Flow and Storage of Powders

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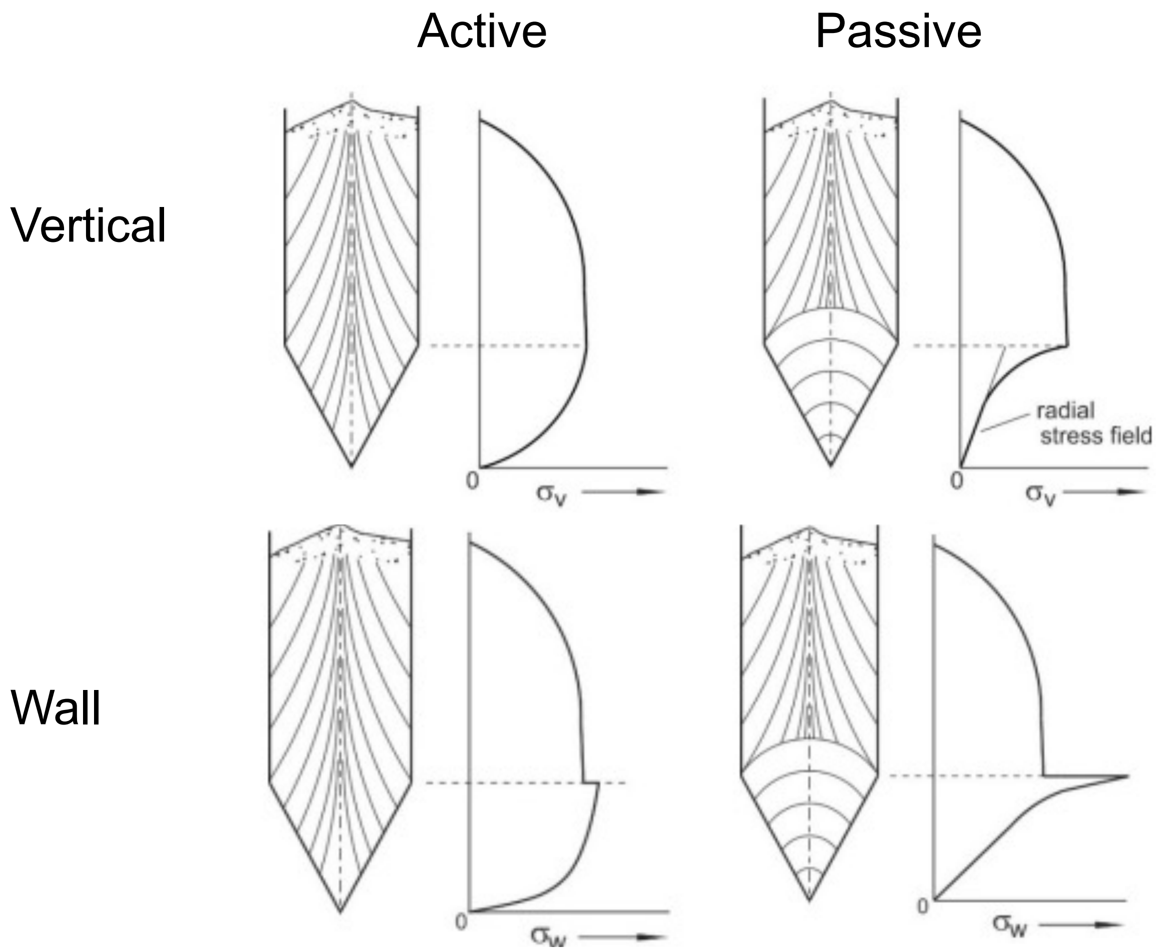
Solids stresses



Solids stresses

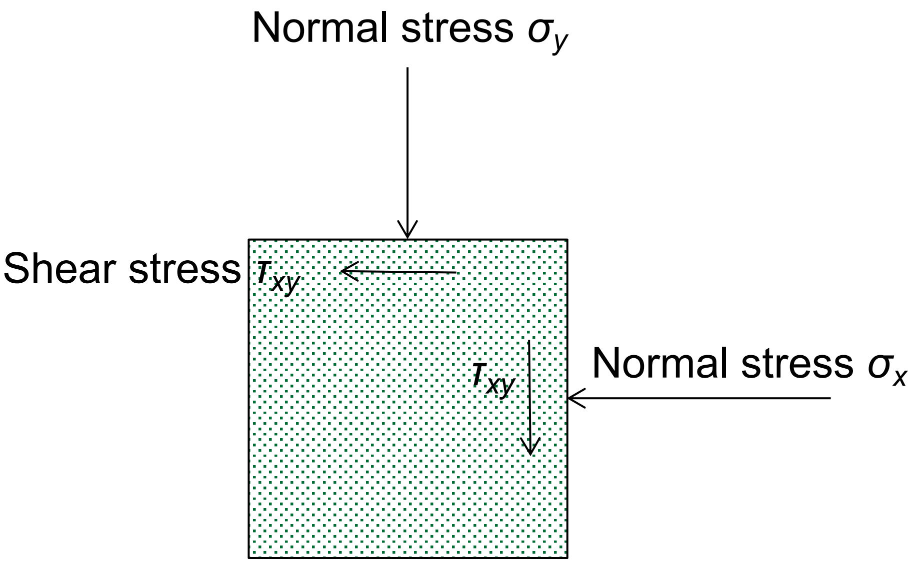
- Normal stresses

  act perpendicular to plane
- Shear stresses

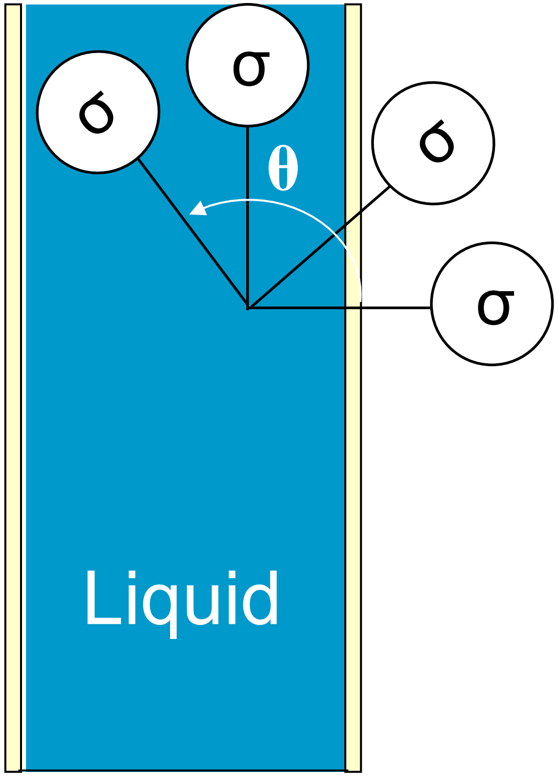
  act parallel to plane

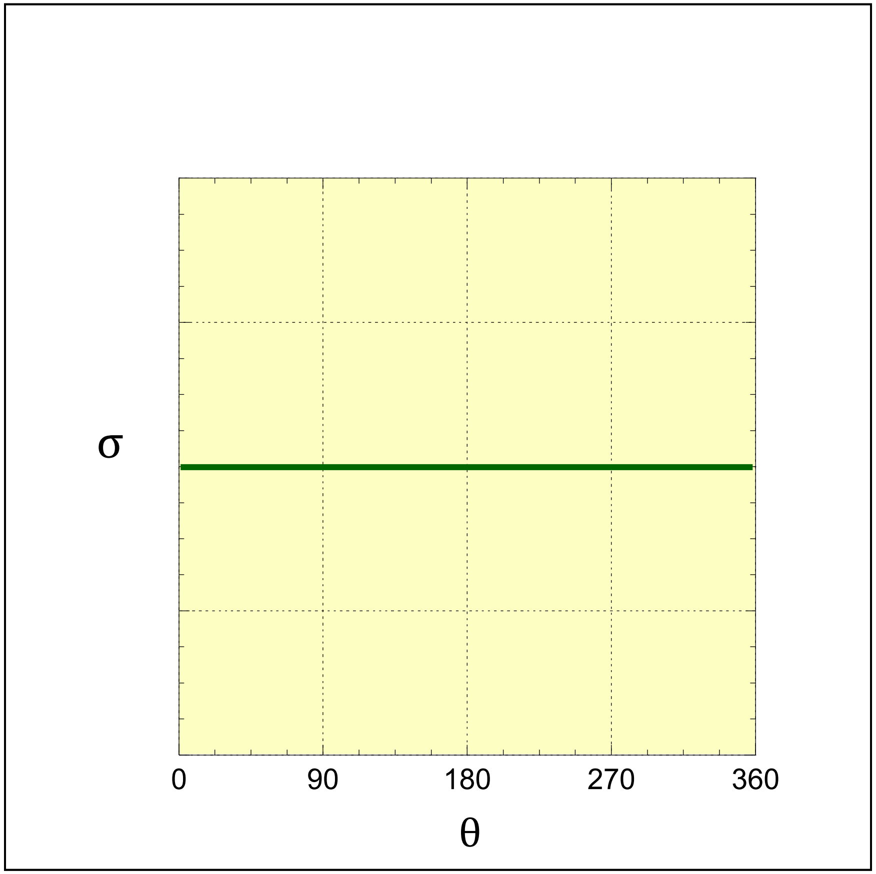
  (plane can be hopper wall,

  or slice of bulk material)

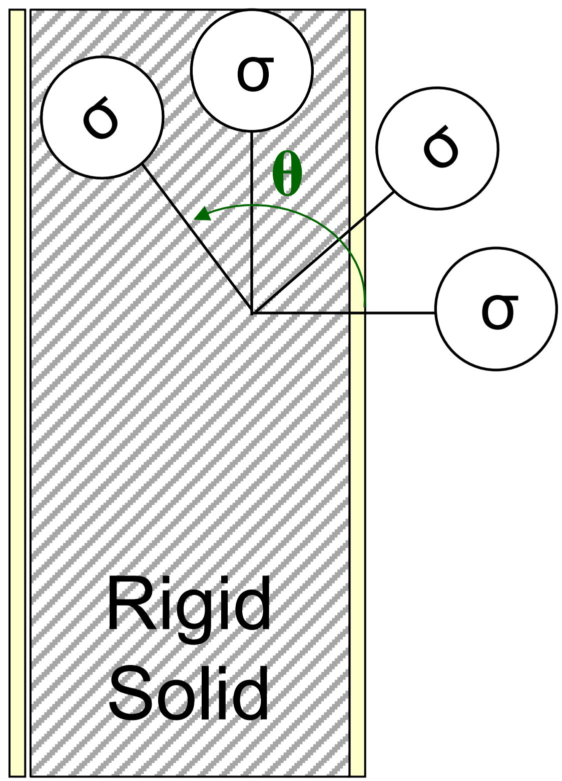


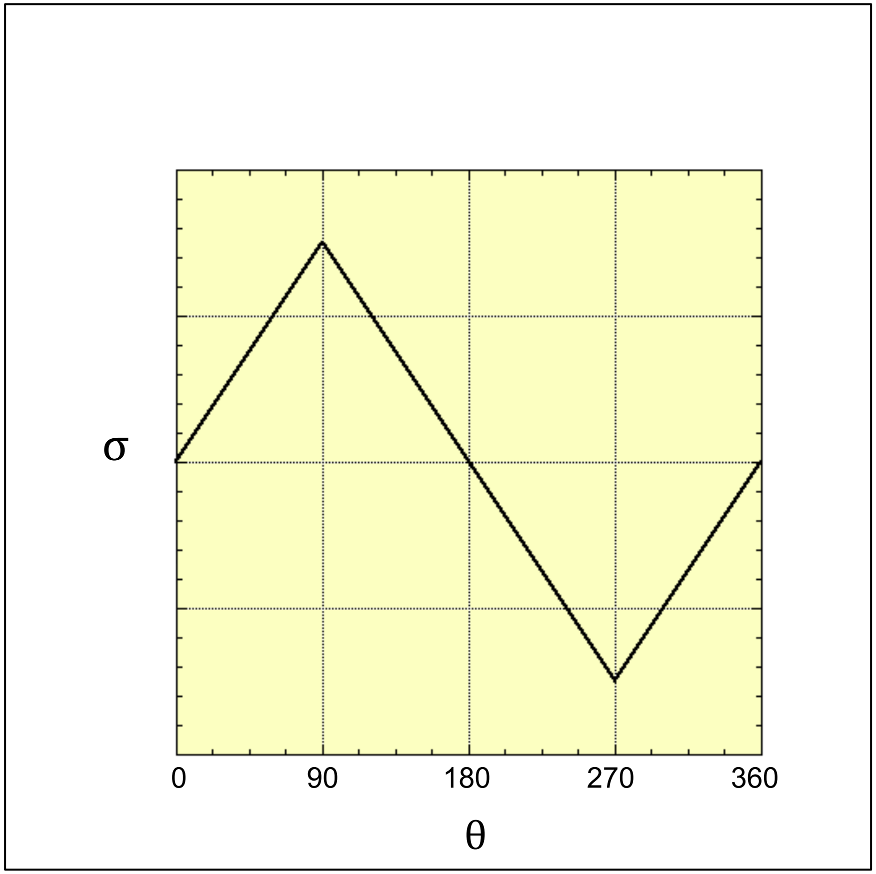
Stresses





Stresses





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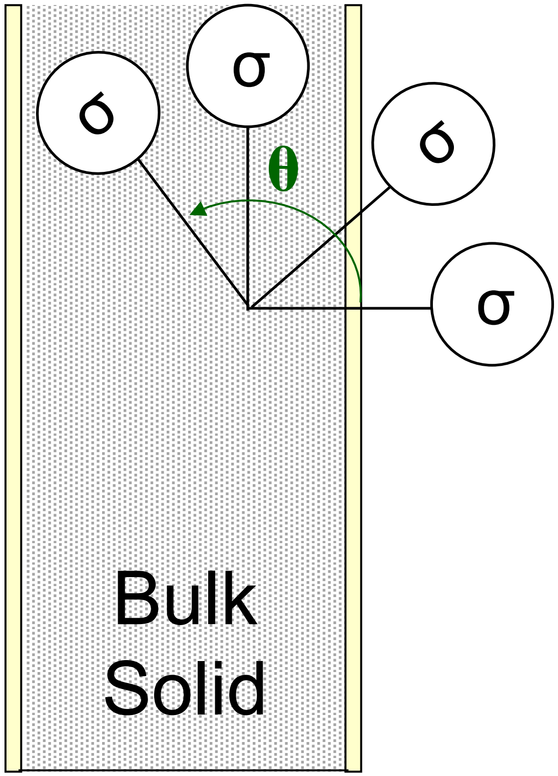
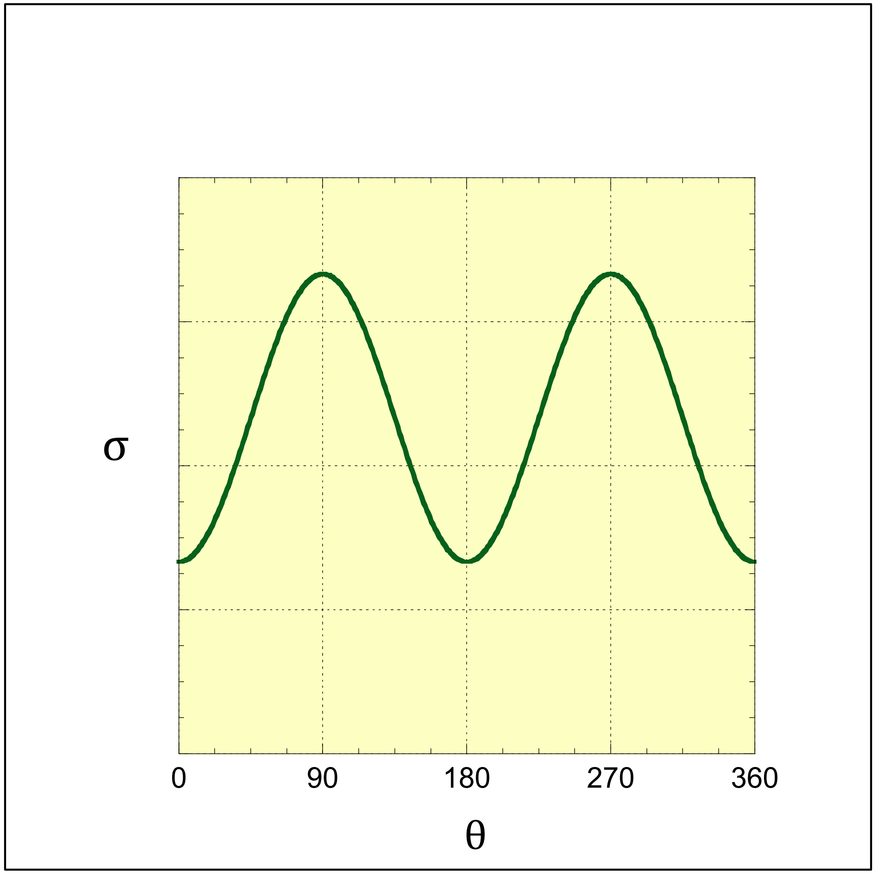




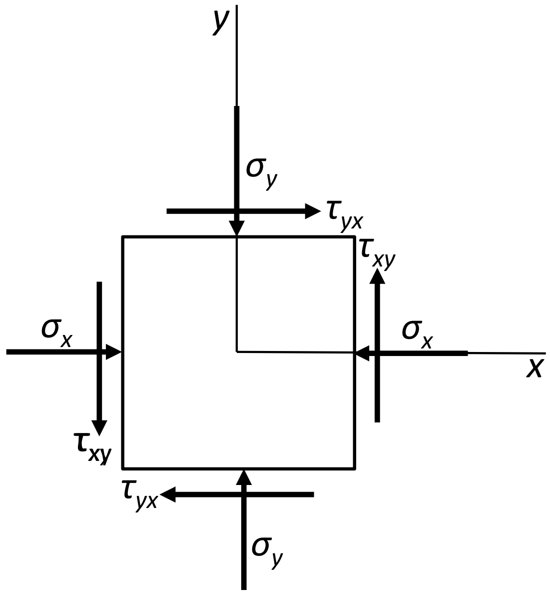
Warning!

- Lots of math ahead!
- The first step is simple! It’s usually just a force balance.
- The derived equations are easy to use.

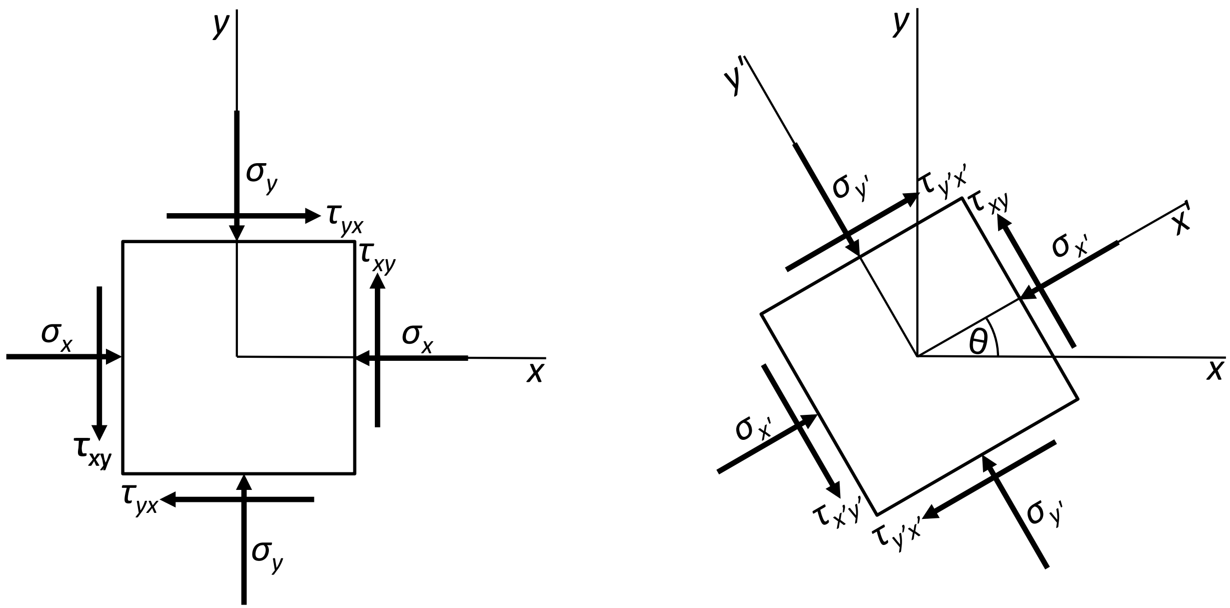
Warning!

- Lots of math ahead!
- The first step is simple! It's usually just a force balance.
- The derived equations are easy to use.
- Understand the first step.
- Know how to apply the final step.
- Be thankful that someone smarter than us came up with all the other steps!

Analysis of stress

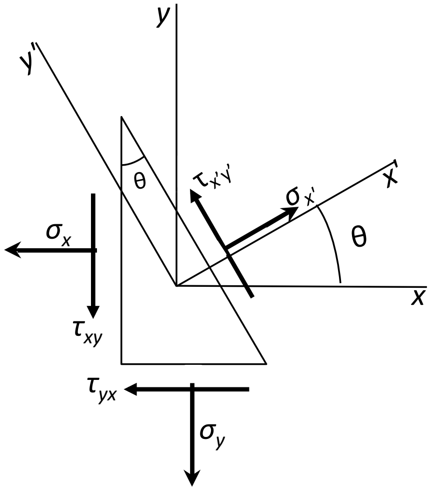


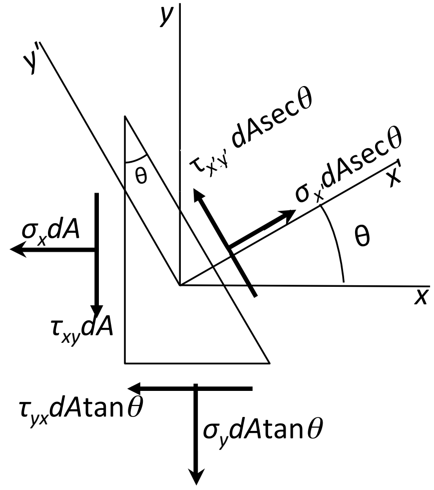
Analysis of stress



Analysis of stress

Equilibrium force balance in *x'* direction:





$$\sigma_{x'}\sec\theta = \sigma_x\cos\theta + \tau_{xy}\sin\theta + \sigma_y\tan\theta + \tau_{xy}\tan\theta\cos\theta$$

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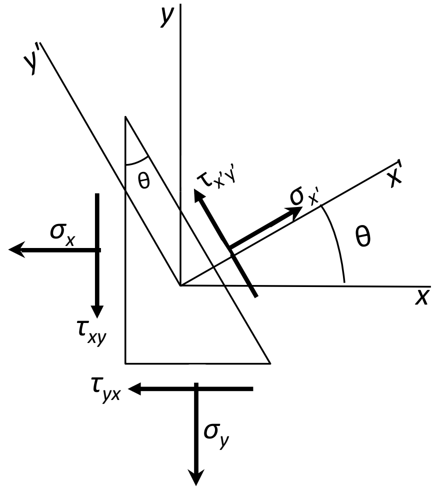
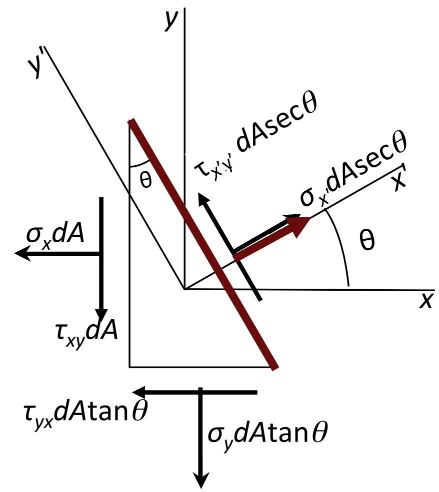
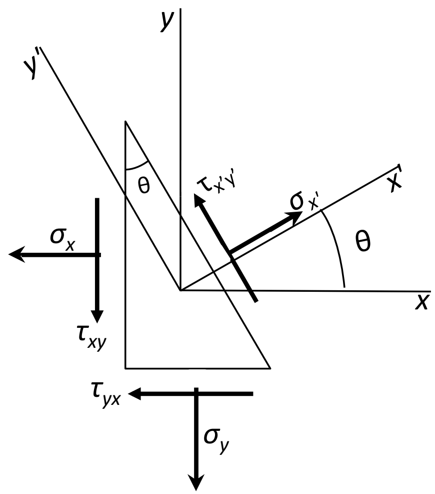


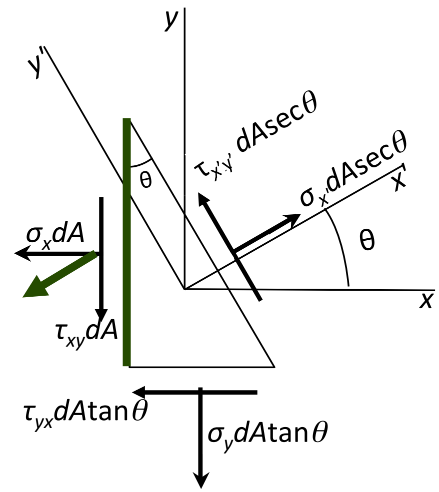


$$\boxed{\sigma_{x'}\sec\theta} = \sigma_x\cos\theta + \tau_{xy}\sin\theta + \sigma_y\tan\theta + \tau_{xy}\tan\theta\cos\theta$$

Analysis of stress

Equilibrium force balance in *x′* direction:





