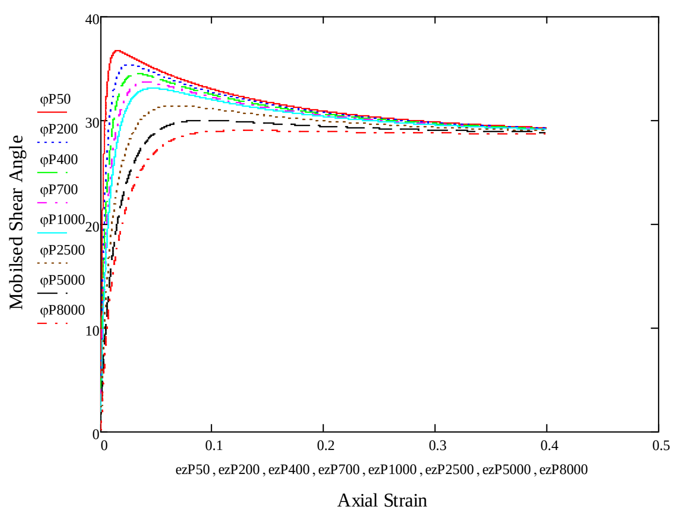
Loose Sand **Dense Sand**

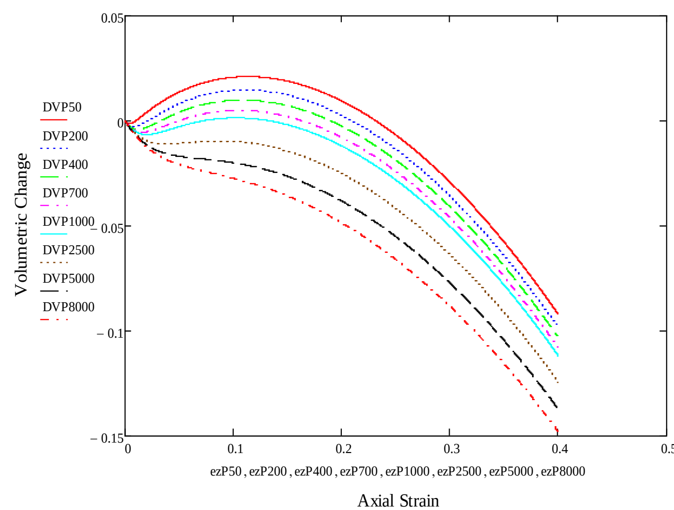
Lee (1965)