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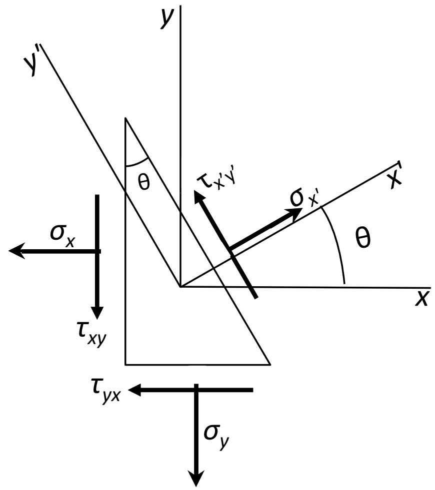
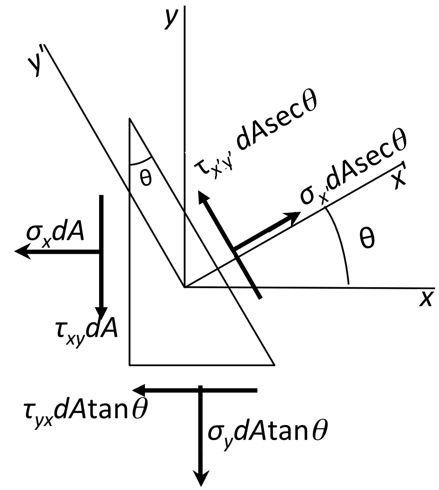
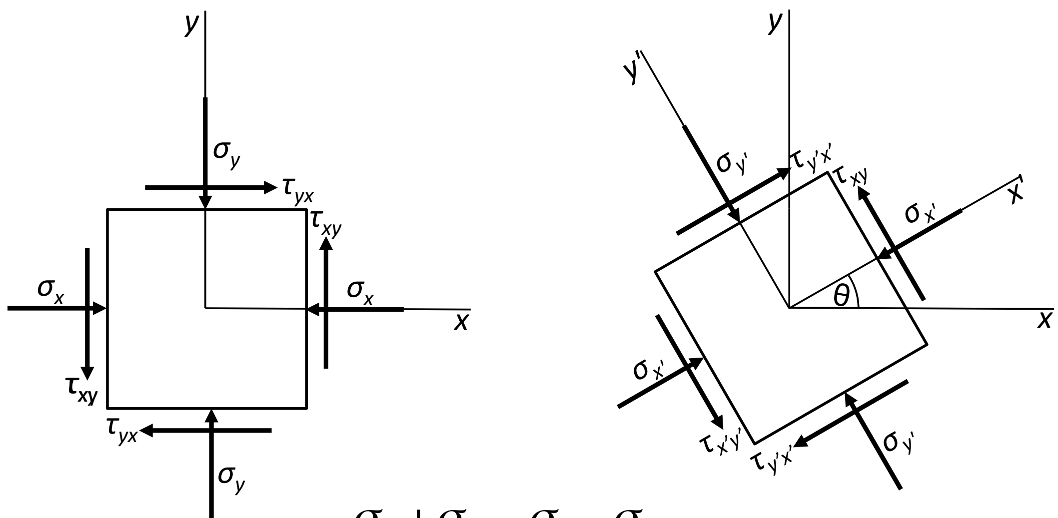




$$\sigma_{x'}\sec\theta = \sigma_x\cos\theta + \tau_{xy}\sin\theta + \sigma_y\tan\theta + \tau_{xy}\tan\theta\cos\theta$$

$$\sigma_{x'} = \frac{\sigma_x+\sigma_y}{2} + \frac{\sigma_x-\sigma_y}{2}\cos 2\theta + \tau_{xy}\sin 2\theta$$

Analysis of stress



$$\sigma_{x'} = \frac{\sigma_x + \sigma_y}{2} + \frac{\sigma_x - \sigma_y}{2}\cos 2\theta + \tau_{xy}\sin 2\theta$$

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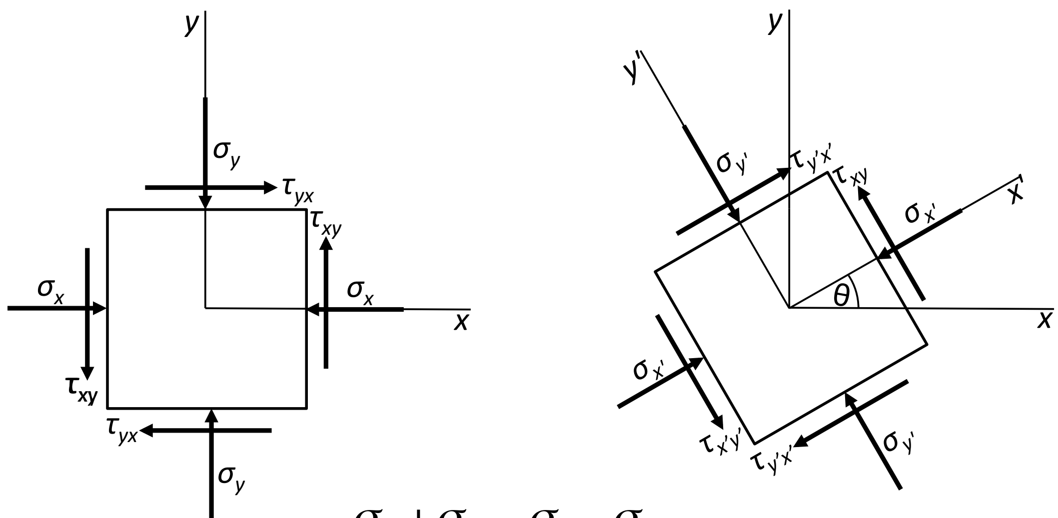
Analysis of stress



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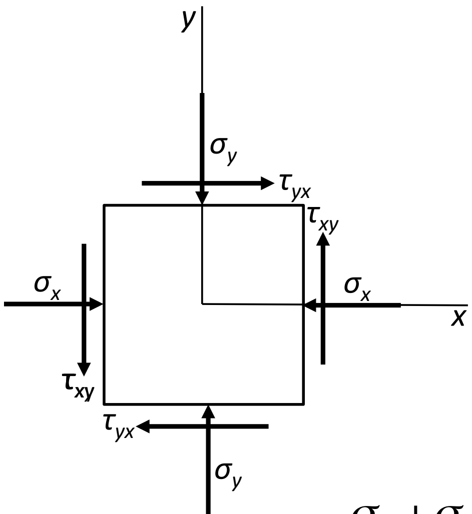
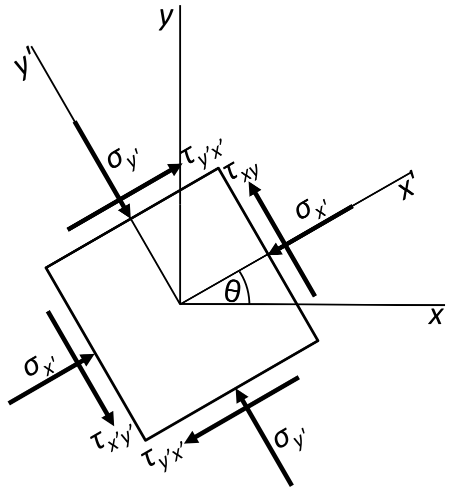
$$\left(\sigma_x - \sigma_{avg}\right)^2 + \tau_{xy}^2 = R^2$$

$$\sigma_{avg} = \frac{\sigma_x + \sigma_y}{2} \qquad R^2 = \left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}^2$$

Mohr's circle





Equation of a Circle!

$$\left(\sigma_x - \sigma_{avg}\right)^2 + \tau_{xy}^2 = R^2$$

$$\sigma_{avg} = \frac{\sigma_x + \sigma_y}{2} \qquad R^2 = \left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}^2$$

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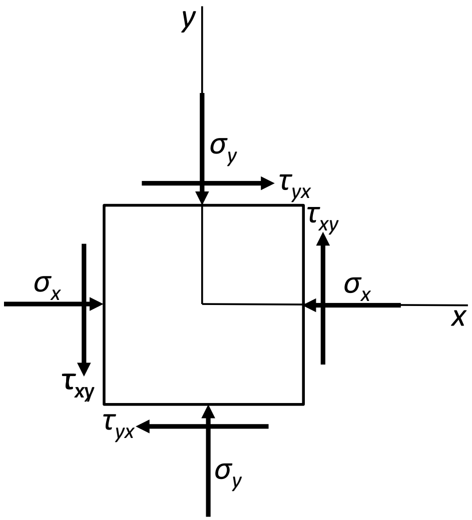

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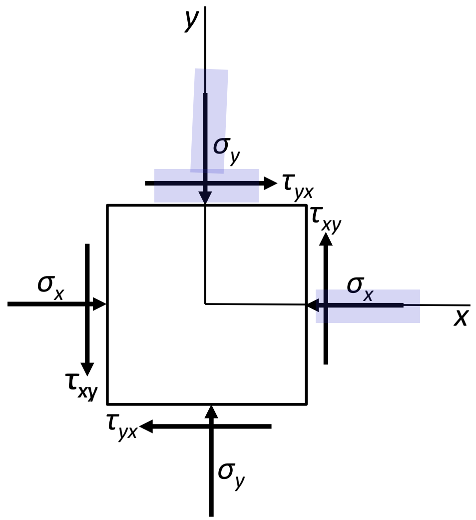

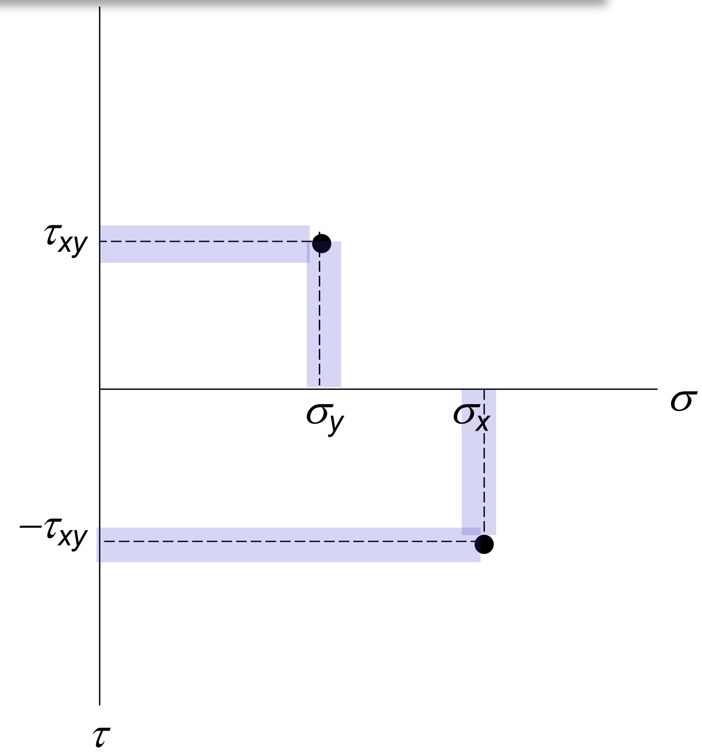

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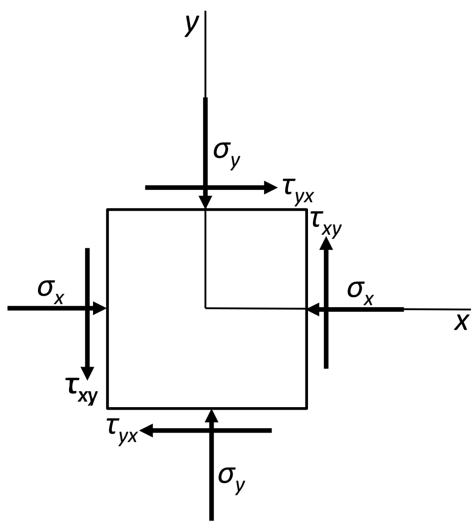

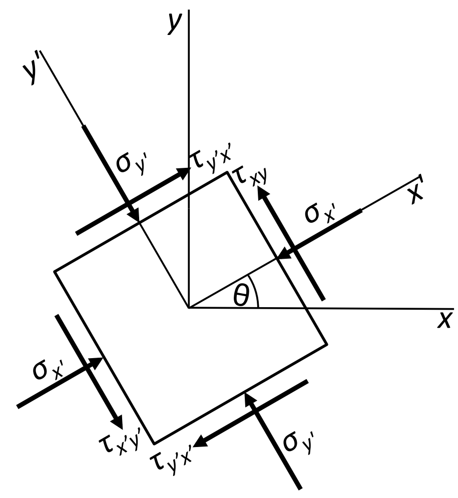

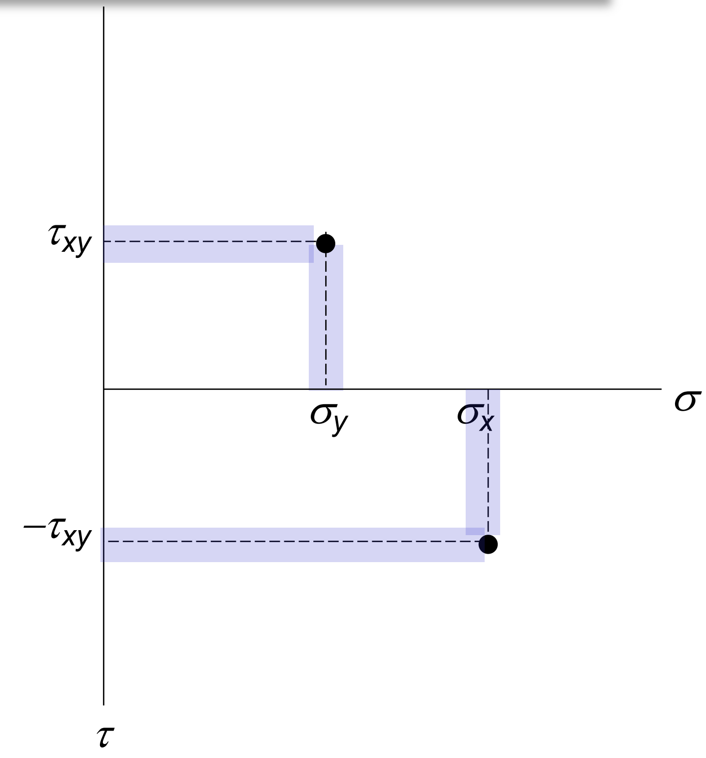

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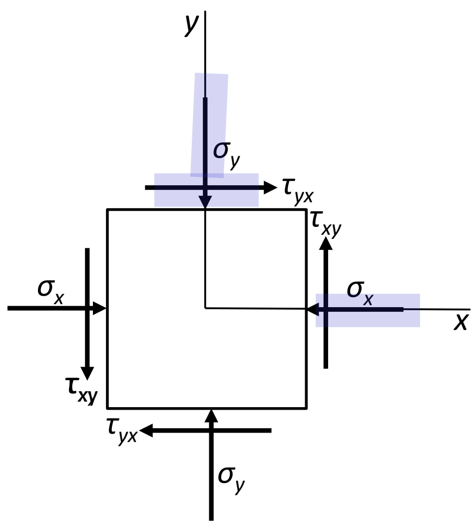

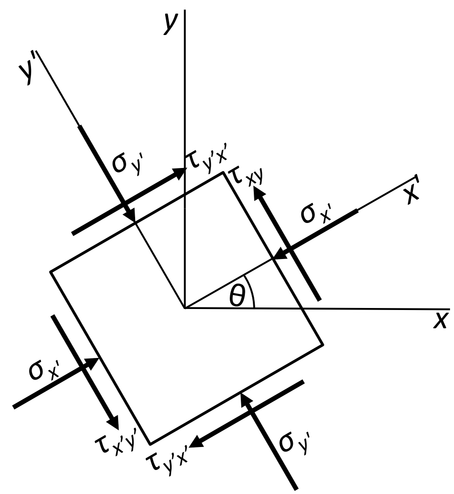

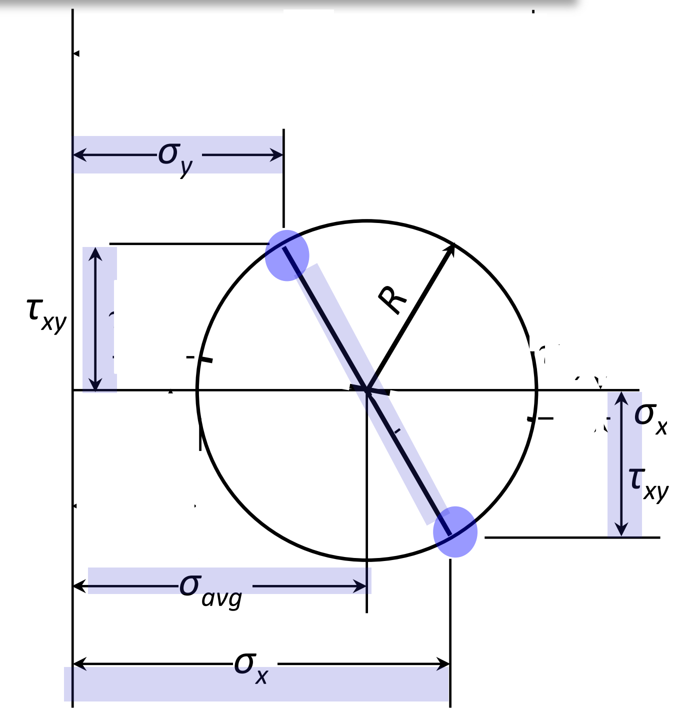

$$\left(\sigma_x - \sigma_{avg}\right)^2 + \tau_{xy}^2 = R^2$$

$$\sigma_{avg} = \frac{\sigma_x + \sigma_y}{2} \qquad R^2 = \left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}^2$$

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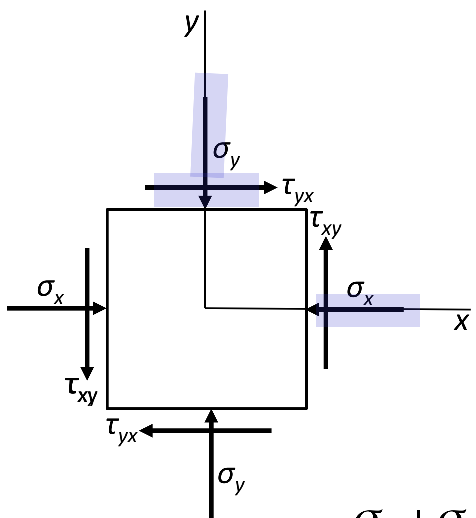

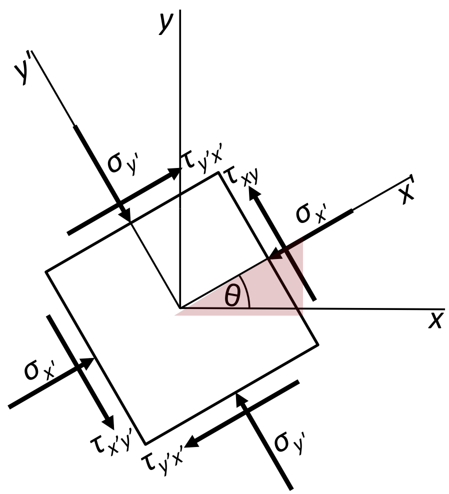

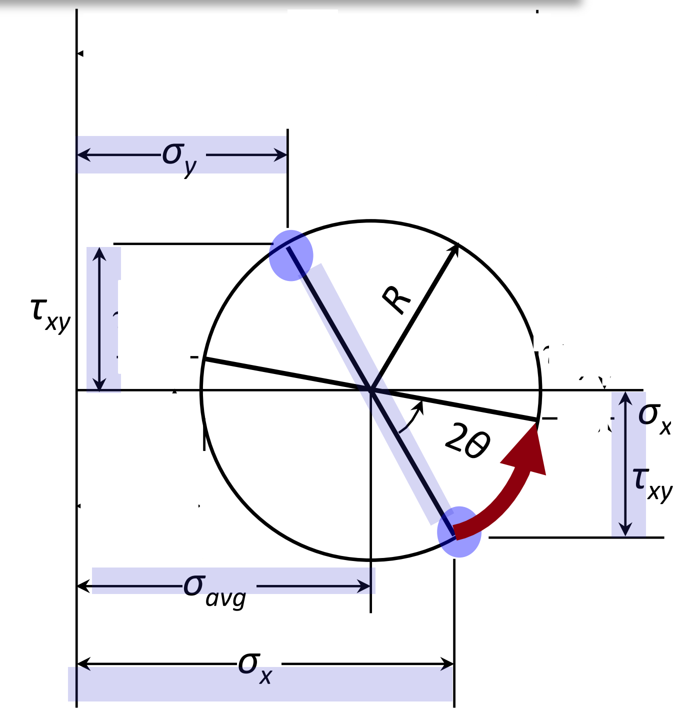

$$\sigma_{x'} = \frac{\sigma_x + \sigma_y}{2} + \frac{\sigma_x - \sigma_y}{2}\cos 2\theta + \tau_{xy}\sin 2\theta$$

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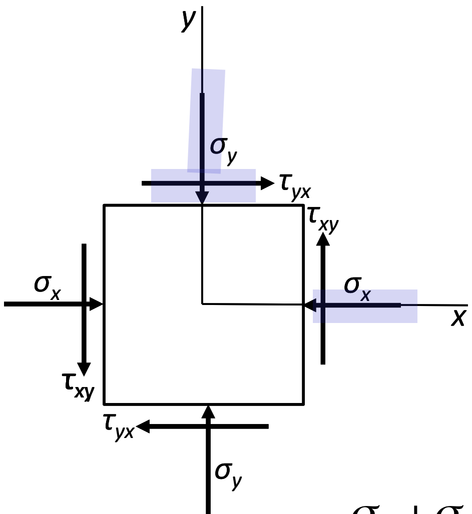

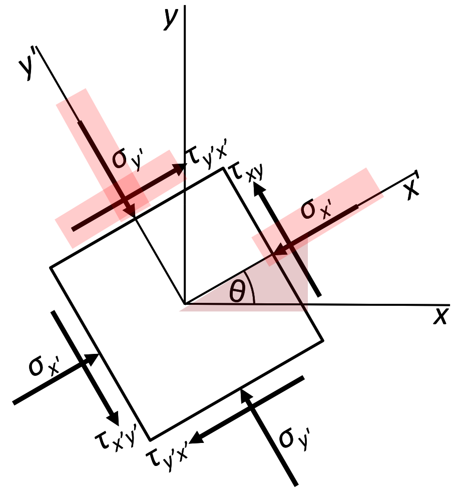

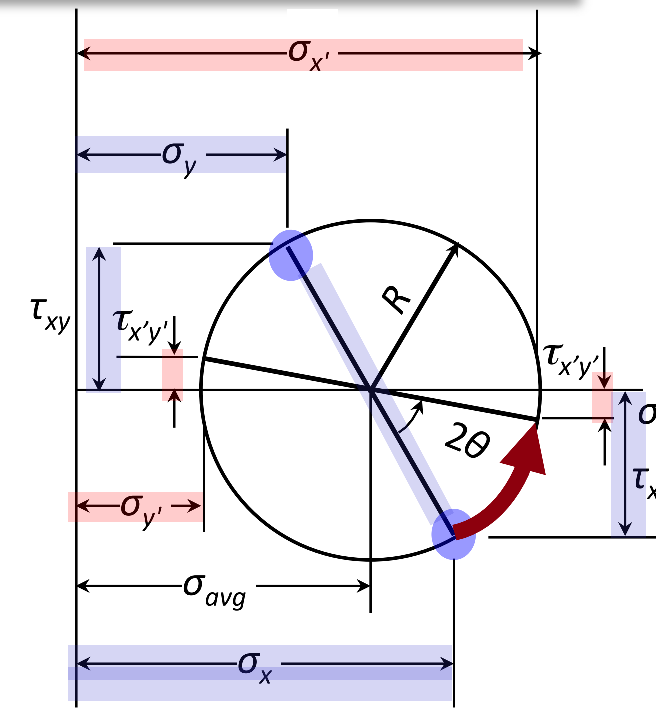

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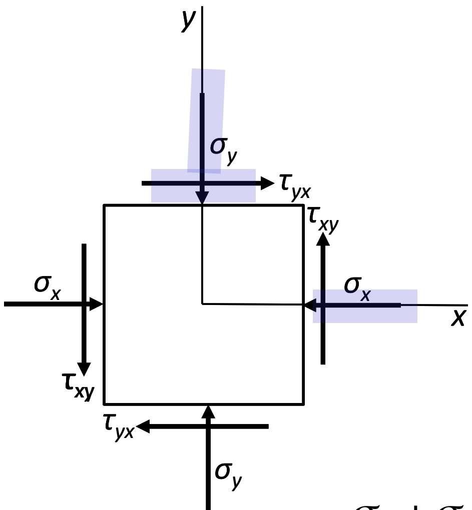

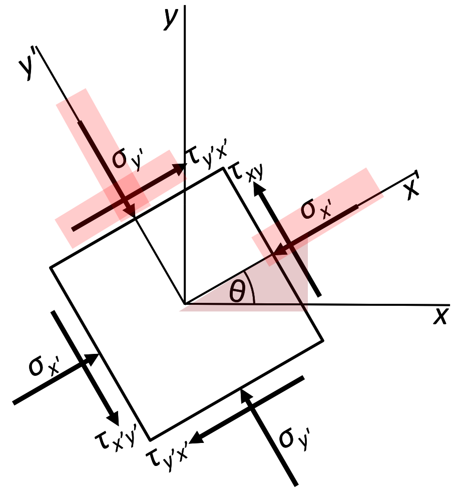

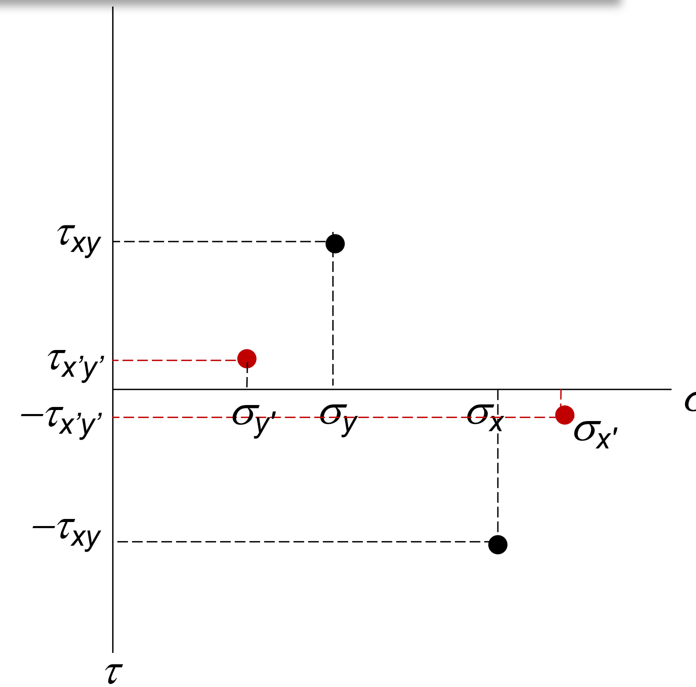

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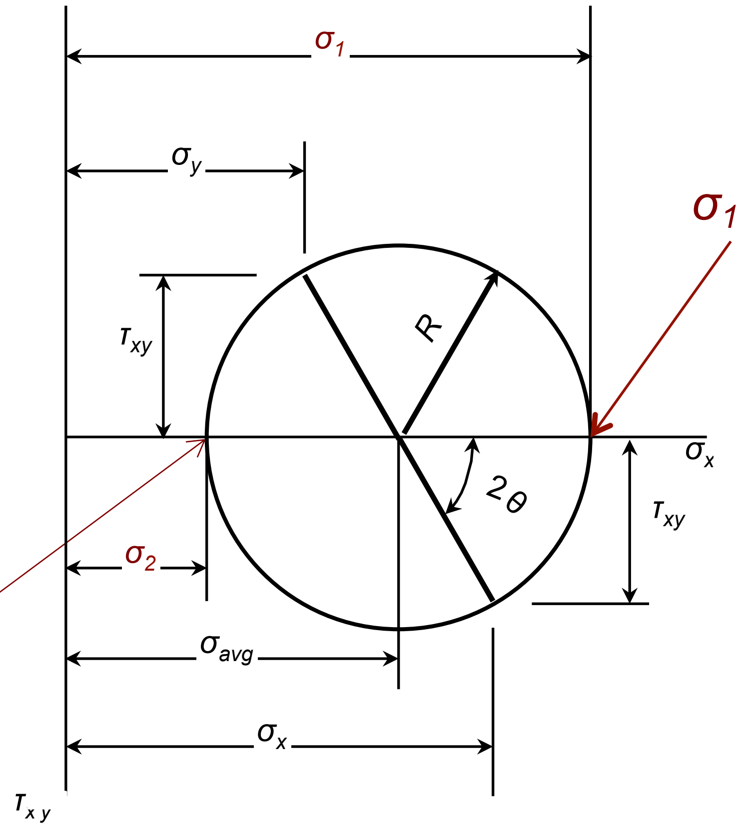
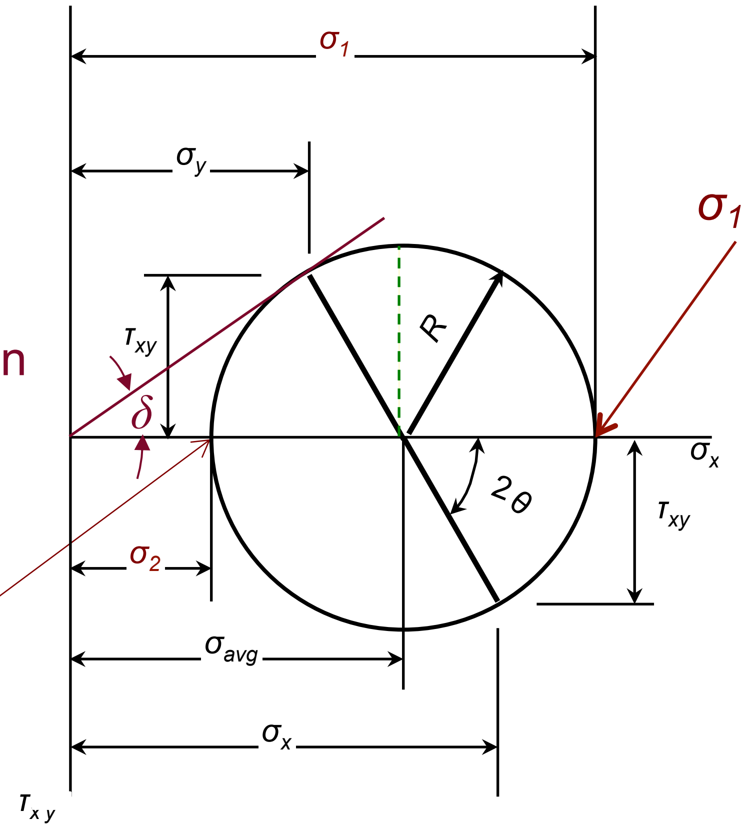
Principal stresses



σ_1 = major principal stress

σ_2 = minor principal stress

Effective angle of friction



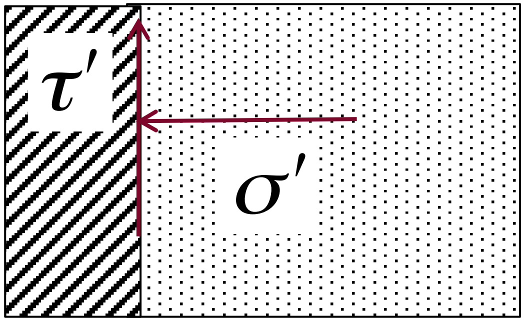
σ_1 = major principal stress

δ = effective angle of friction

$\sin \delta = (\sigma_1 - \sigma_2)/(\sigma_1 + \sigma_2)$

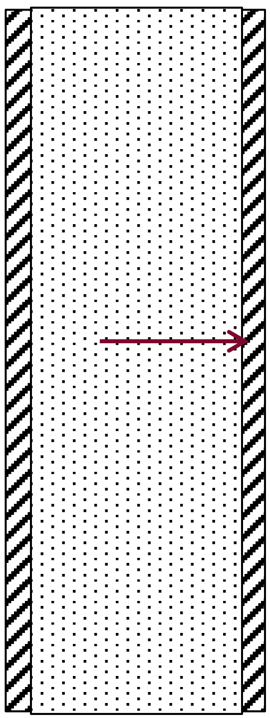
σ_2 = minor principal stress

Wall stresses



$$\frac{\tau'}{\sigma'} = \mu = \tan\phi'$$

Wall stresses



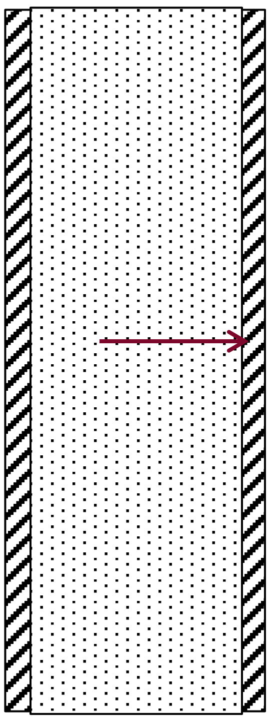
$$\sigma' = k\sigma_v$$

$$\sigma_v(z) = \frac{\rho_b g R_H}{k \tan\phi'}\left[1 - \exp\left(\frac{-k\tan\phi' z}{R_H}\right)\right]$$

$$k = \frac{\sigma_h}{\sigma_v}$$

$$\sigma_h(z) = \frac{\rho_b g R_H}{\tan\phi'}\left[1 - \exp\left(\frac{-k\tan\phi' z}{R_H}\right)\right]$$

Wall stresses



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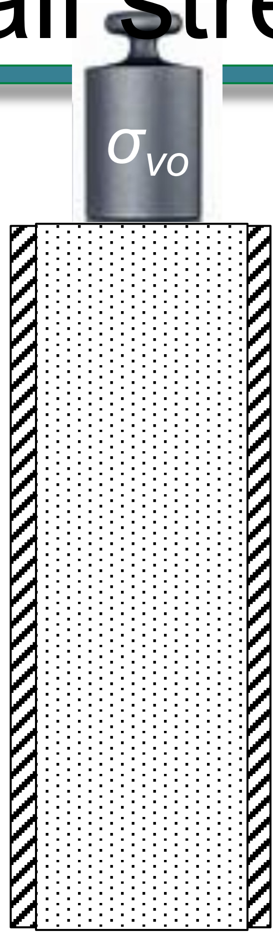
$$\sigma_h(z) = \frac{\rho_b g R_H}{\tan\phi'}\left[1 - \exp\left(\frac{-k\tan\phi' z}{R_H}\right)\right]$$

$$k = 0.4 - 0.6$$

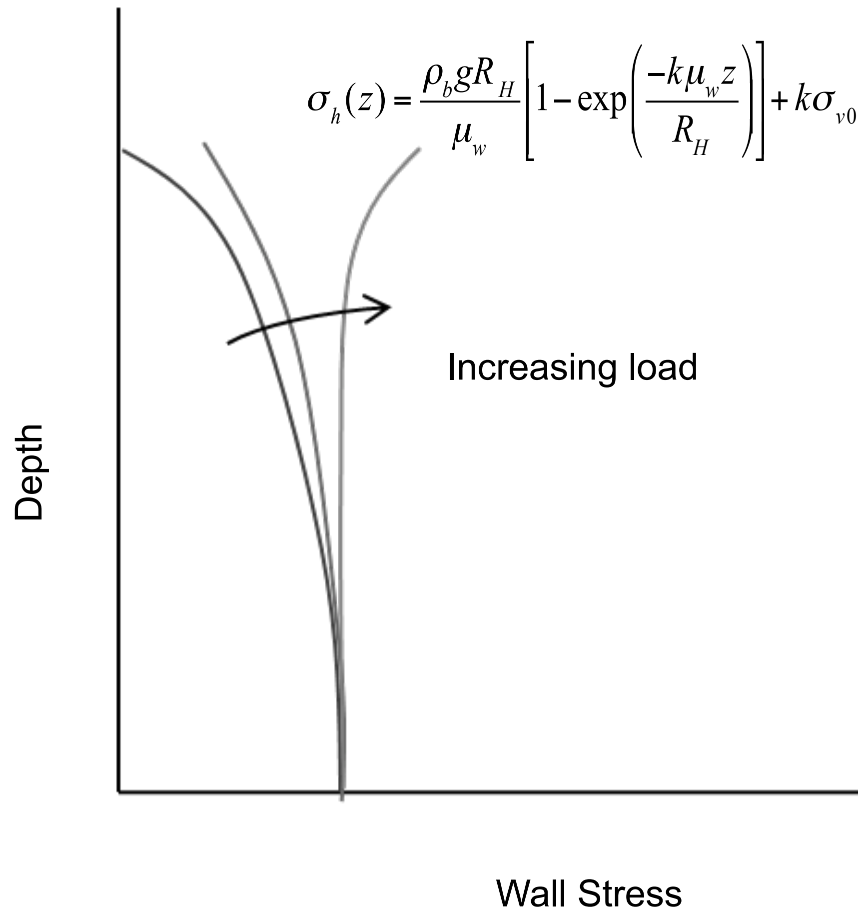
Max. wall stress calculations

Max. vertical load calculations

Wall stresses



$$\sigma_h(z) = \frac{\rho_b g R_H}{\mu_w}\left[1 - \exp\left(\frac{-k\mu_w z}{R_H}\right)\right] + k\sigma_{v0}\exp\left(\frac{-k\mu_w z}{R_H}\right)$$



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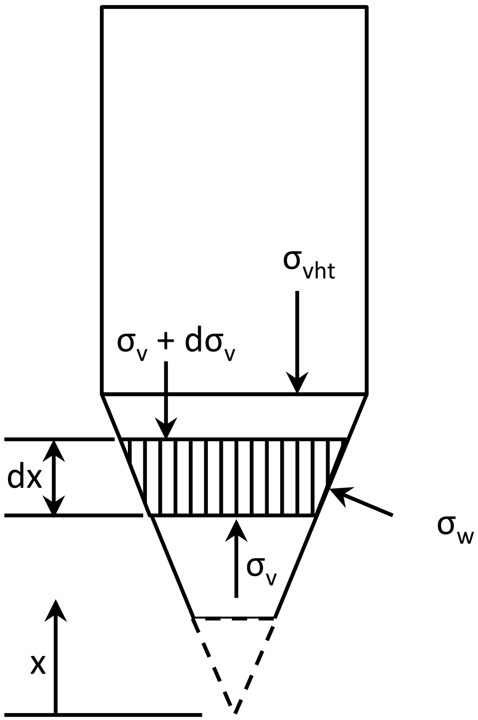


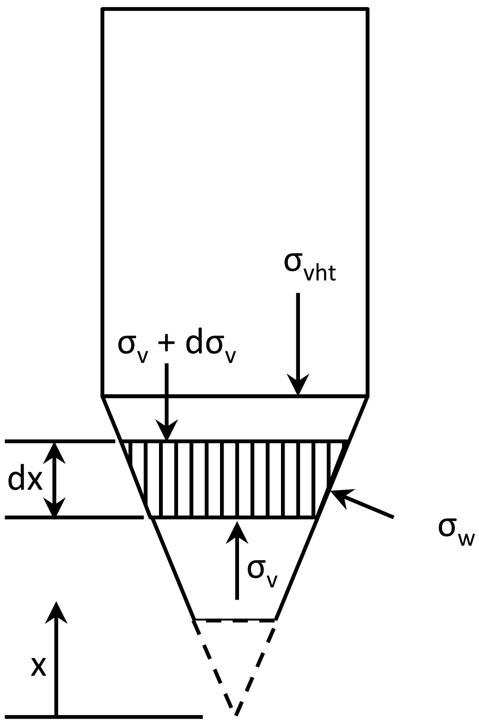
$$\frac{d\sigma_v}{dz} - n\frac{\sigma_v}{z} = -g\rho_b$$

$$n = (m+1)\left[k\left(1+\frac{\tan\phi'}{\tan\theta}\right)-1\right]$$

$$\sigma_v = \frac{\rho_b g h}{n-1}\left[\frac{x}{h} - \left(\frac{x}{h}\right)^n\right] + \sigma_{vht}\left(\frac{x}{h}\right)^n$$

$$\sigma_w = k\sigma_v$$

Wall stresses



$$\sigma_v = \frac{\rho_b g h}{n-1}\left[\frac{x}{h} - \left(\frac{x}{h}\right)^n\right] + \sigma_{vht}\left(\frac{x}{h}\right)^n$$

Initial fill

$$k = 1 - \frac{0.2}{1 + \dfrac{\tan\theta'}{\tan\phi'}}$$

Discharge

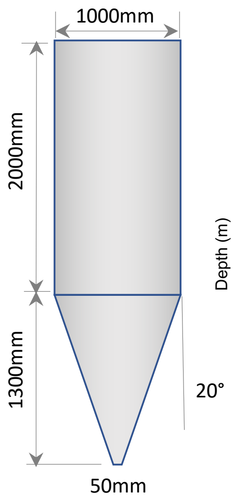
$$k = \frac{1 + \sin\delta\cos\varepsilon}{1 - \sin\delta\cos(2\theta' + \varepsilon)}$$

$$\varepsilon = \phi' + \sin^{-1}\left(\frac{\sin\phi'}{\sin\delta}\right)$$

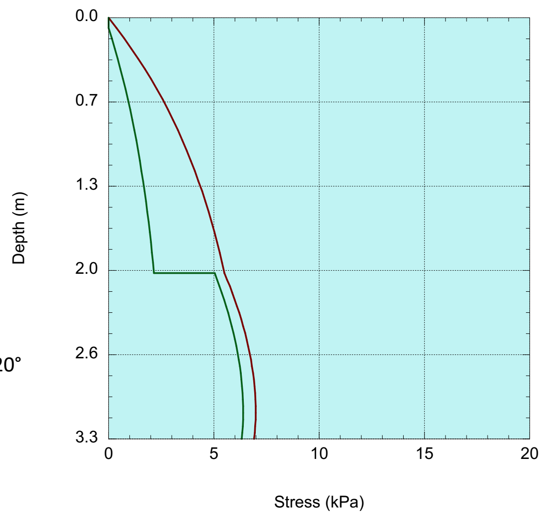
$$k = \left(\frac{1}{1 + \dfrac{\tan\phi'}{\tan\theta'}}\right)\left\{1 + 2\left[1 + \left(\frac{\sin\delta}{1+\sin\delta}\right)\left(\frac{\cos\varepsilon\sin(\varepsilon - \theta')}{\sin\theta'}\right)\right]\right\}$$

$$\varepsilon = \theta' + \frac{1}{2}\left[\phi' + \sin^{-1}\left(\frac{\sin\phi'}{\sin\delta}\right)\right]$$

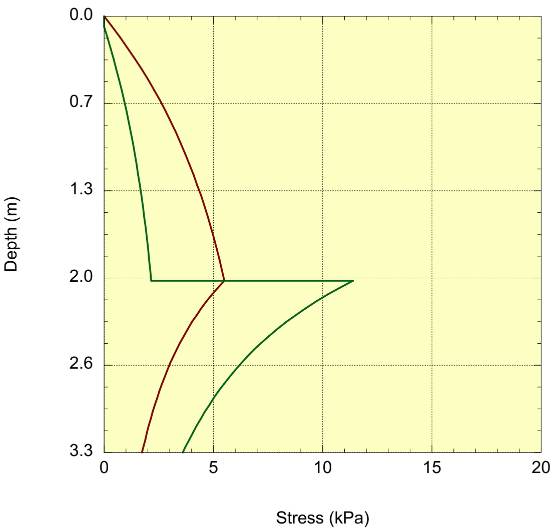
Solids stresses



Initial fill



After discharge



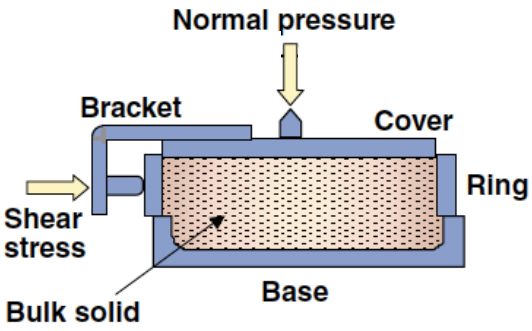
Fundamental flow properties

- Cohesive strength
- Internal friction
- Compressibility
- Wall friction
- Permeability

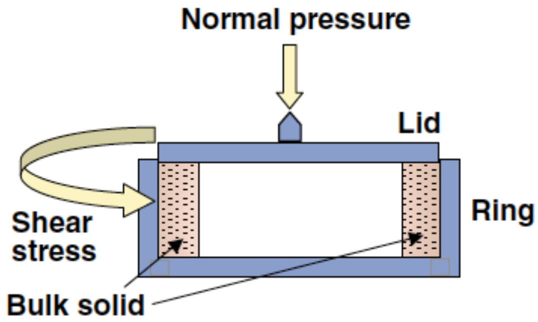
Test equipment

- Shear cell testers
  - Cohesive strength
  - Internal friction
  - Compressibility
  - Wall friction
- Permeability testers

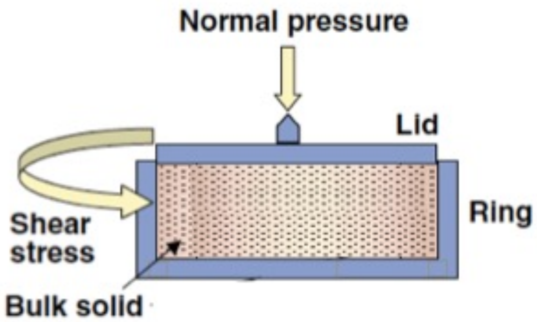
Shear cell testers



Direct



Annular



Torsional

- Cohesive strength
- Internal friction
- Compressibility
- Wall friction (use caution)