Confining Pressure
Nevada MD Sand e_o=0.83

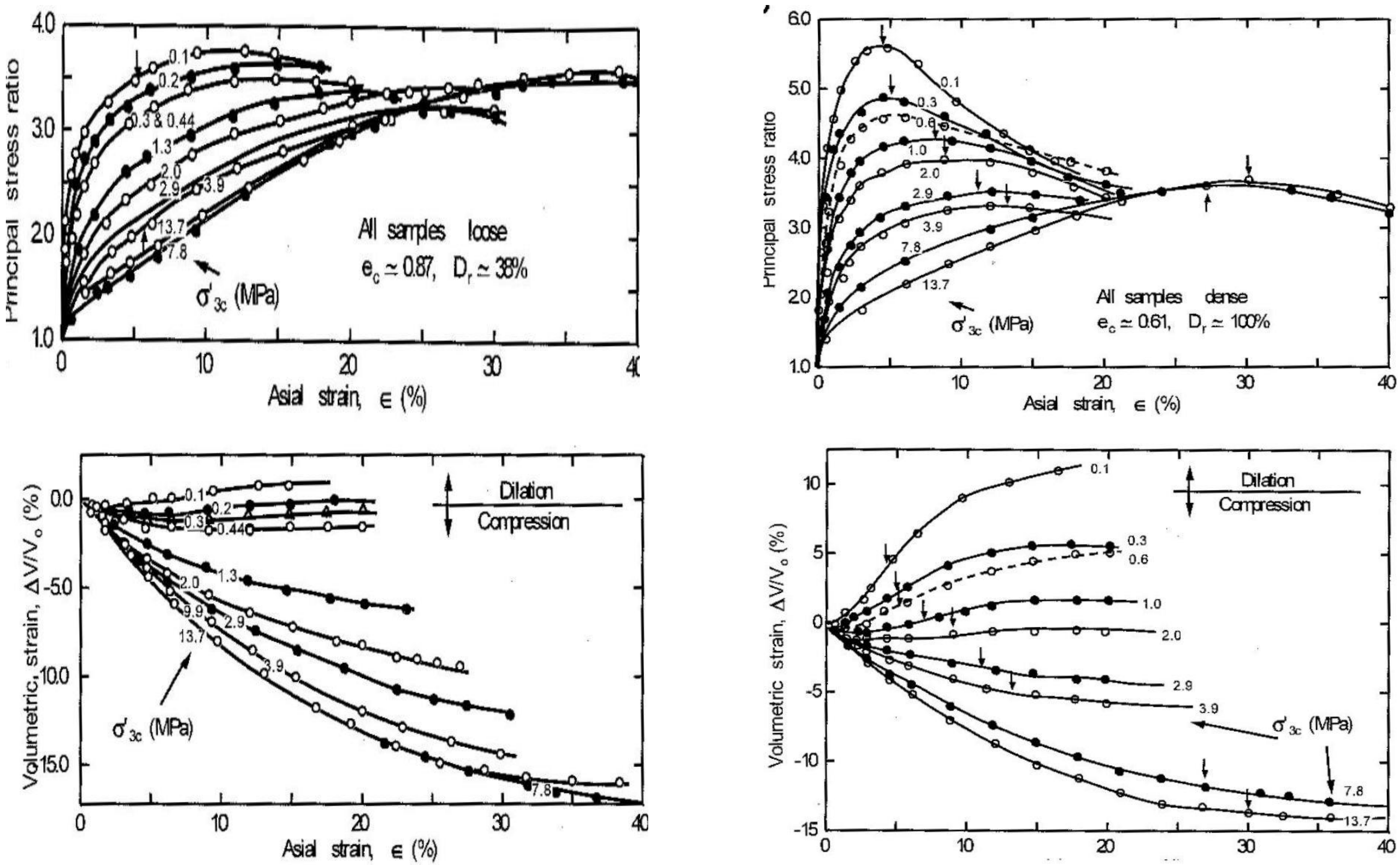








Confining Pressure
PDMY and Manzari-Dafalias

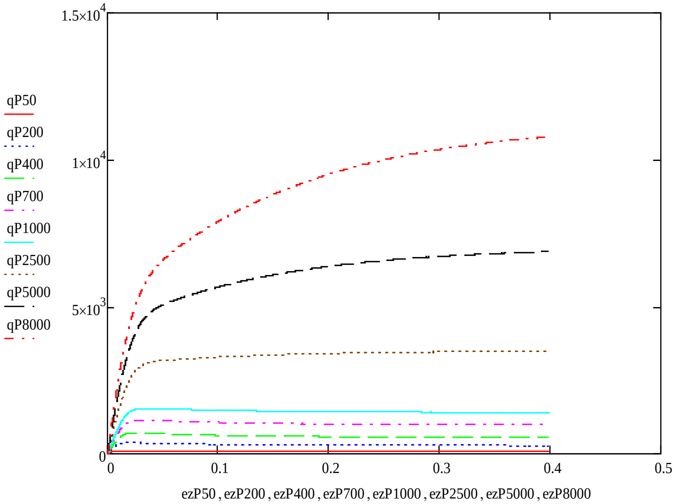


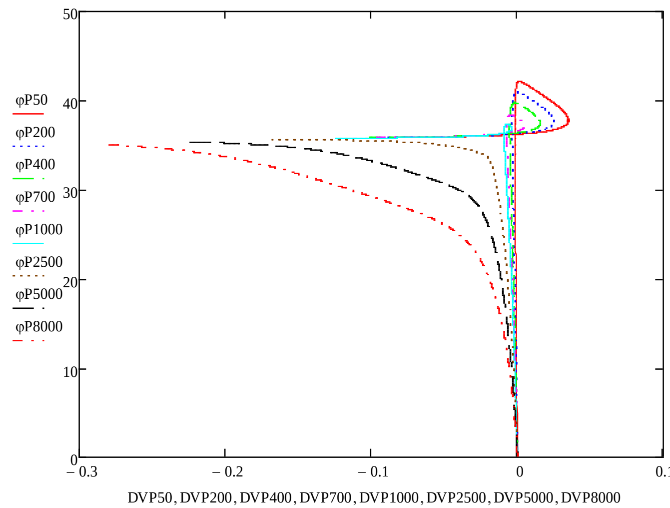
Loose Sand

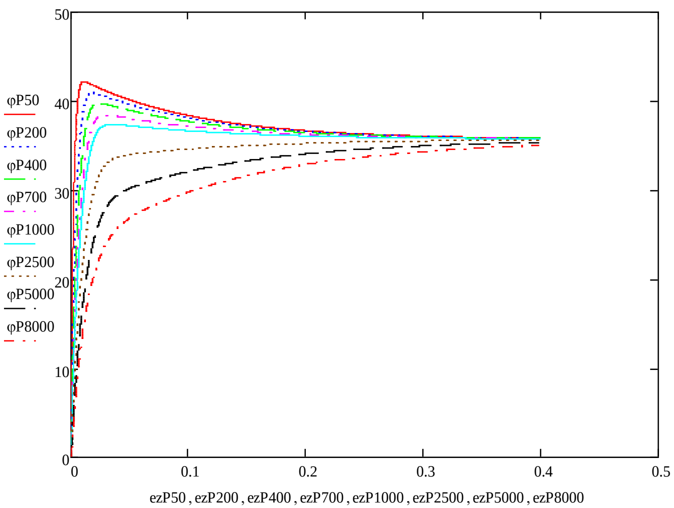
Dense Sand

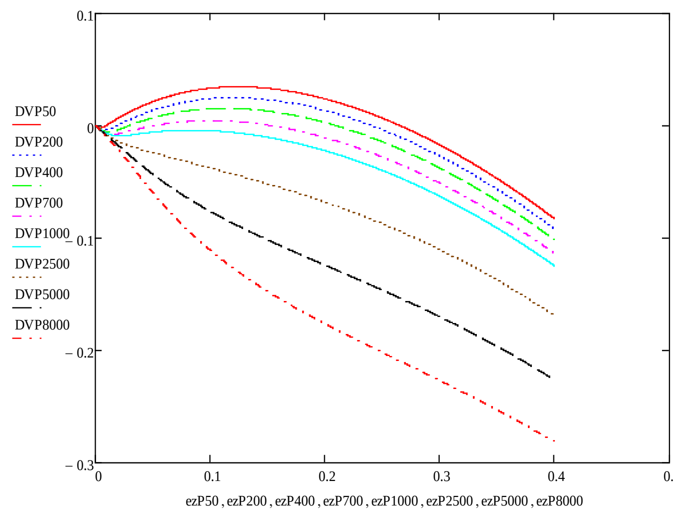
Lee (1965)

Confining Pressure
Babolsar MD Sand e_o=0.781









PDMY & Manzari-Dafalias Comparison

- PDMY: According to Lee (1965) at large axial strains for loose and dense materials the volumetric change rate decrease while this increases in PDMY material.

- PDMY: No large peak shear strength could be seen for dense materials at low confining pressures.

- MD: Although all three available ManzariDafalias materials were able to show peak shear strength at smaller confining pressures, according to Lee (1965) this peak happens in case of dense material and all three Manzari Dafalias materials have large initial void ratios which indicate the sand materials are loose.

- MD: The volumetric strain graphs seem to have good agreement with Lee (1965) graphs.

- MD: At the peak shear strengths, the sample change behavior from dilatancy to contraction.