Shear cell testers

Jenike & Johanson

Dietmar Schulze

Brookfield Engineering

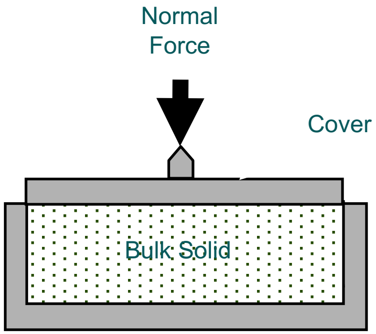
Anton Paar

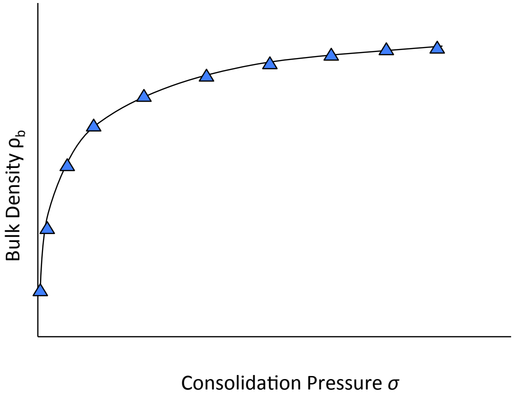
Freeman Technology

E&G Associates

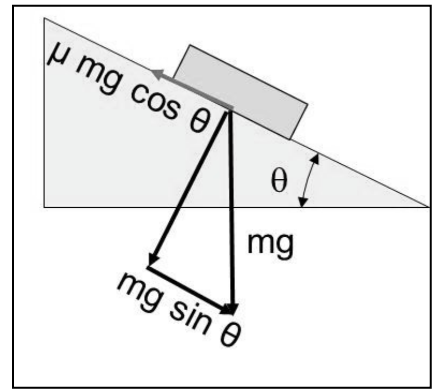
Compressibility

Compressibility





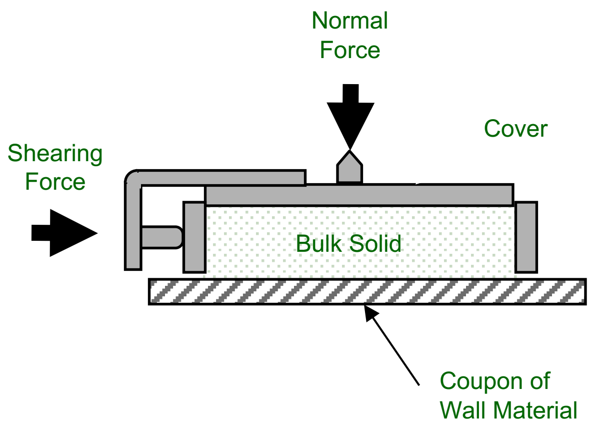
Wall friction



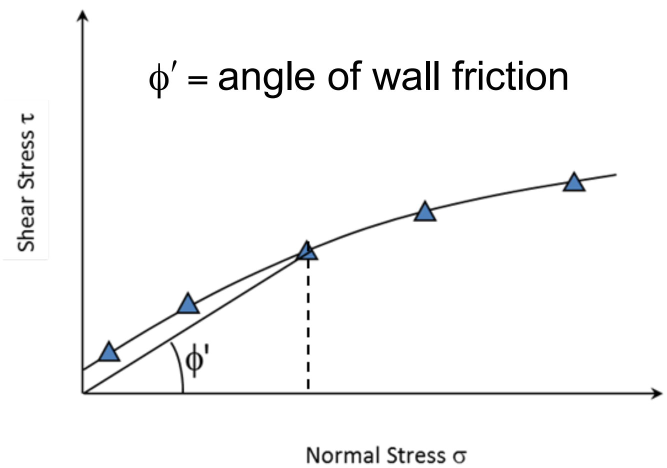
$$mg \sin\theta = \mu\, mg \cos\theta$$

$$\mu = \tan\theta$$

Wall friction

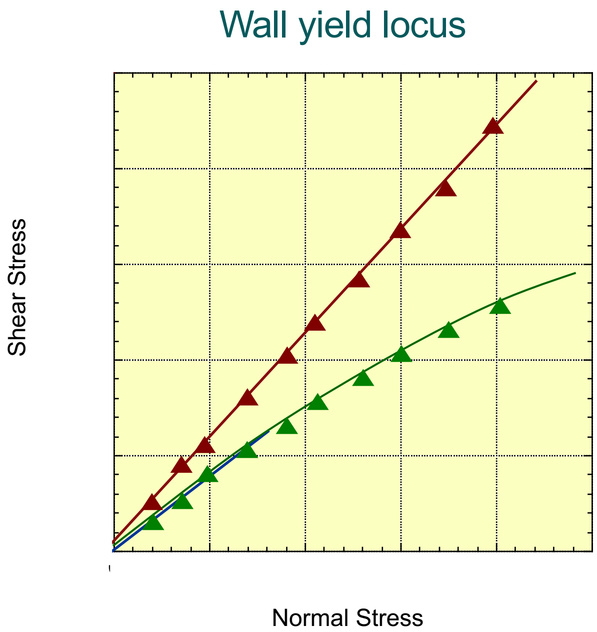


Wall Yield Locus

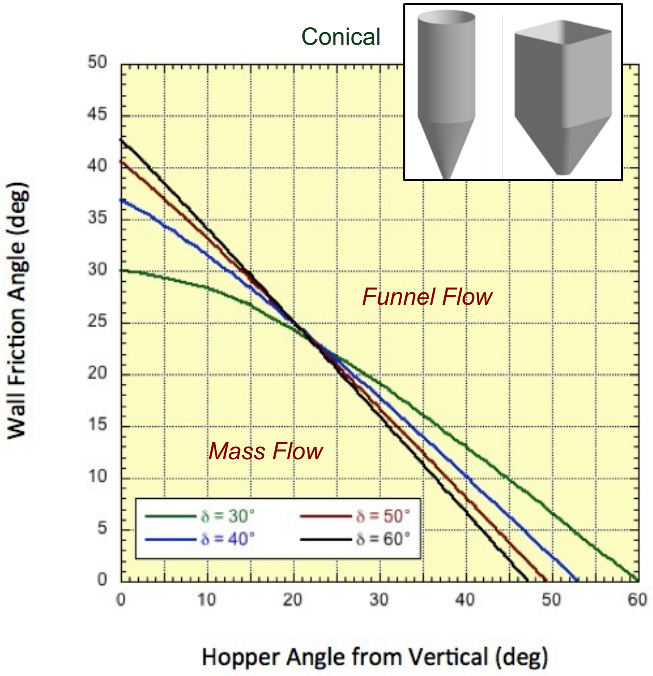


$$\tan\phi' = \frac{\text{Shear Stress}}{\text{Normal Stress}} = \mu$$

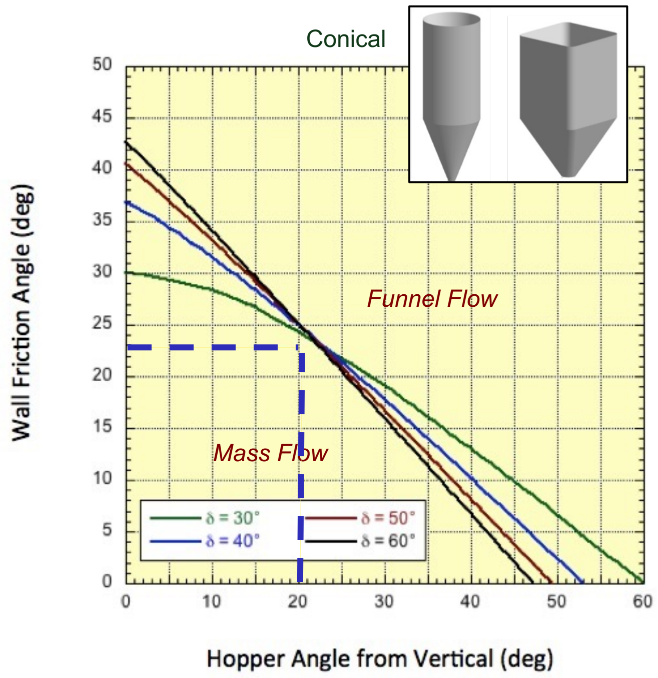
Wall friction



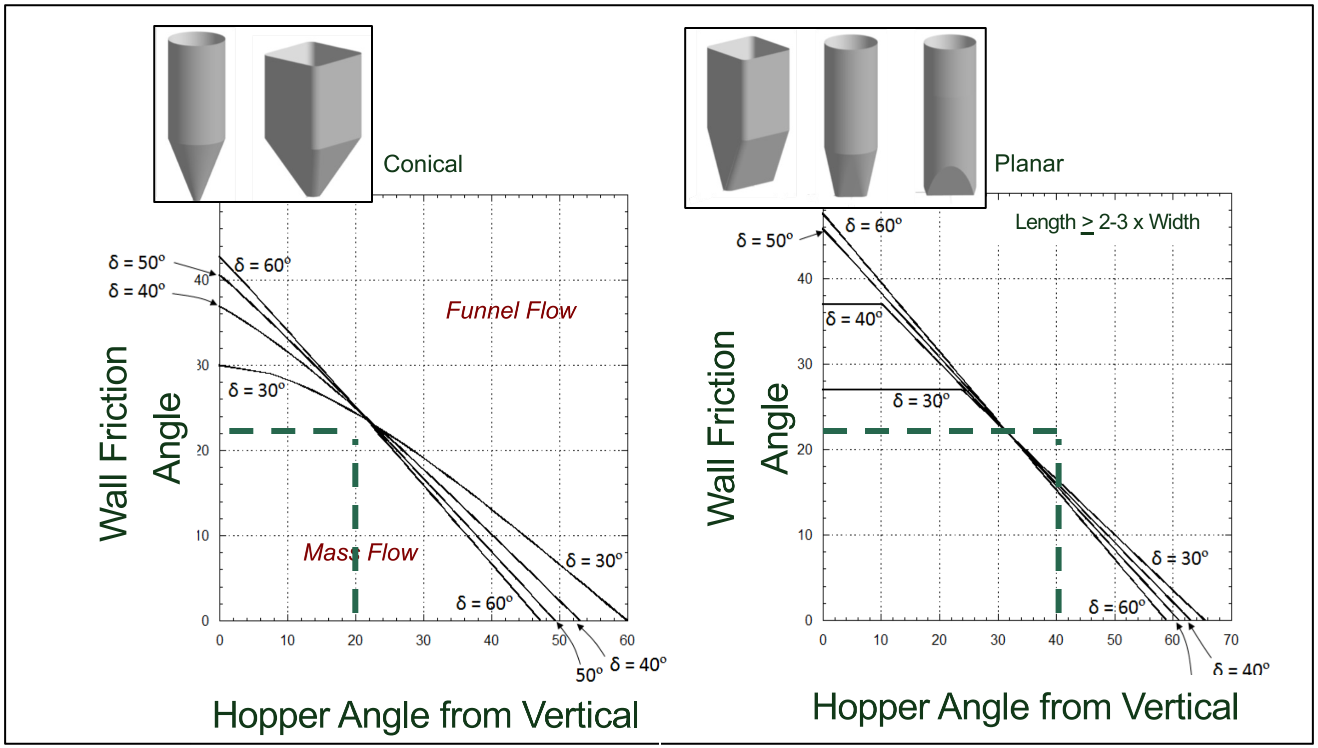
Mass flow hopper angle



Mass flow hopper angle

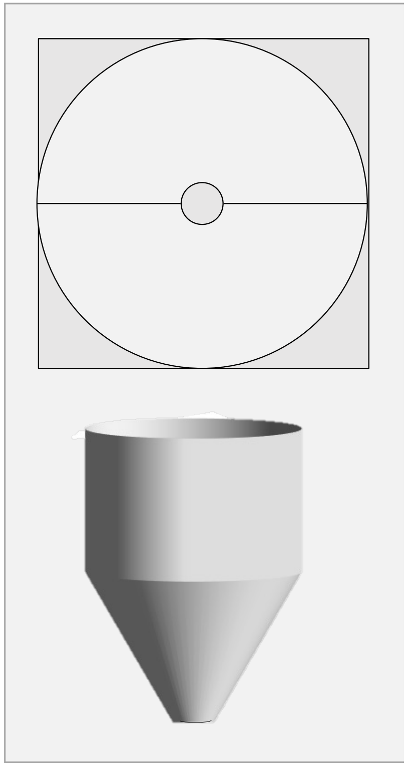


Mass flow hopper angles

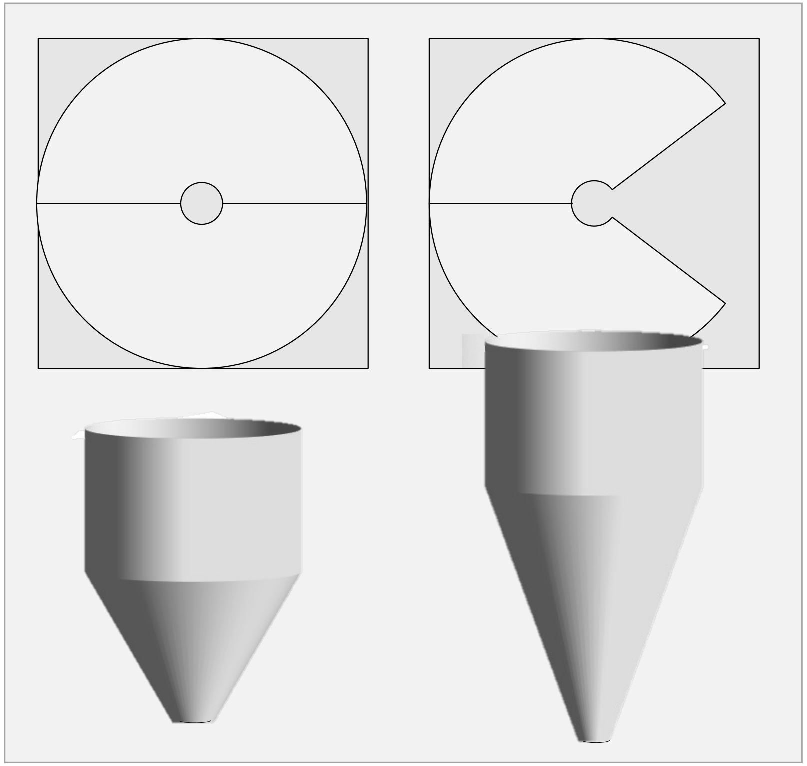


From Jenike Bulletin 123

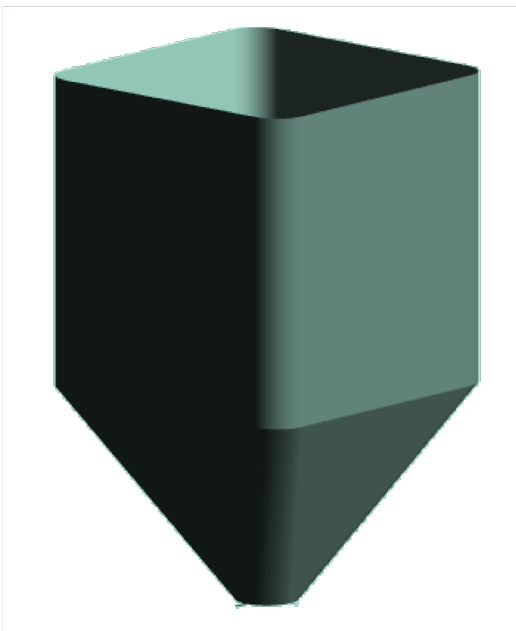
Mass flow hopper angle



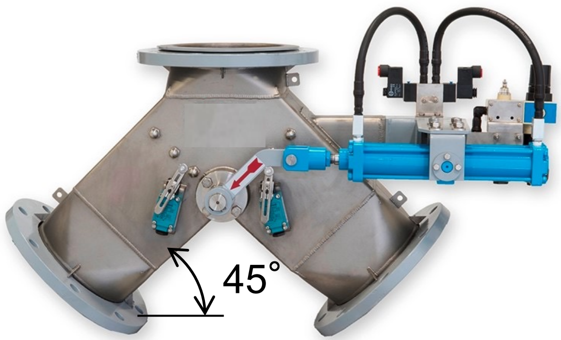
Mass flow hopper angle



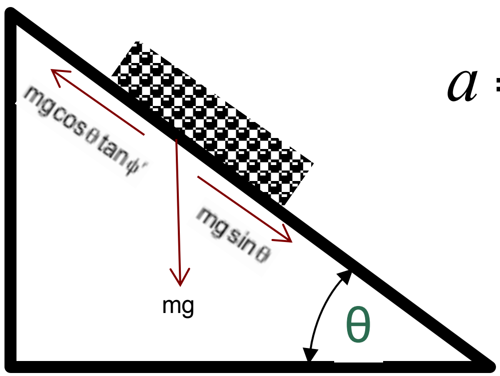
Valley angles



Transfer chutes and diverter valves



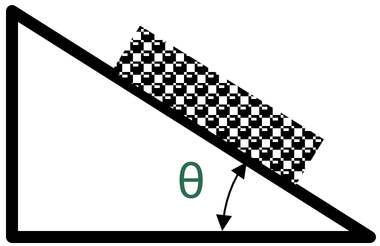
Transfer chutes



$$a = g(\sin\theta - \cos\theta\tan\phi')$$
$$= g\cos\theta(\tan\theta - \tan\phi')$$

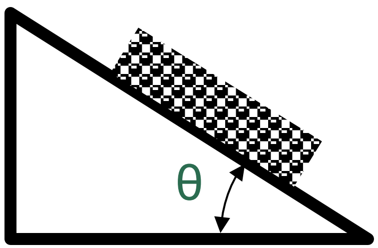
For dependable flow, $\theta' = \phi' + 5^\circ$

Transfer chutes



$$a = g\cos\theta(\tan\theta - \tan\phi')$$

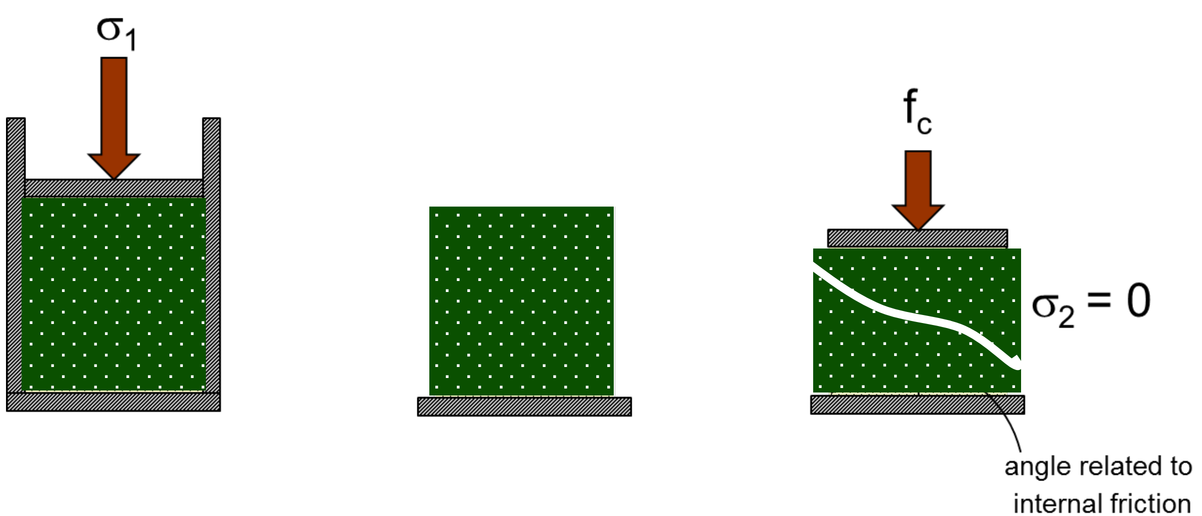
Transfer chutes



$$a = g\cos\theta(\tan\theta - \tan\phi')$$

Cohesive strength

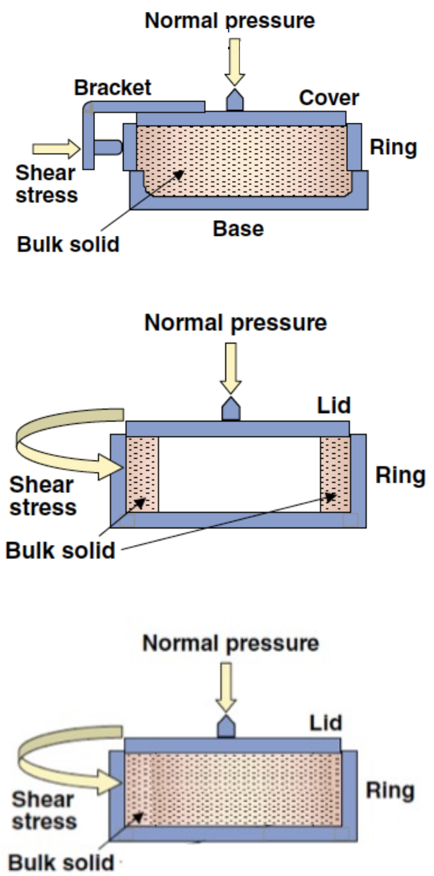
Cohesive strength

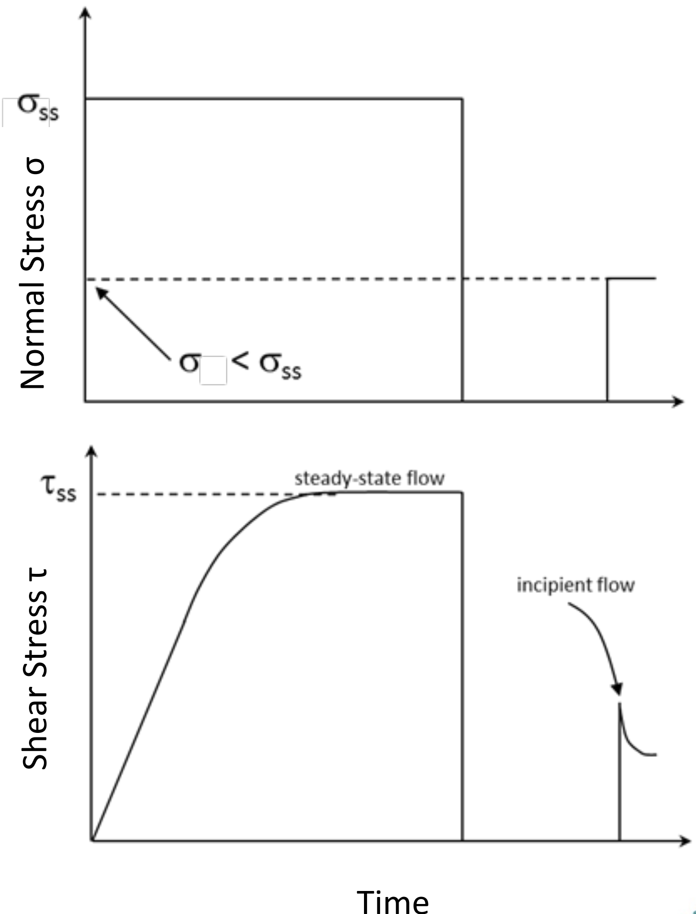


Consolidation

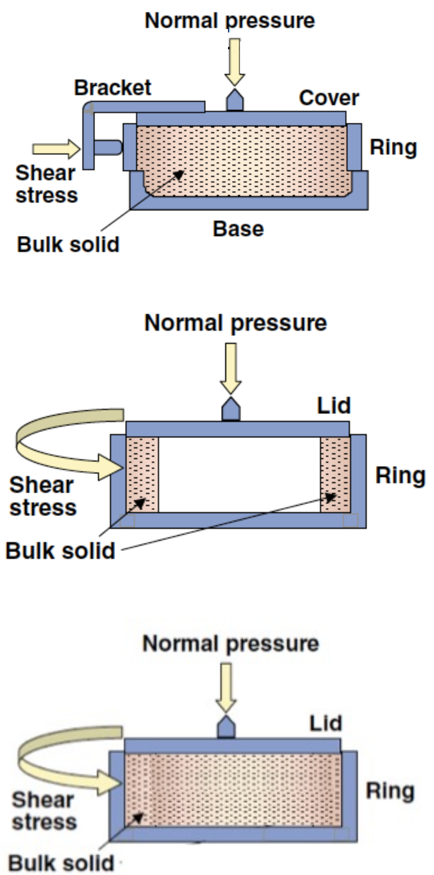
Failure

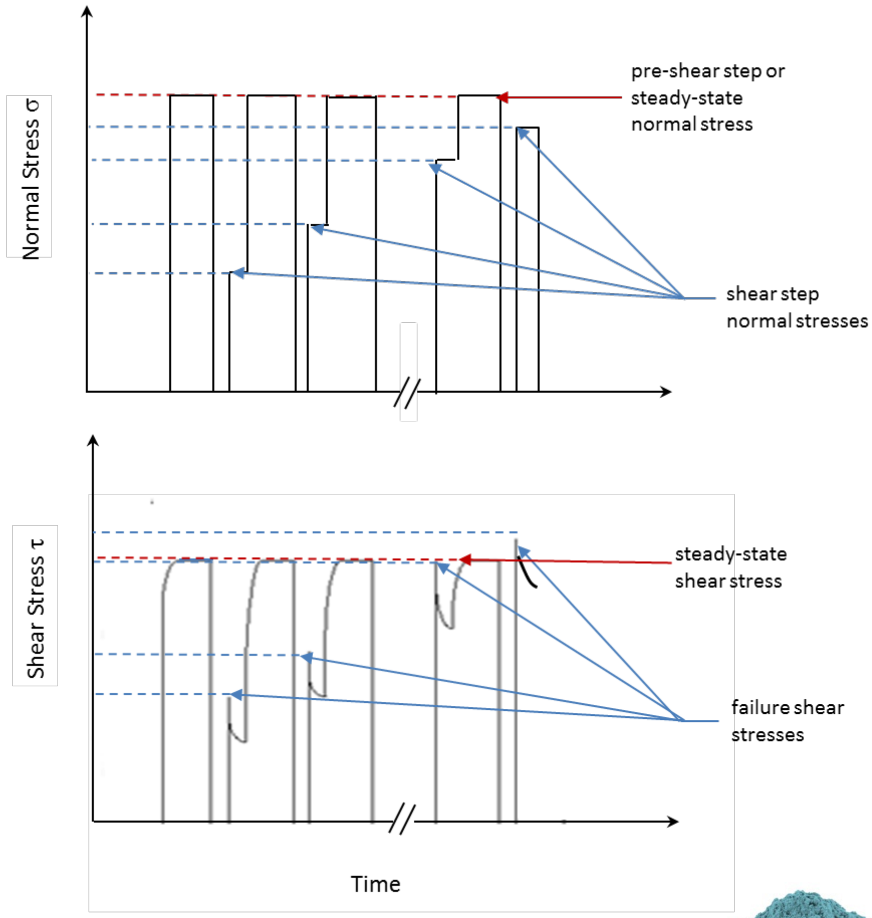
Cohesive strength



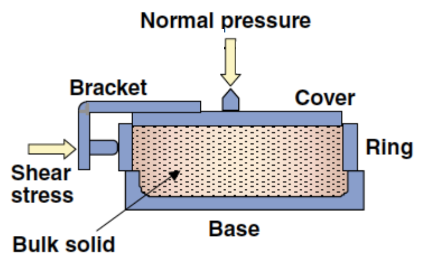


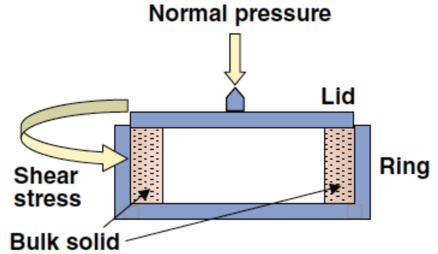
Cohesive strength

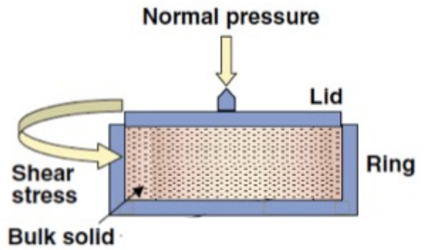


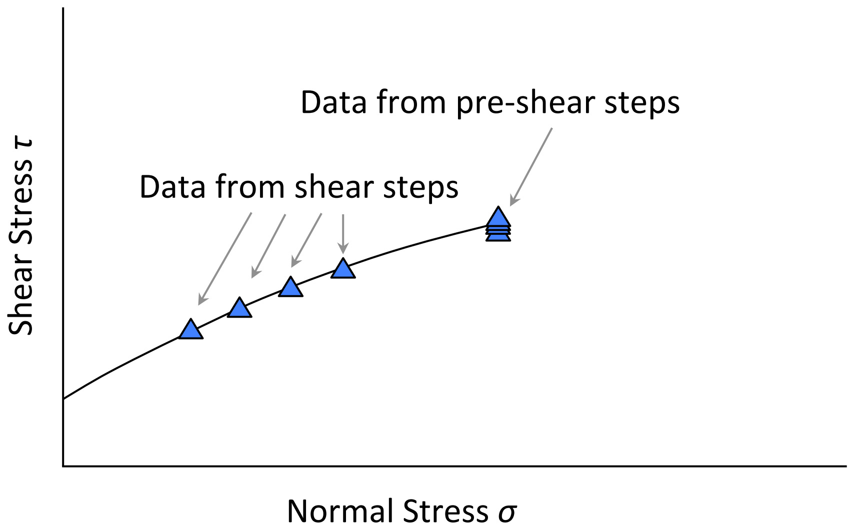


Yield locus

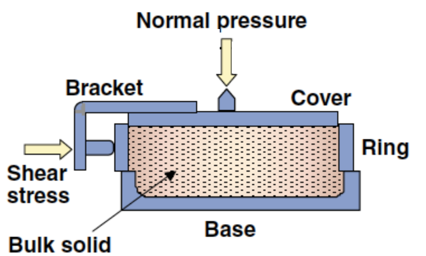

Normal pressure
Bracket
Cover
Ring
Shear stress
Bulk solid
Base


Normal pressure
Lid
Ring
Shear stress
Bulk solid

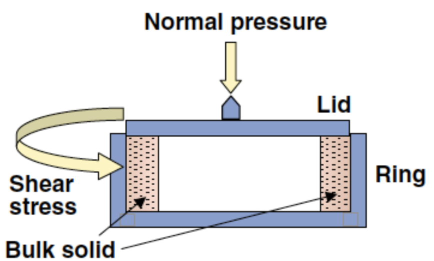

Normal pressure
Lid
Ring
Shear stress
Bulk solid


Data from pre-shear steps
Data from shear steps
Shear Stress τ
Normal Stress σ

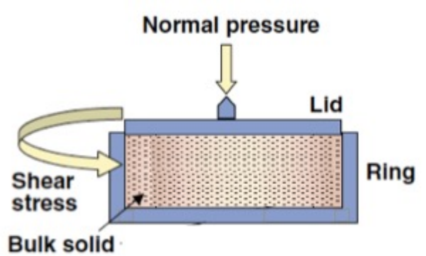
Yield locus



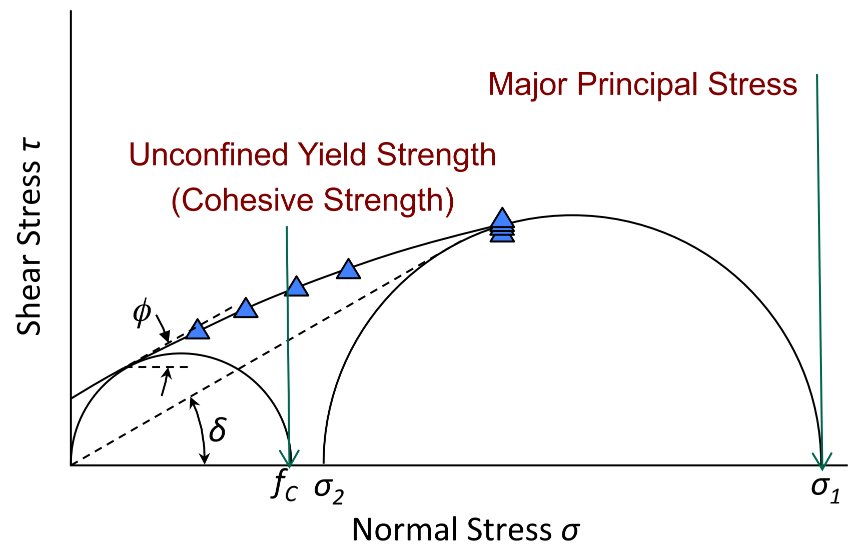
Normal pressure
Bracket
Cover
Ring
Shear
stress
Bulk solid
Base



Normal pressure
Lid
Ring
Shear
stress
Bulk solid

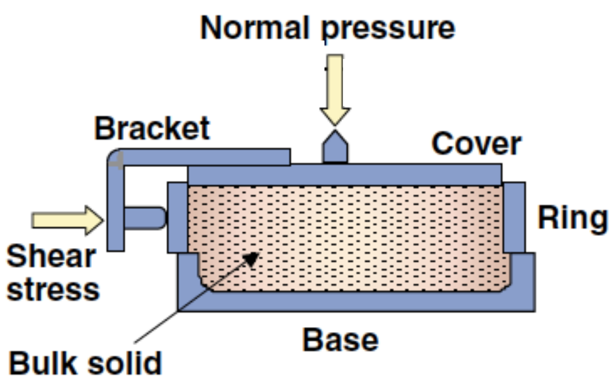


Normal pressure
Lid
Ring
Shear
stress
Bulk solid

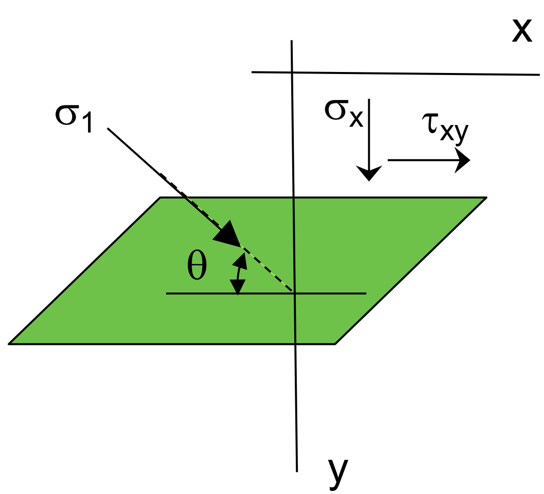


Major Principal Stress
Unconfined Yield Strength
(Cohesive Strength)
Shear Stress τ
ϕ
δ
f_C
σ_2
σ_1
Normal Stress σ

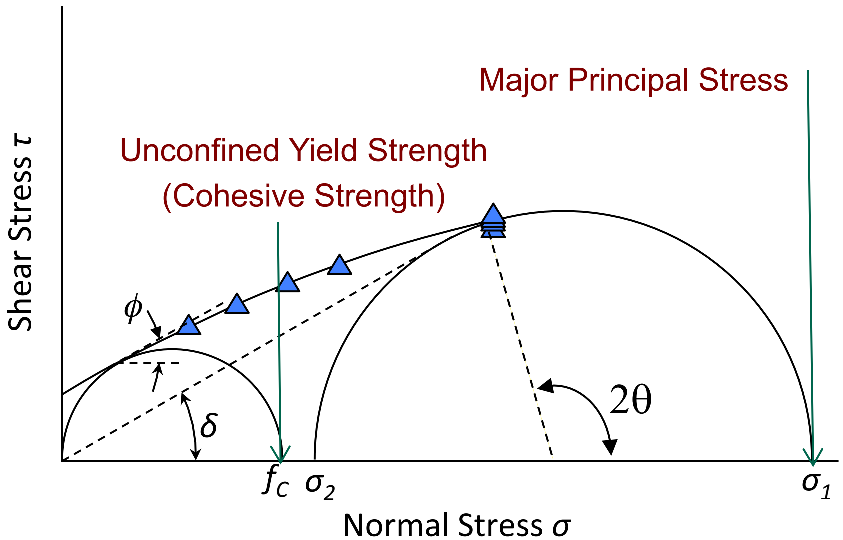
Yield locus



Normal pressure
Bracket
Cover
Ring
Shear
stress
Bulk solid
Base

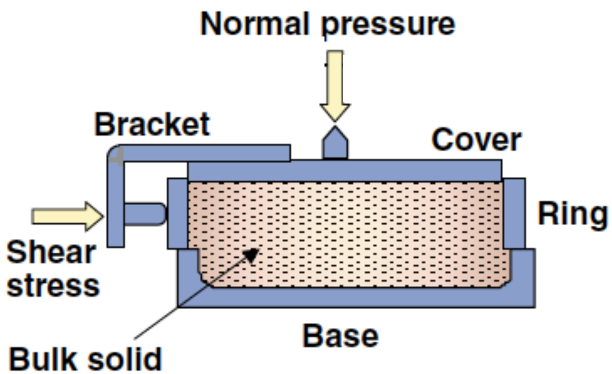


x
σ1
σx
τxy
θ
y

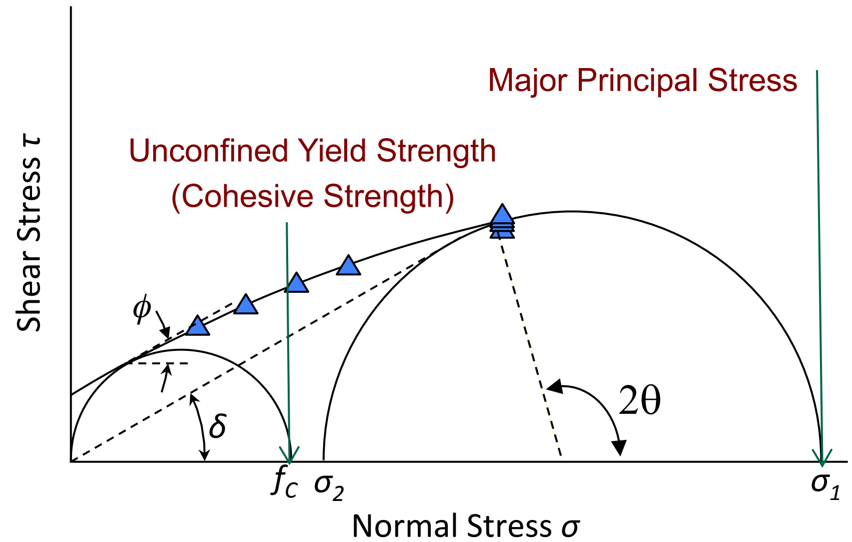


Major Principal Stress
Unconfined Yield Strength
(Cohesive Strength)
Shear Stress τ
ϕ
δ
2θ
fc
σ2
σ1
Normal Stress σ

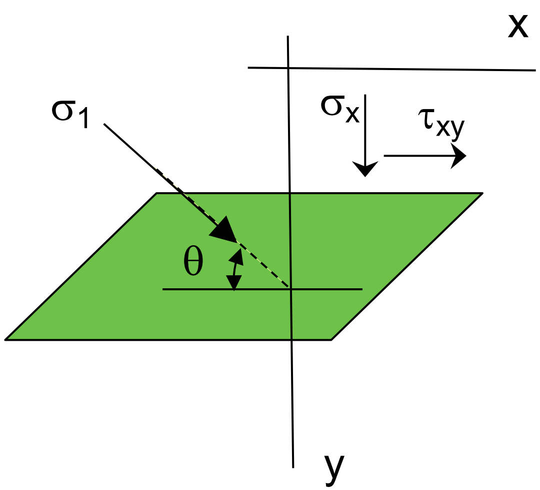
Yield locus



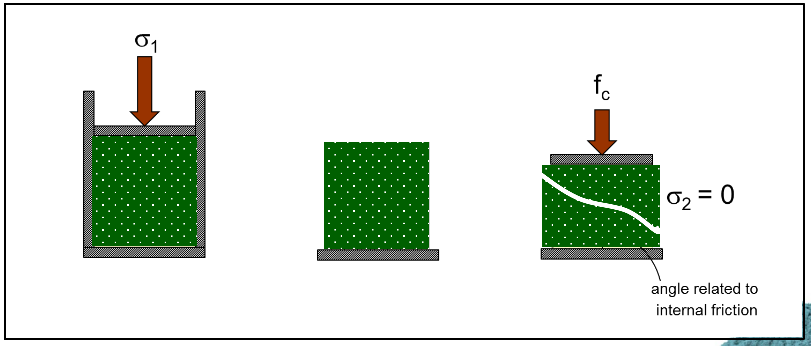
Normal pressure
Bracket
Cover
Ring
Shear stress
Bulk solid
Base



Major Principal Stress
Unconfined Yield Strength
(Cohesive Strength)
Shear Stress τ
ϕ
δ
2θ
fc
σ2
σ1
Normal Stress σ

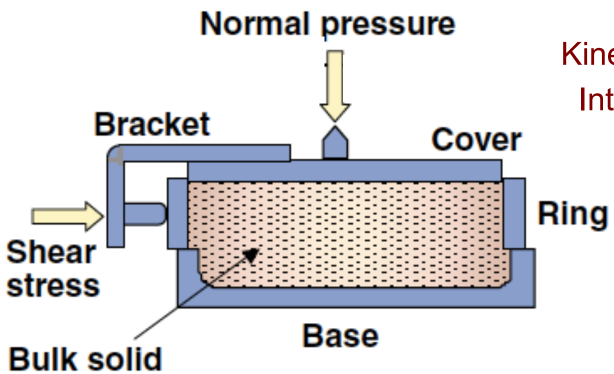


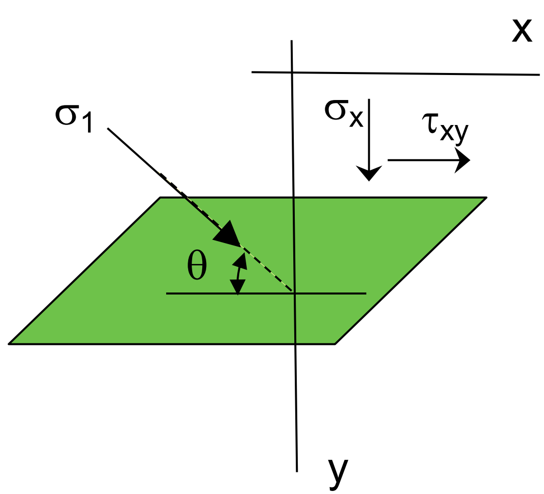
x
σ1
σx
τxy
θ
y

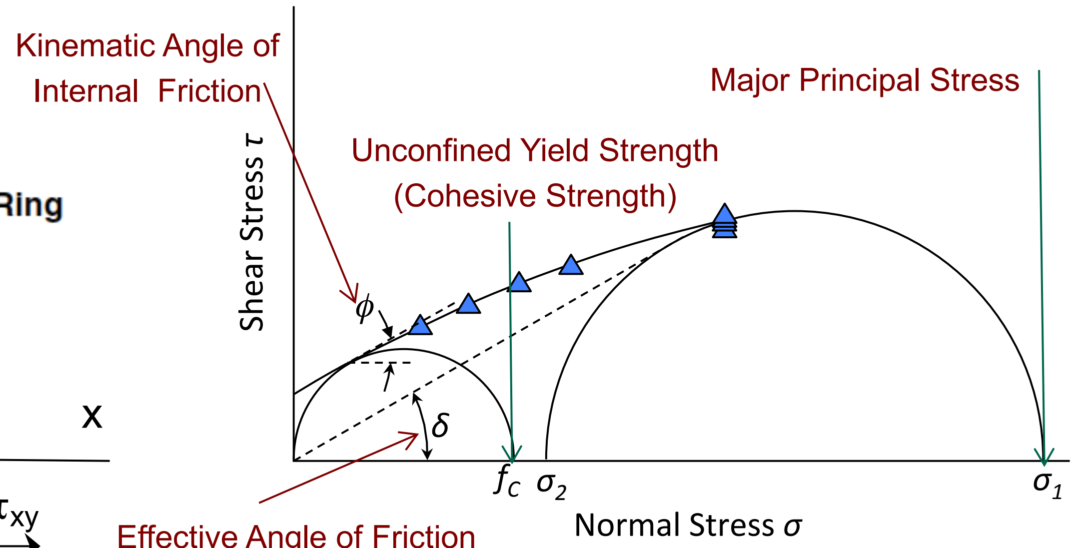


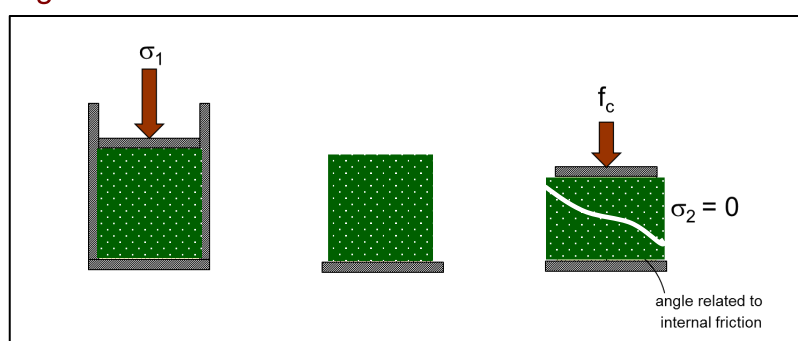
σ1
fc
σ2 = 0
angle related to
internal friction

Yield locus

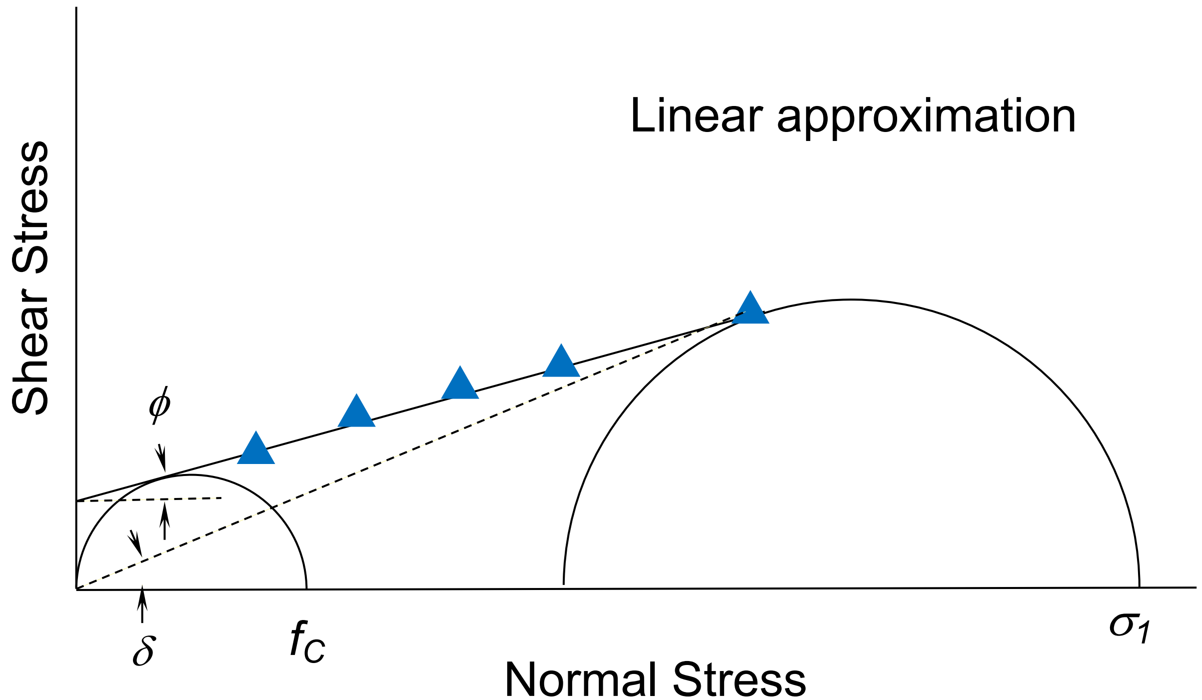

Normal pressure
Bracket
Cover
Ring
Shear stress
Base
Bulk solid


x
σ_1
σ_x
τ_{xy}
θ
y

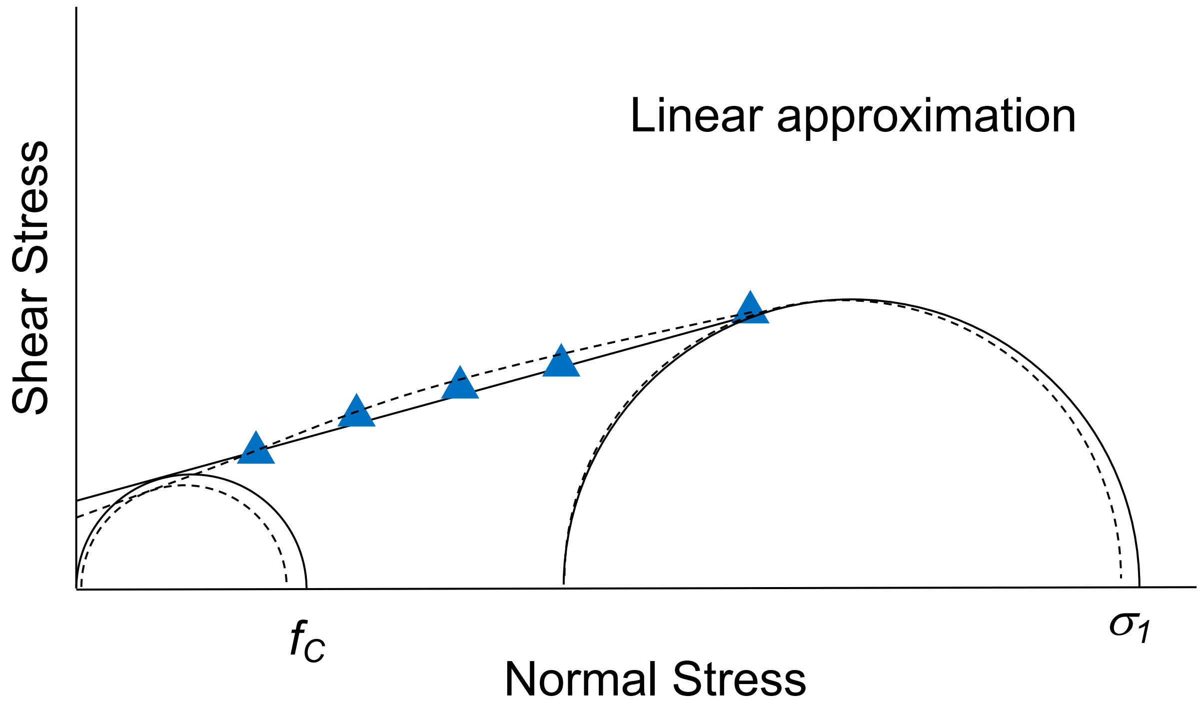

Kinematic Angle of Internal Friction
Major Principal Stress
Unconfined Yield Strength (Cohesive Strength)
Shear Stress τ
ϕ
δ
f_C
σ_2
σ_1
Normal Stress σ
Effective Angle of Friction


σ_1
f_c
$\sigma_2 = 0$
angle related to internal friction

Yield locus

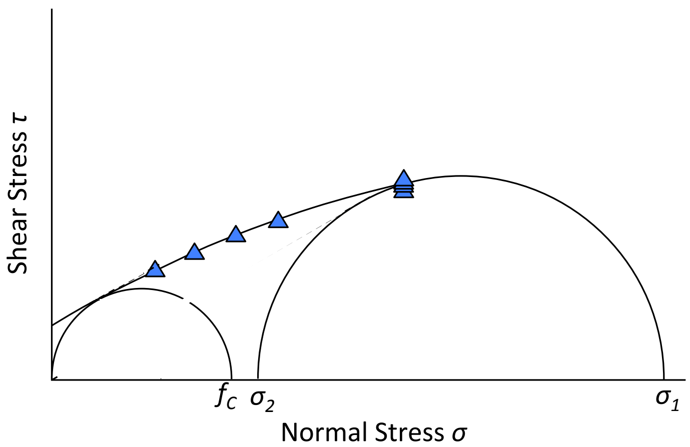

Linear approximation
Shear Stress
ϕ
δ
f_C
σ_1
Normal Stress

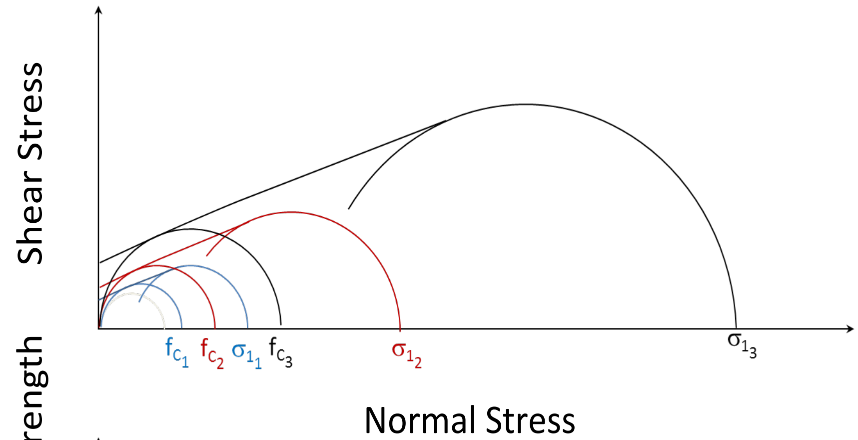
Yield locus

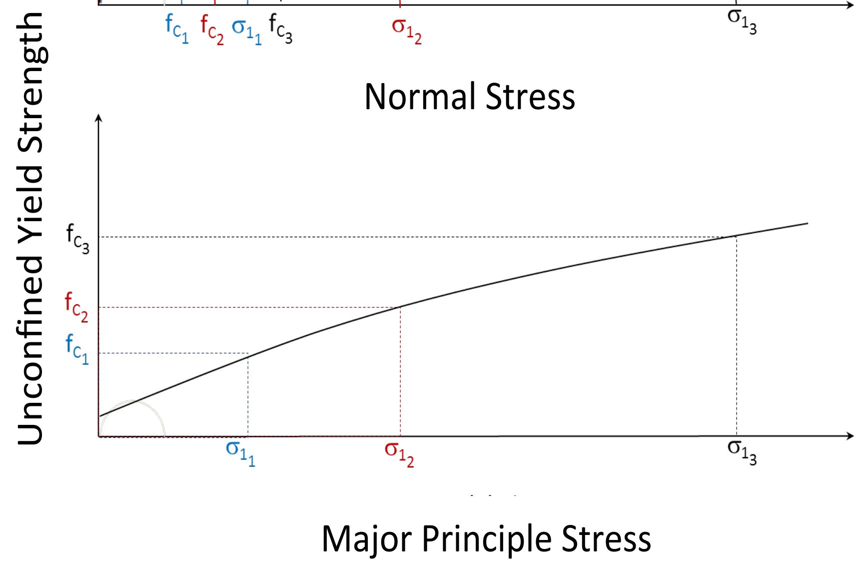


Linear approximation
Shear Stress
f_C
σ_1
Normal Stress

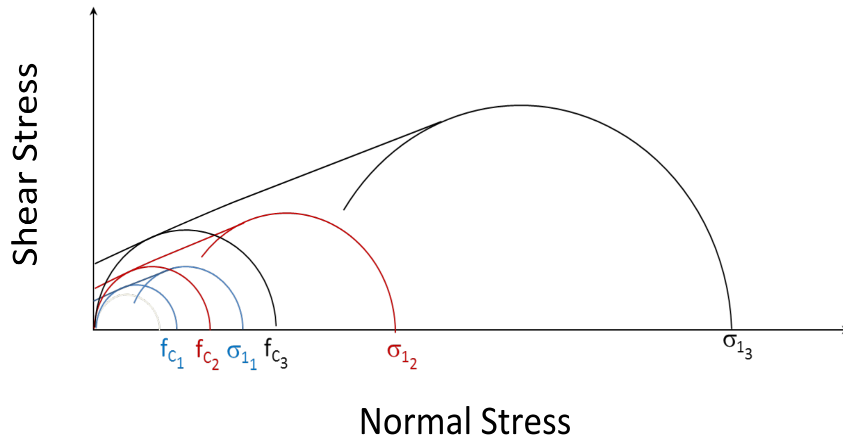
Flow function

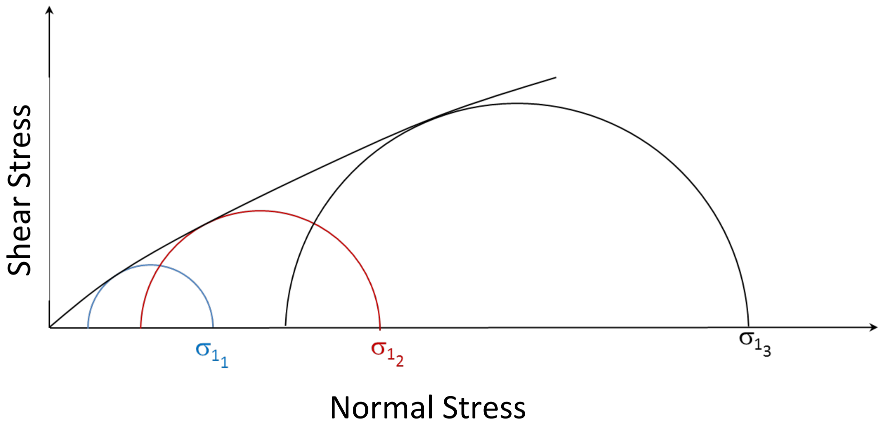




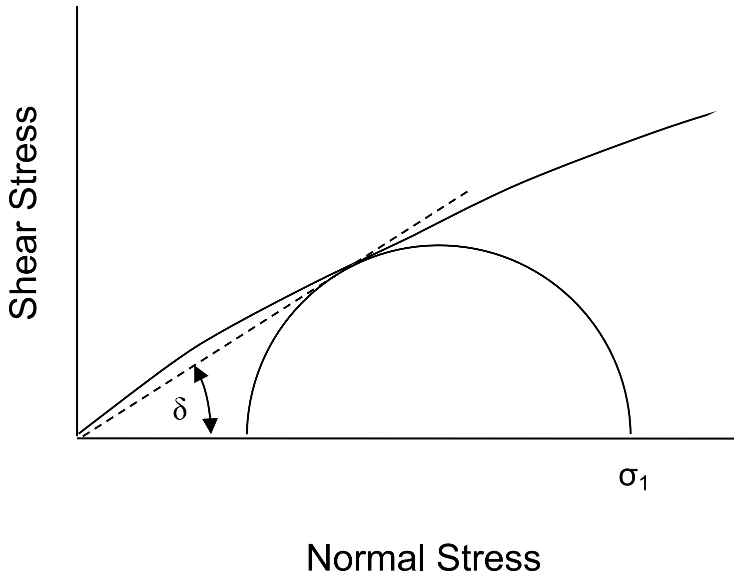


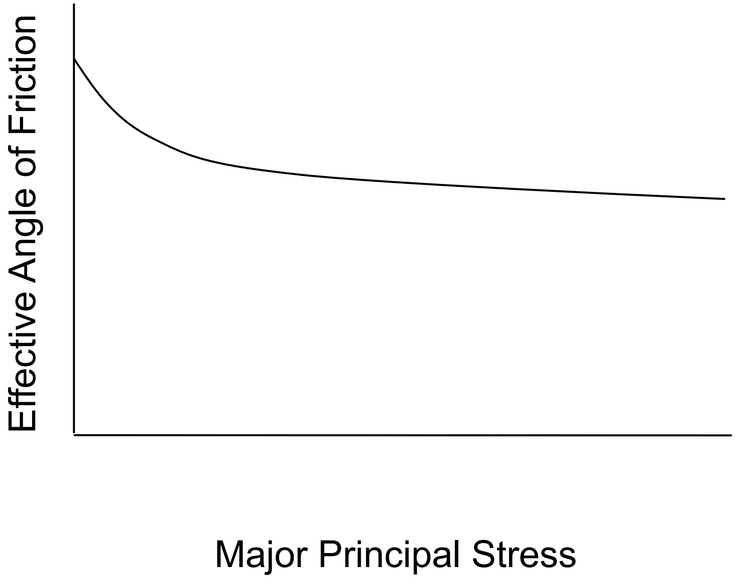
Effective yield locus



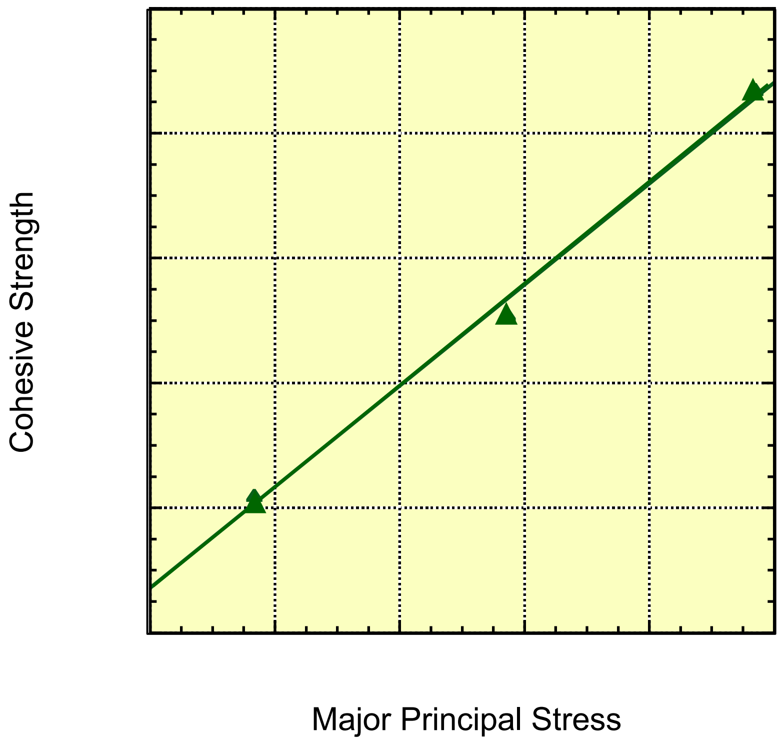


Effective yield locus

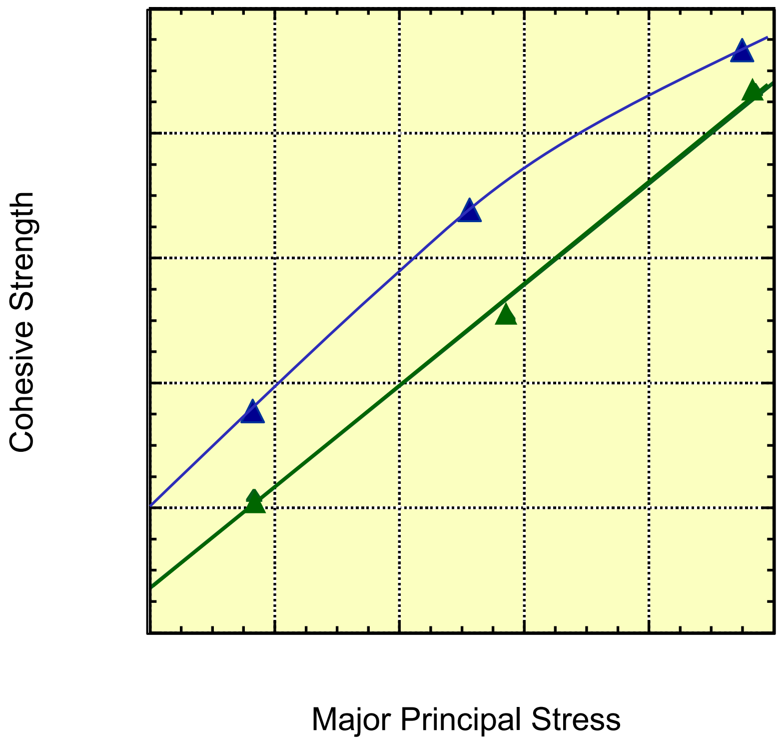




Flow function

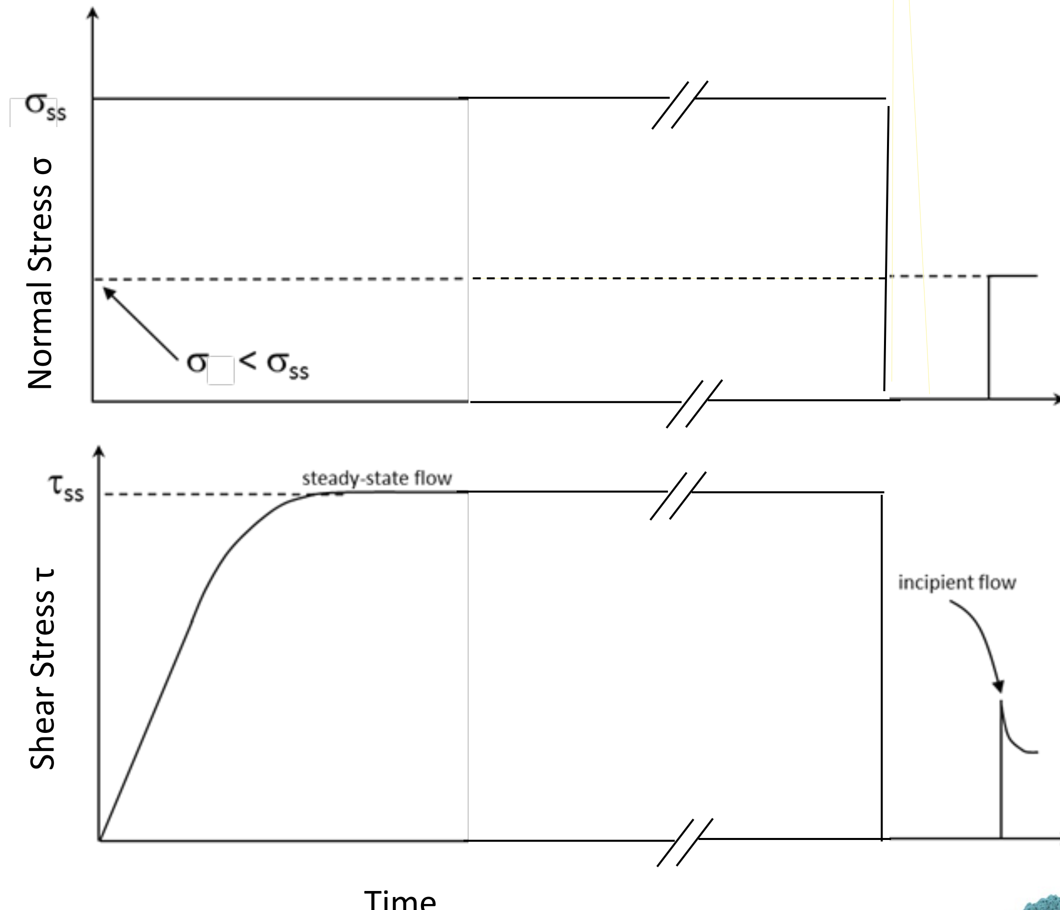


Flow function

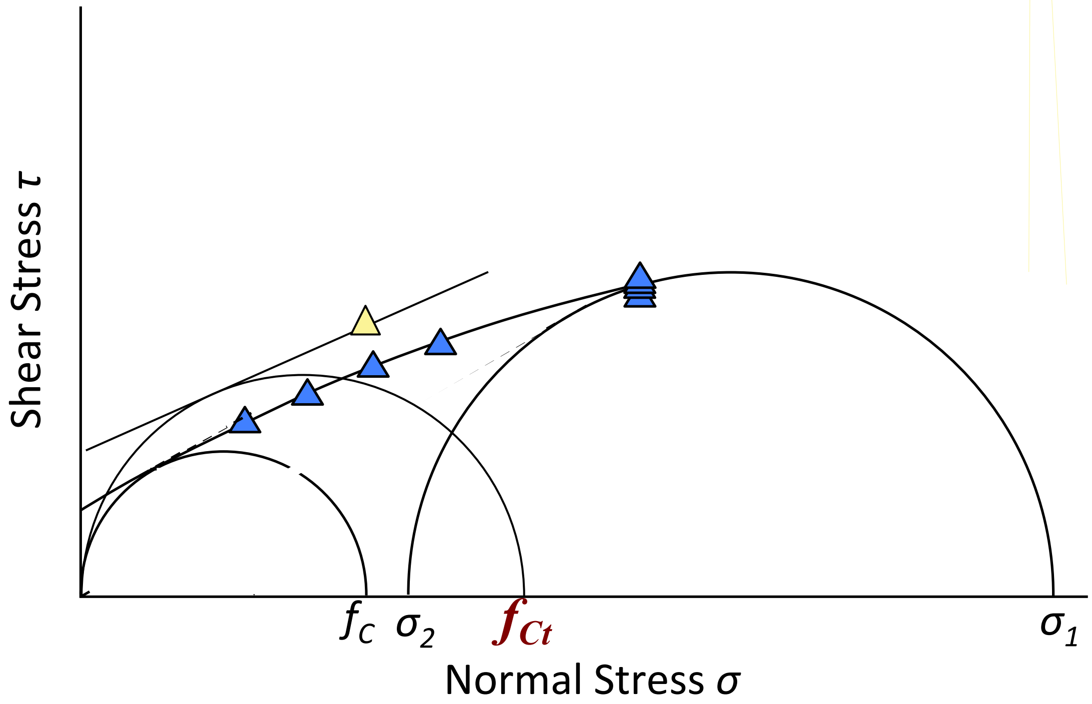


Time tests

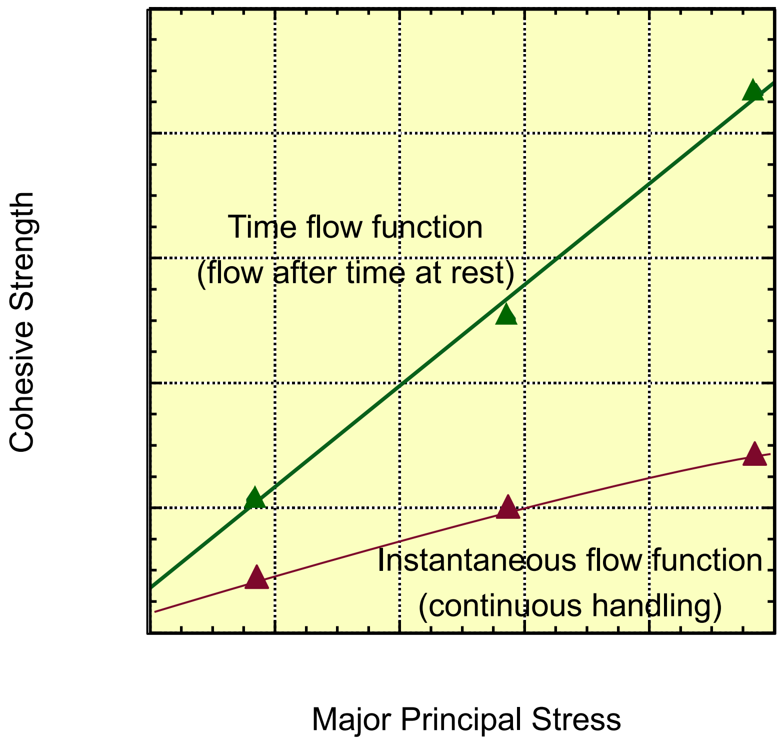

π/2
π/3
π/6
2π
11π/6
5π/3
3π/2
4π/3
7π/6
π
5π/6
2π/3


σss
Normal Stress σ
σ < σss
τss
steady-state flow
Shear Stress τ
incipient flow
Time

Time tests

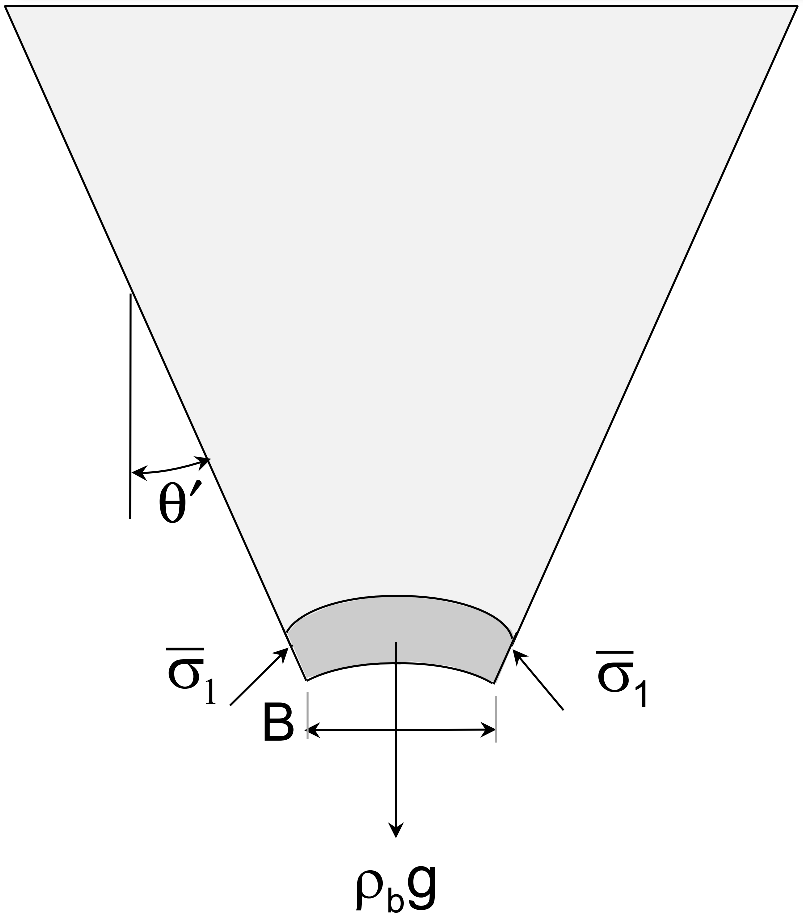


Time flow function



Arch stress

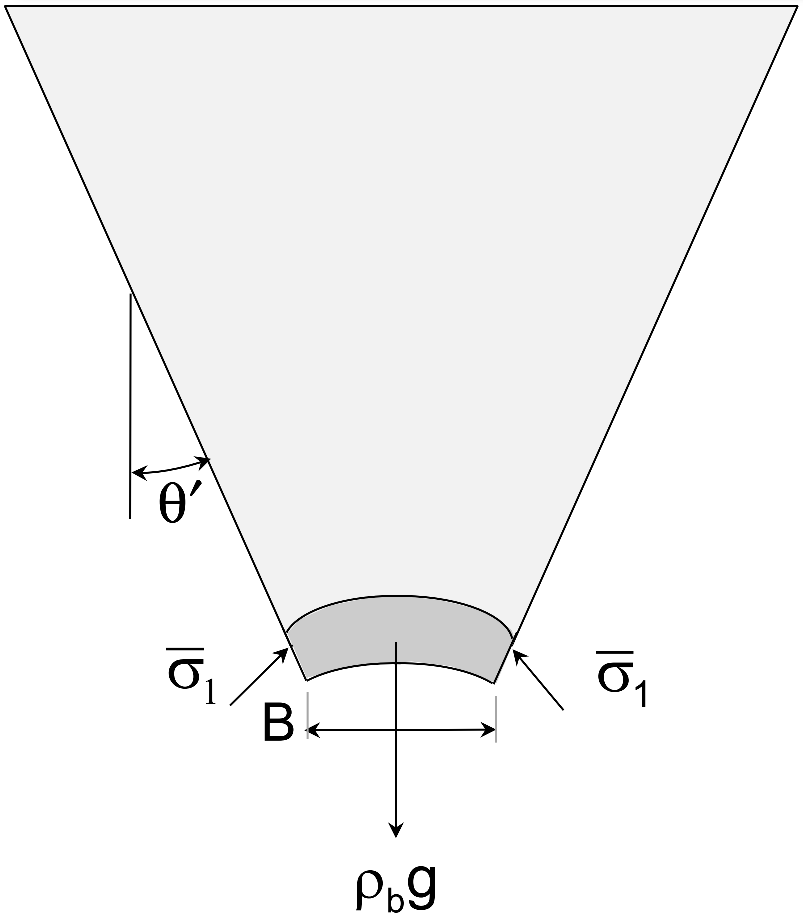
Arch stress



Stress on abutments of arch:

$$\boxed{\bar{\sigma}_1 \approx \frac{\rho_b g B}{2}}$$

Arch stress



Stress on abutments of arch:

$$\boxed{\bar{\sigma}_1 = \frac{\rho_b g B}{H(\theta')}}$$

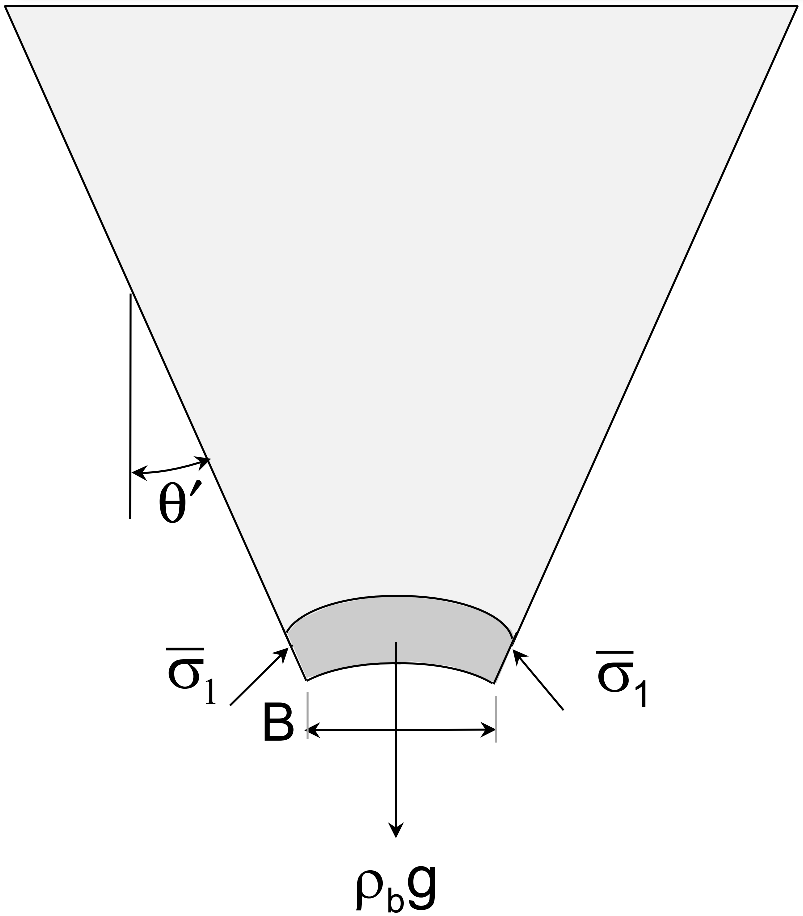
Conical:

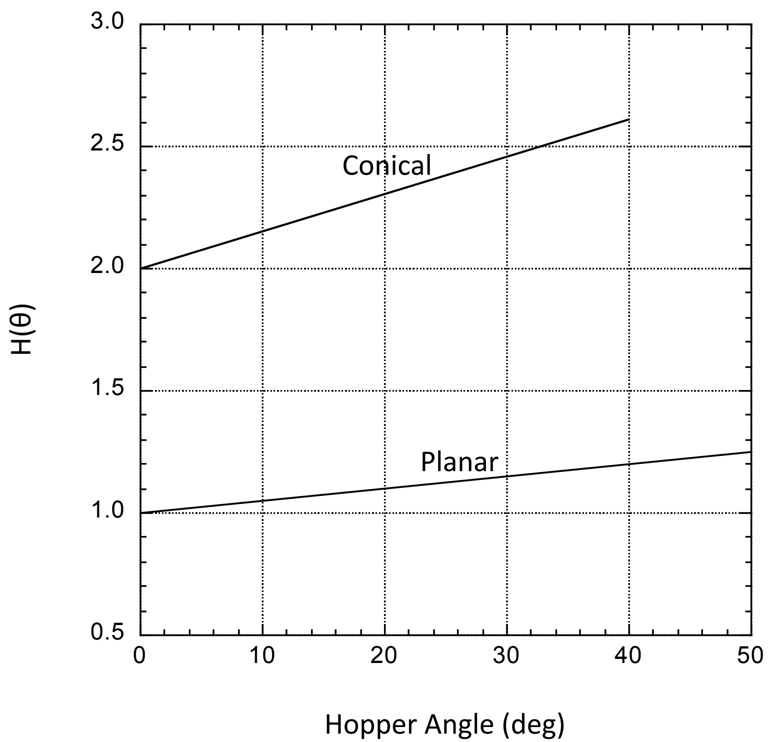
$$H(\theta') \approx 2$$

Slot:

$$H(\theta') \approx 1$$

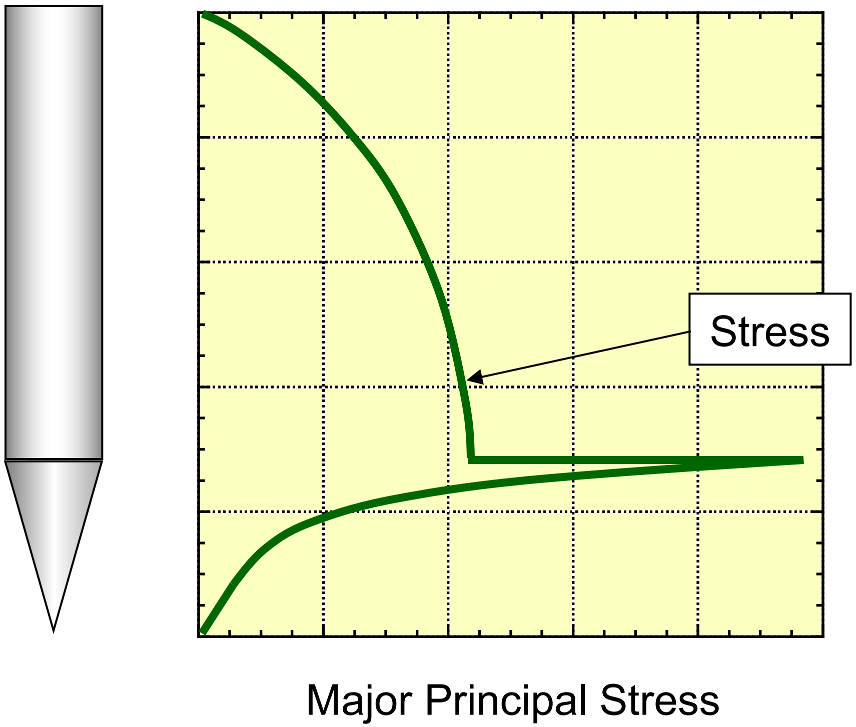
Arch stress



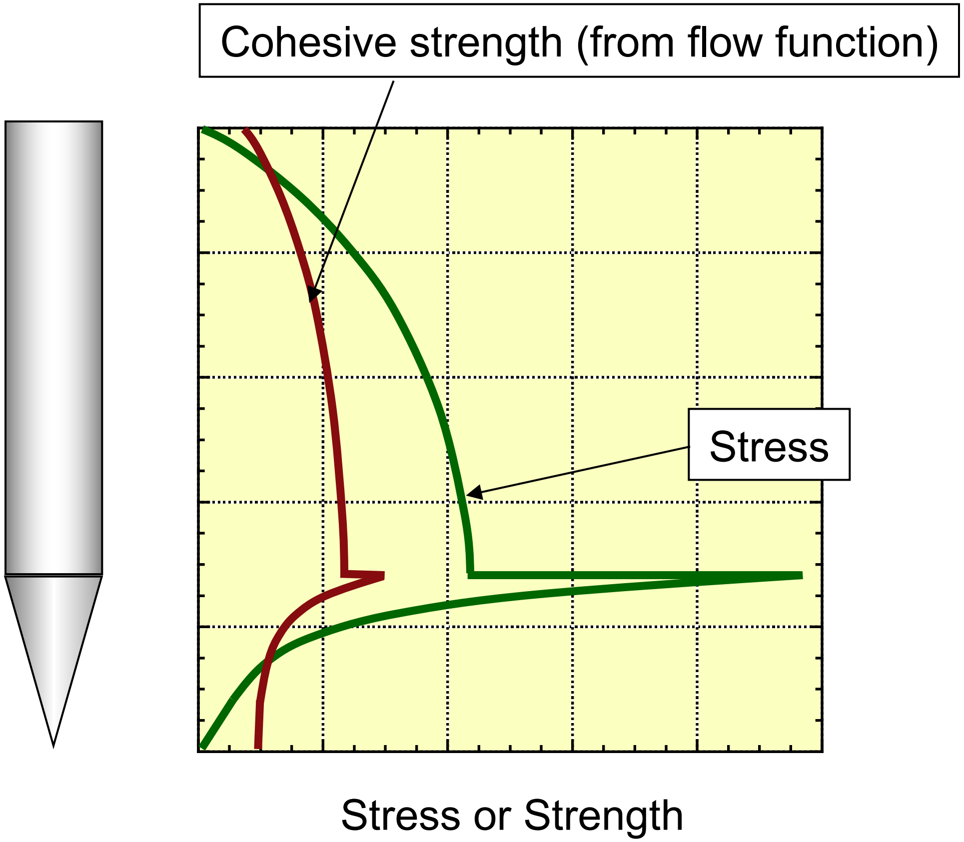


$$\bar{\sigma}_1 = \frac{\rho_b g B}{H(\theta')}$$

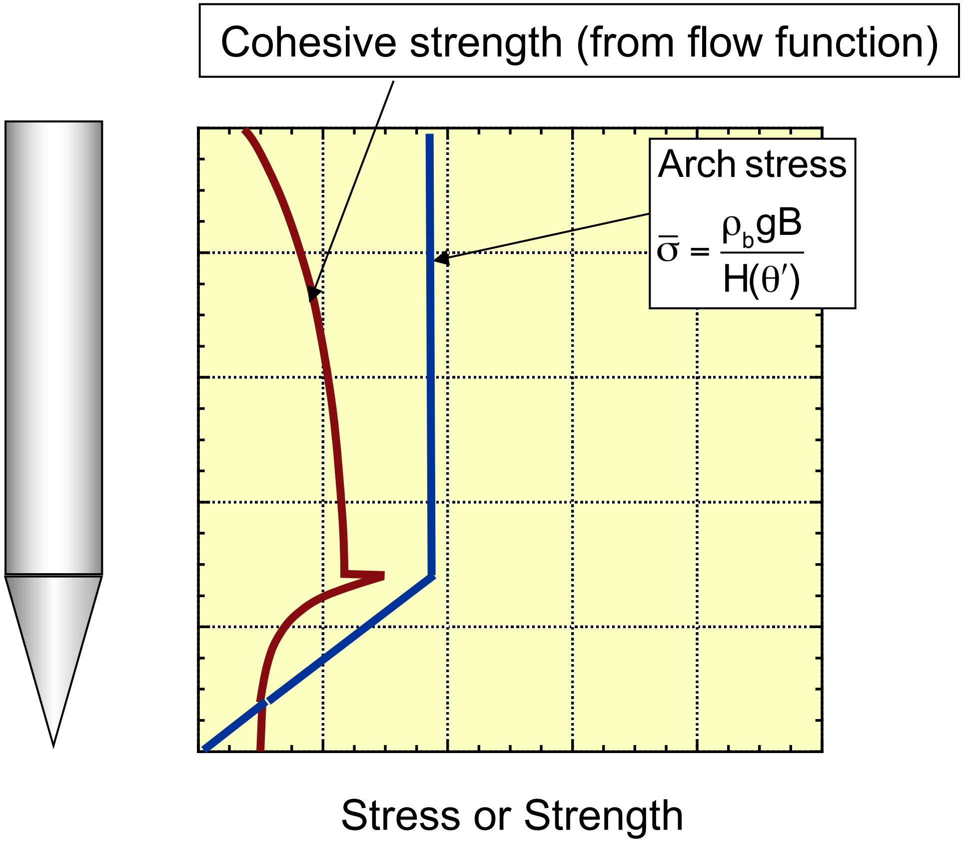
Pressure distribution



Cohesive strength

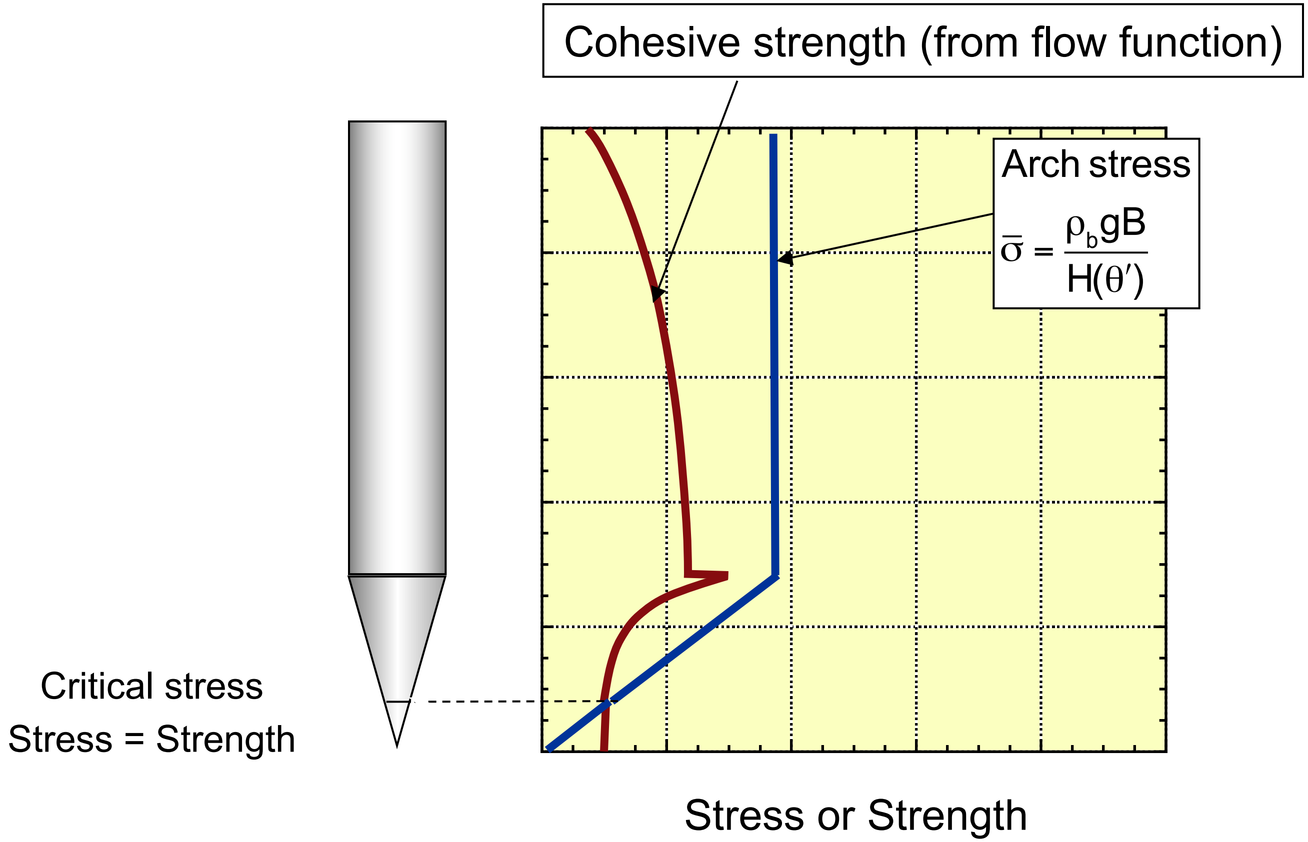


Arch stress



Cohesive strength (from flow function)
Arch stress
$\bar{\sigma} = \frac{\rho_b g B}{H(\theta')}$
Stress or Strength

Critical arching diameter

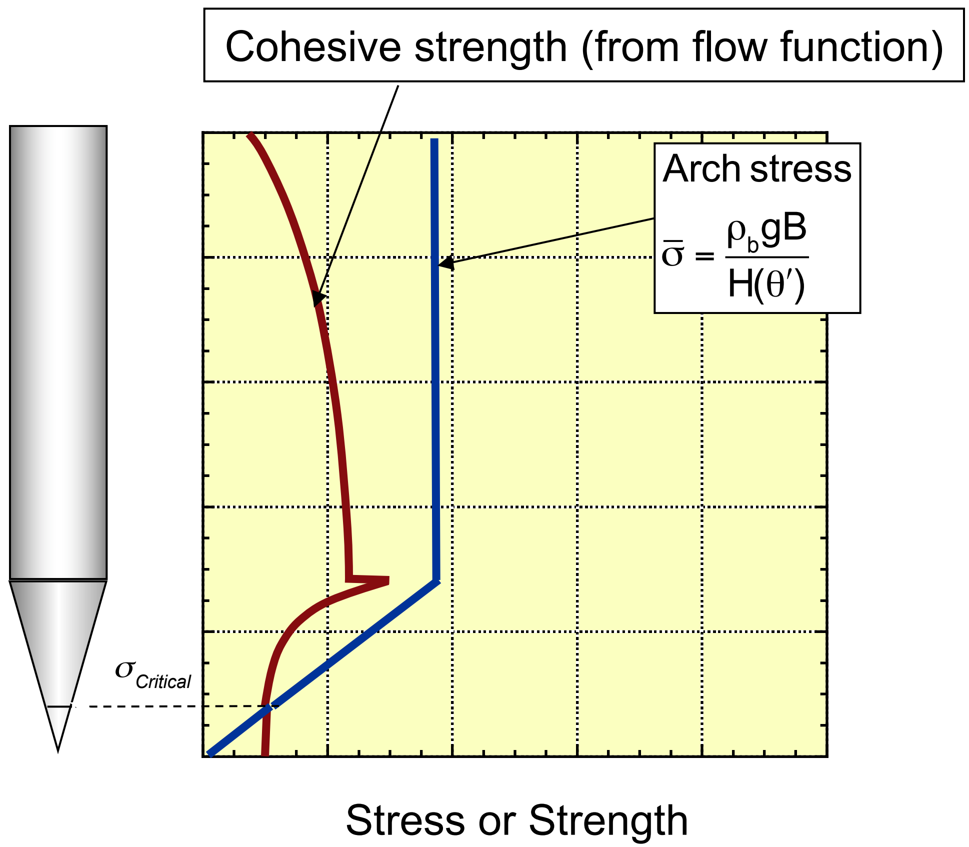


Critical arching diameter

$$B_{min} = \frac{H(\theta')\sigma_{Critical}}{\rho_b g}$$

Critical stress

Stress = Strength



Flow factor

- Flow function (FF)
  - Relationship between major principal stress and cohesive strength
- Flow factor (ff)
  - Ratio of major principal stress and arch supporting stress

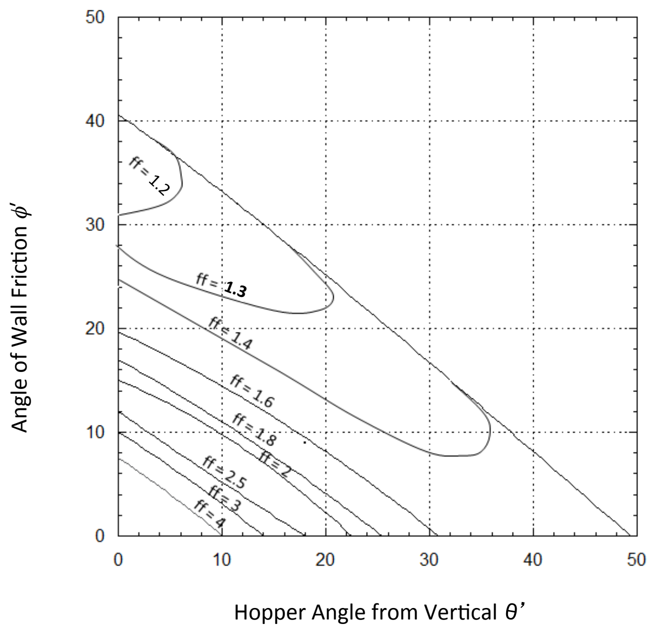
$$\text{ff} = \frac{\sigma_1}{\bar{\sigma}_1} = \frac{\text{major principal stress}}{\text{arch stress}}$$

Flow factor

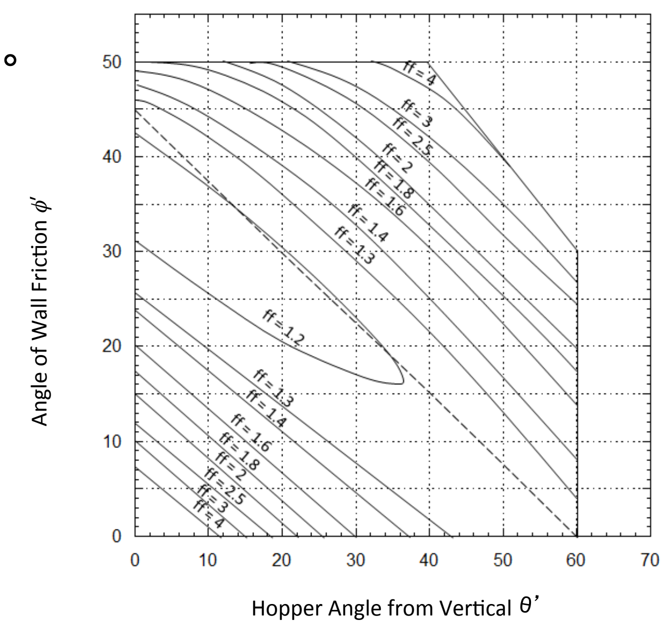
$$ff = \frac{\sigma_1}{\bar{\sigma}_1} = \frac{\text{major principal stress}}{\text{arch stress}}$$

$\delta = 50°$

Conical



Planar



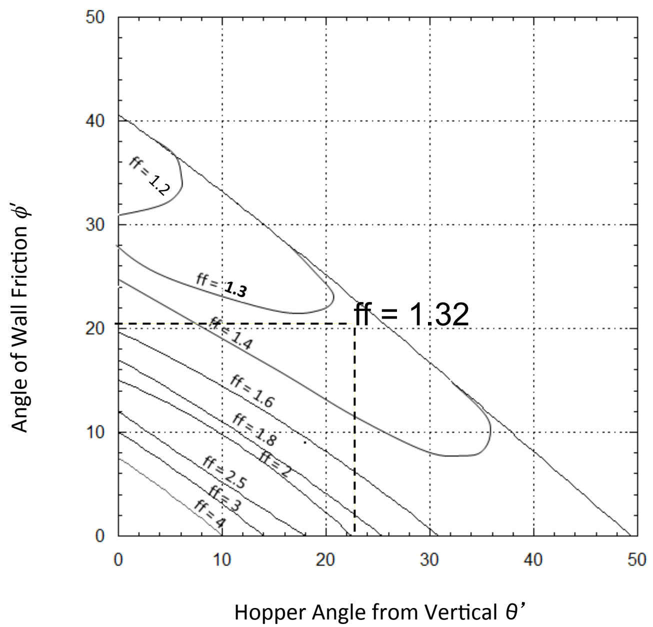
https://digital.library.unt.edu/ark:/67531/metadc1067072/m2/1/high_res_d/5240257.pdf

From Jenike Bulletin 123

Flow factor

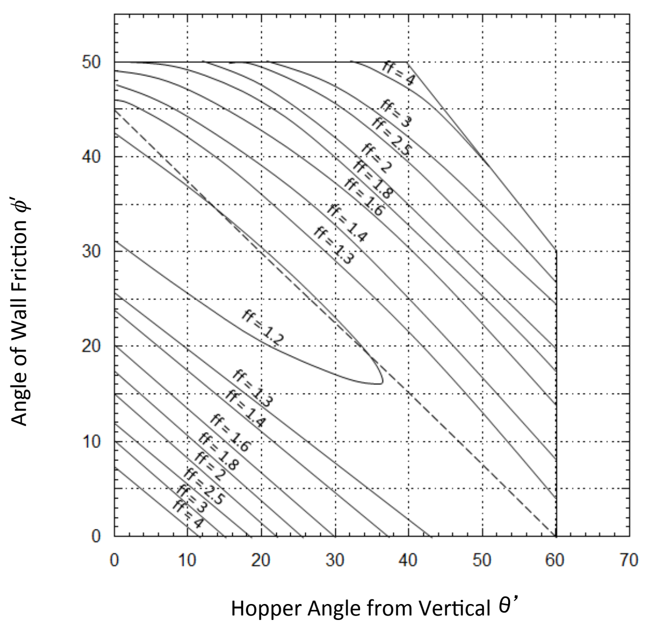
$$ff = \frac{\sigma_1}{\bar{\sigma}_1} = \frac{\text{major principle stress}}{\text{arch stress}}$$

Conical



$\delta = 50°$

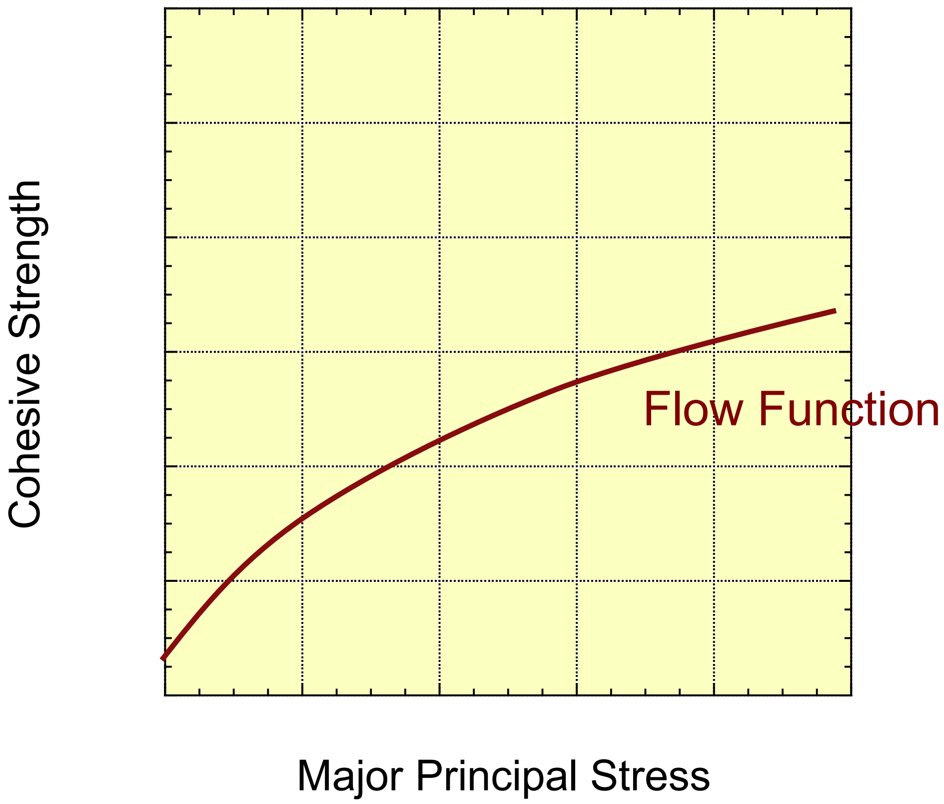
Planar



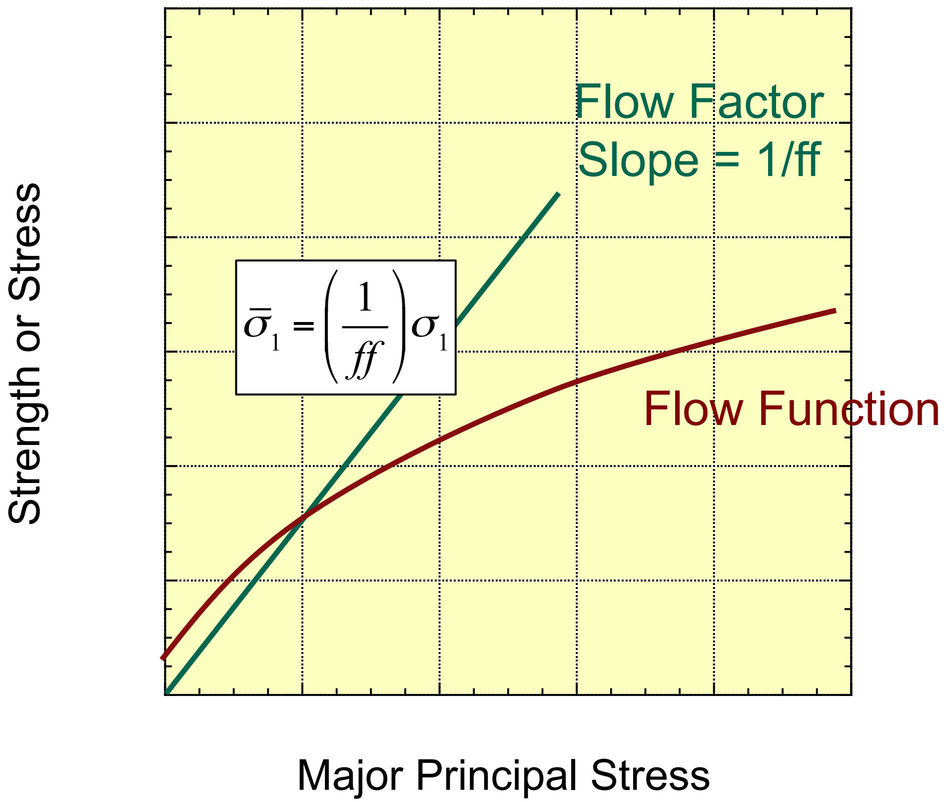
https://digital.library.unt.edu/ark:/67531/metadc1067072/m2/1/high_res_d/5240257.pdf

From Jenike Bulletin 123

Flow function



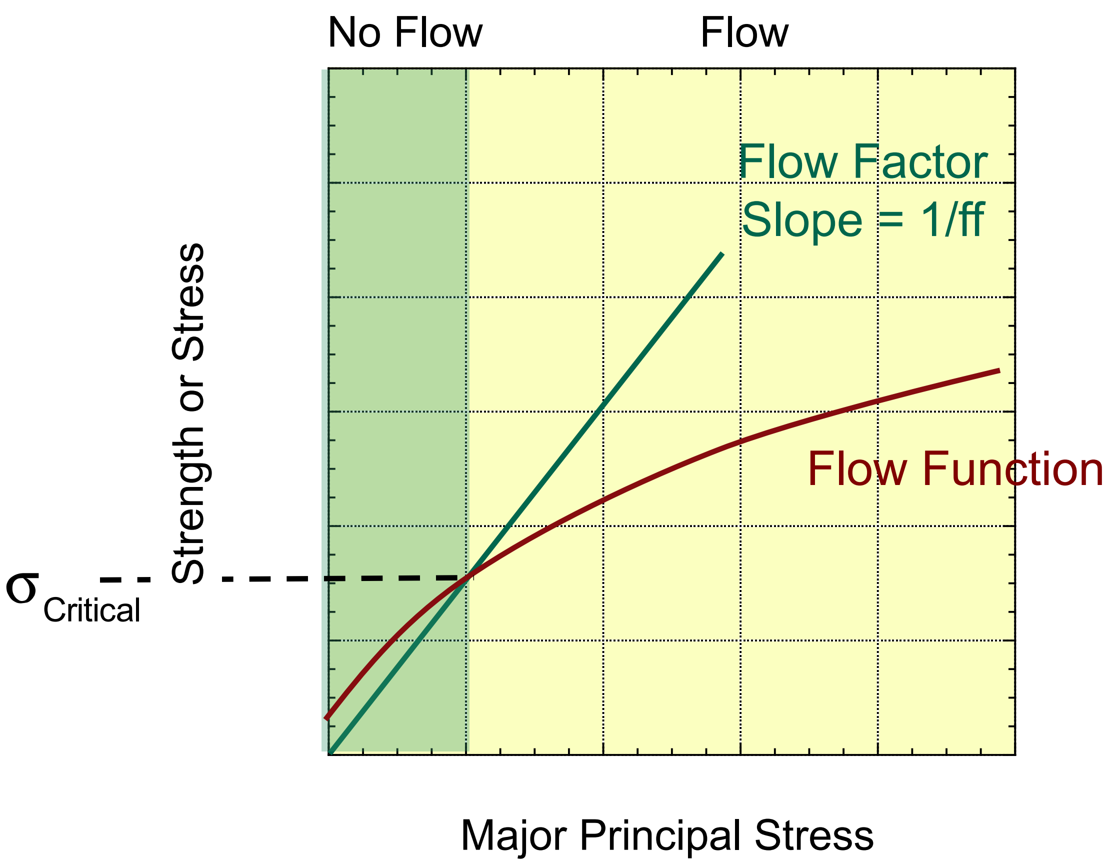
Flow factor



$$ff = \frac{\sigma_1}{\bar{\sigma}_1}$$

$$\bar{\sigma}_1 = \left(\frac{1}{ff}\right)\sigma_1$$

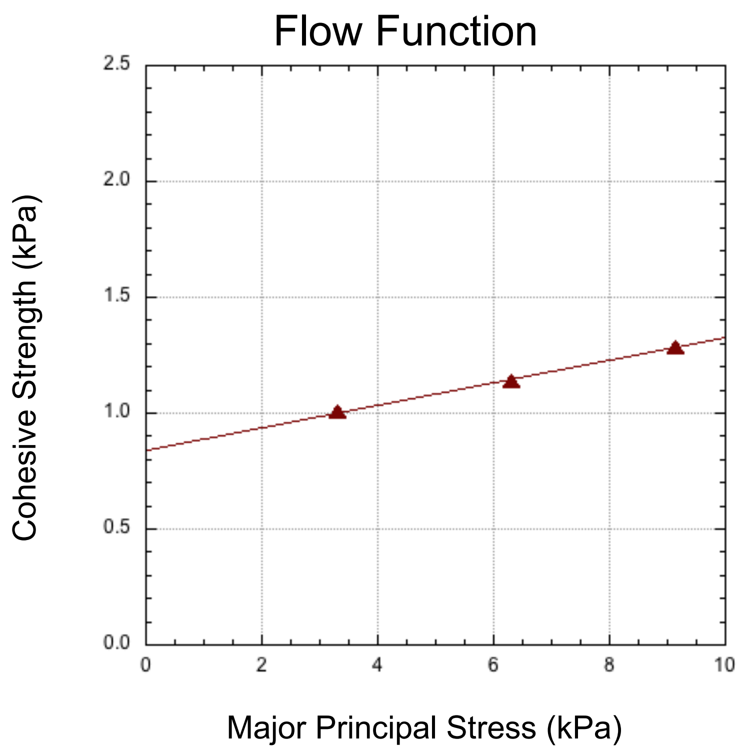
Critical stress

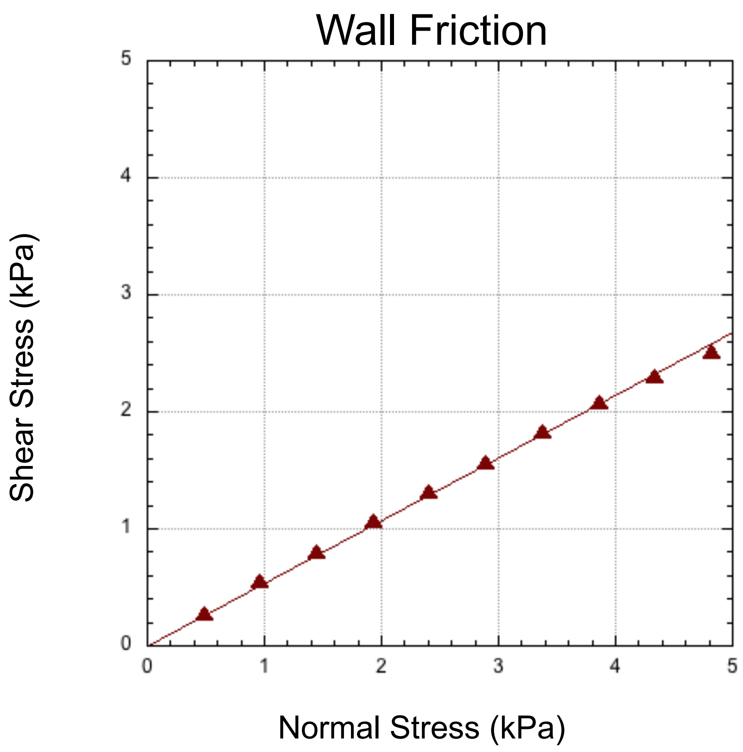


$$B_{min} = \frac{H(\theta')\sigma_{Critical}}{\rho_b g}$$

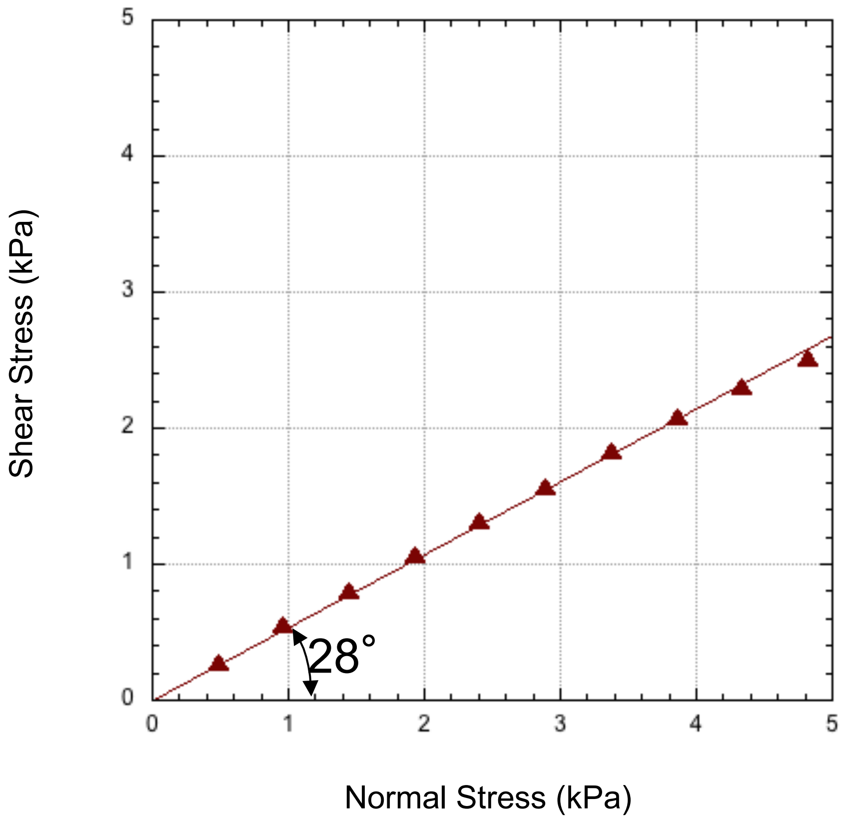
Example

Design a hopper that reliable handles 67/29/4 blend of acetaminophen/Avicel/hydroxypropyl cellulose

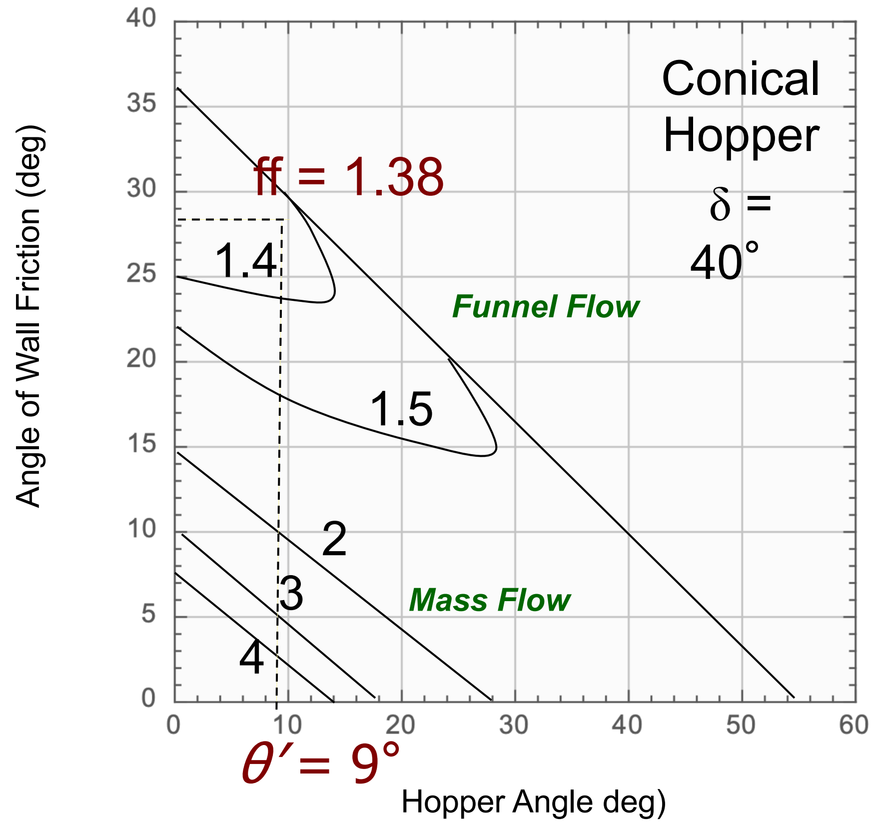




Example

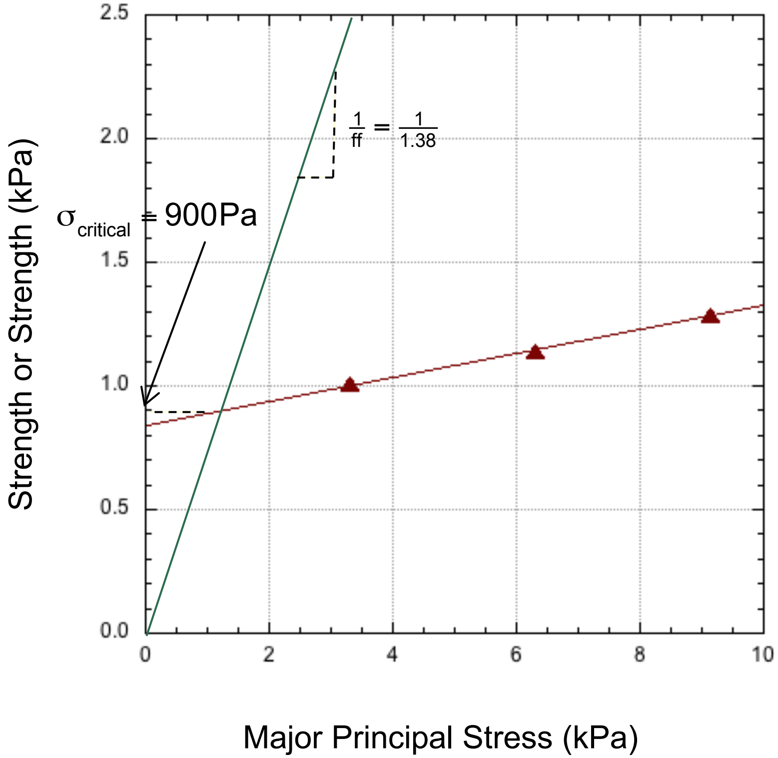


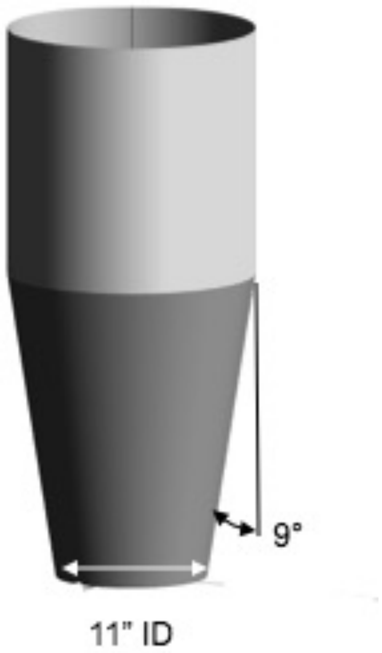
Shear Stress (kPa)
Normal Stress (kPa)
28°
0
1
2
3
4
5



Angle of Wall Friction (deg)
Hopper Angle deg)
Conical Hopper
δ = 40°
ff = 1.38
1.4
1.5
2
3
4
Funnel Flow
Mass Flow
θ′= 9°
0
5
10
15
20
25
30
35
40
50
60

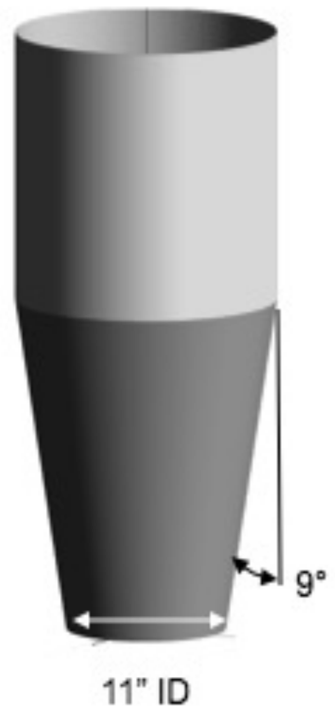
Example



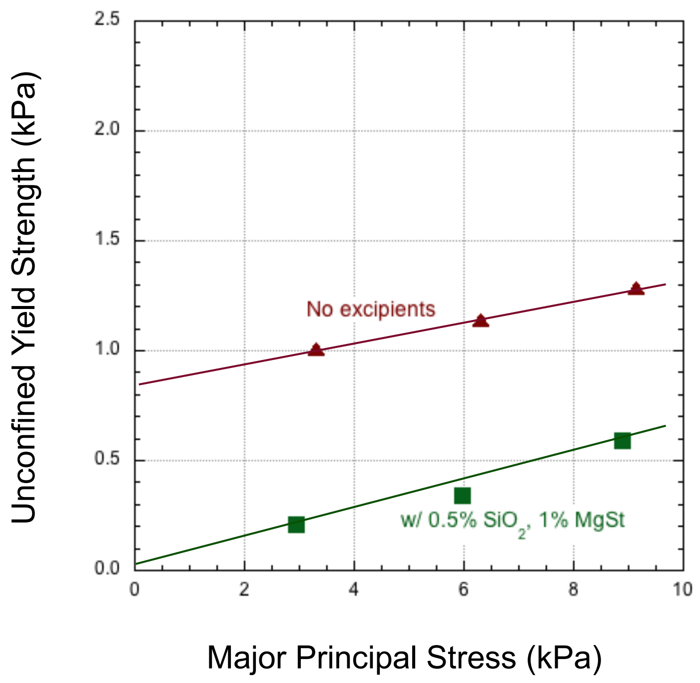


$$B_{\min} = \frac{H(\theta')\sigma_{Critical}}{\rho_b g} = \frac{(2.14)(900)}{(690)(9.8)} = 0.28 \text{ m} = 11 \text{ in.}$$

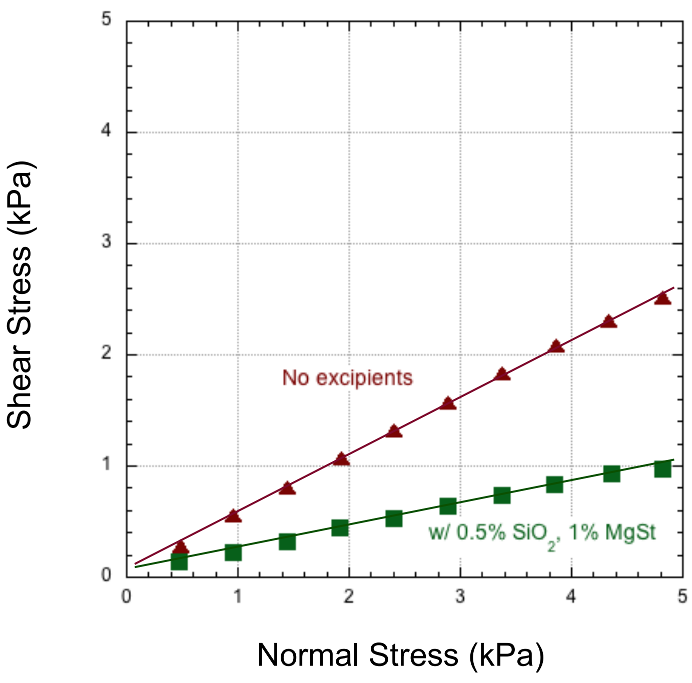
Example



Example

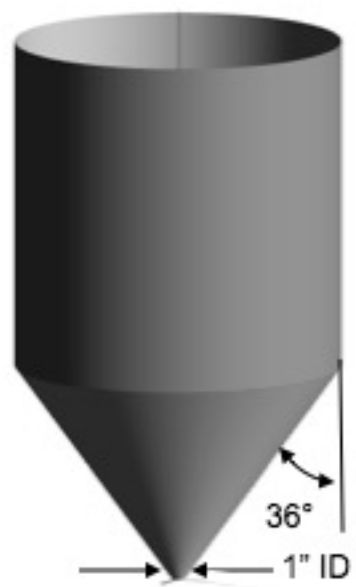


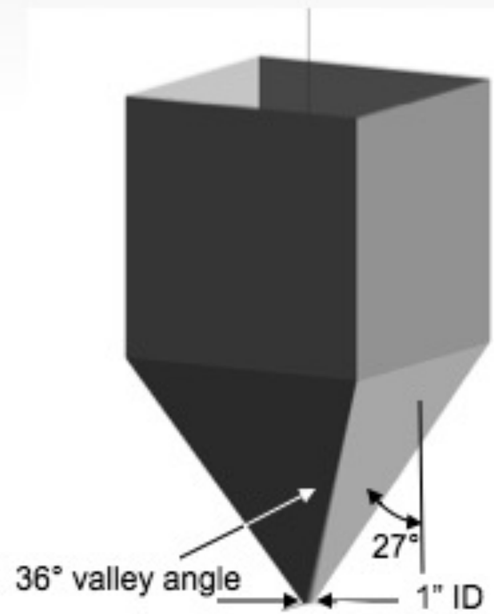
Unconfined Yield Strength (kPa)
2.5
2.0
1.5
1.0
0.5
0.0
0
2
4
6
8
10
No excipients
w/ 0.5% SiO_2, 1% MgSt
Major Principal Stress (kPa)



Shear Stress (kPa)
5
4
3
2
1
0
0
1
2
3
4
5
No excipients
w/ 0.5% SiO_2, 1% MgSt
Normal Stress (kPa)

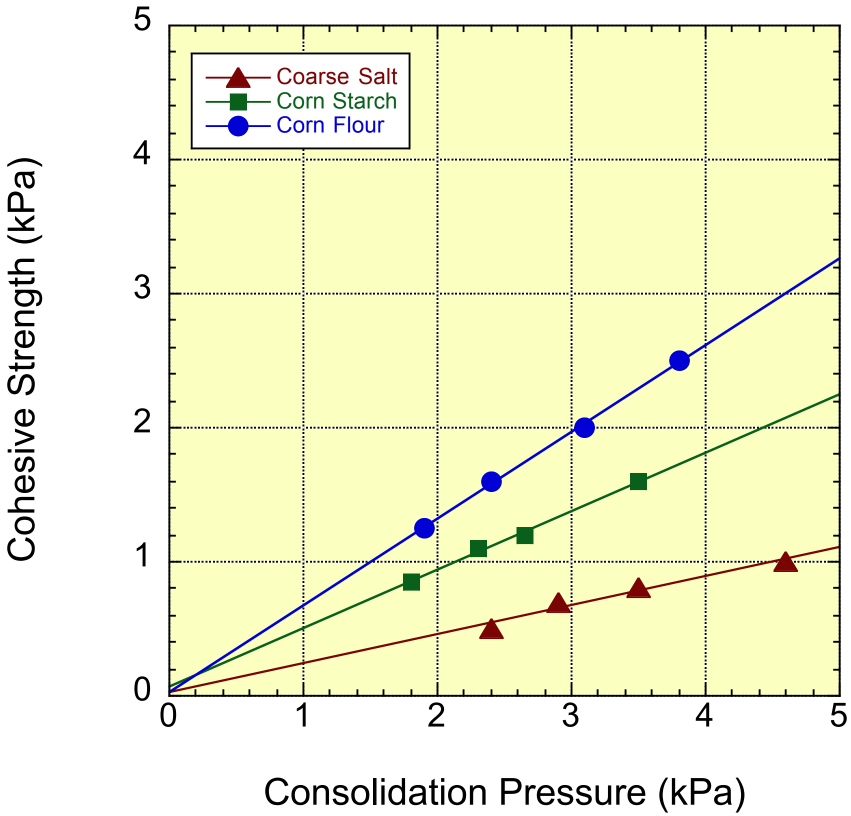
Example





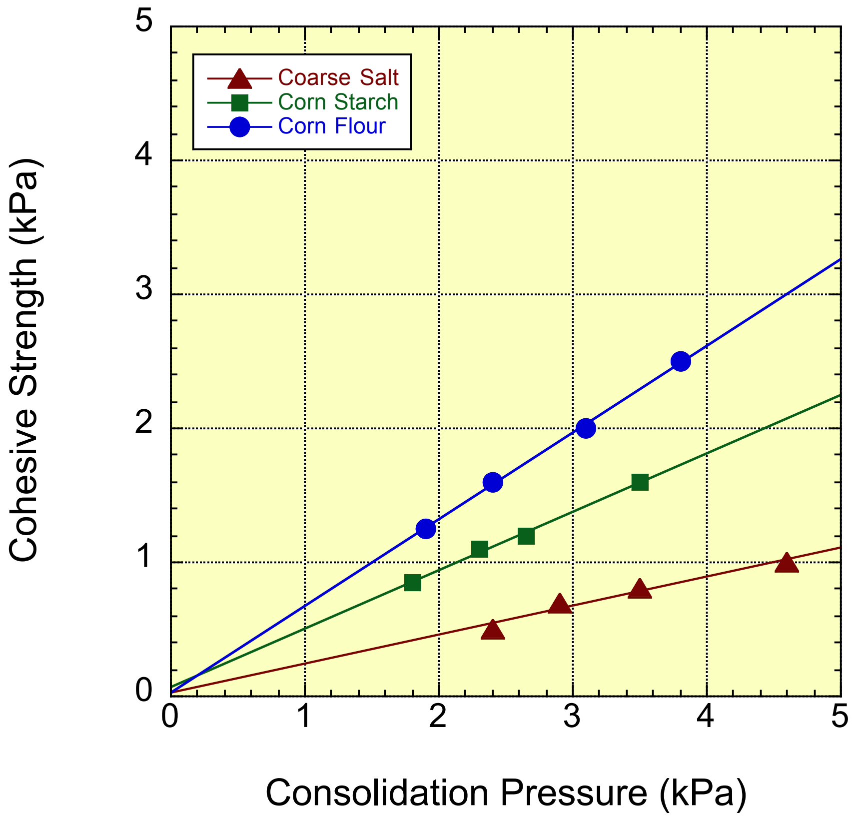
Note ♪: need to confirm outlet size will allow required discharge rate

Example

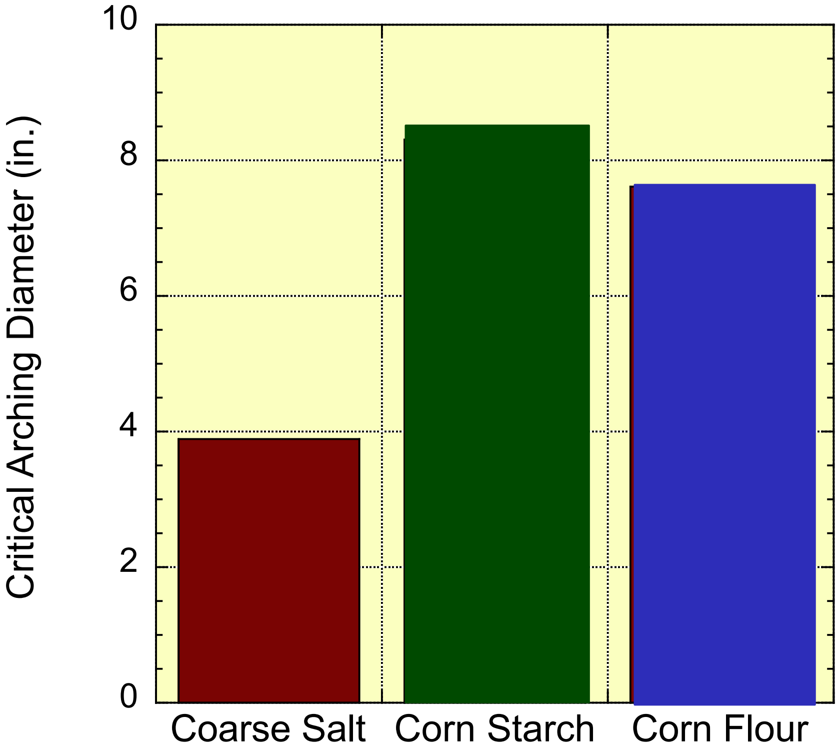


Coarse Salt
Corn Starch
Corn Flour
Cohesive Strength (kPa)
Consolidation Pressure (kPa)
0
1
2
3
4
5

Example



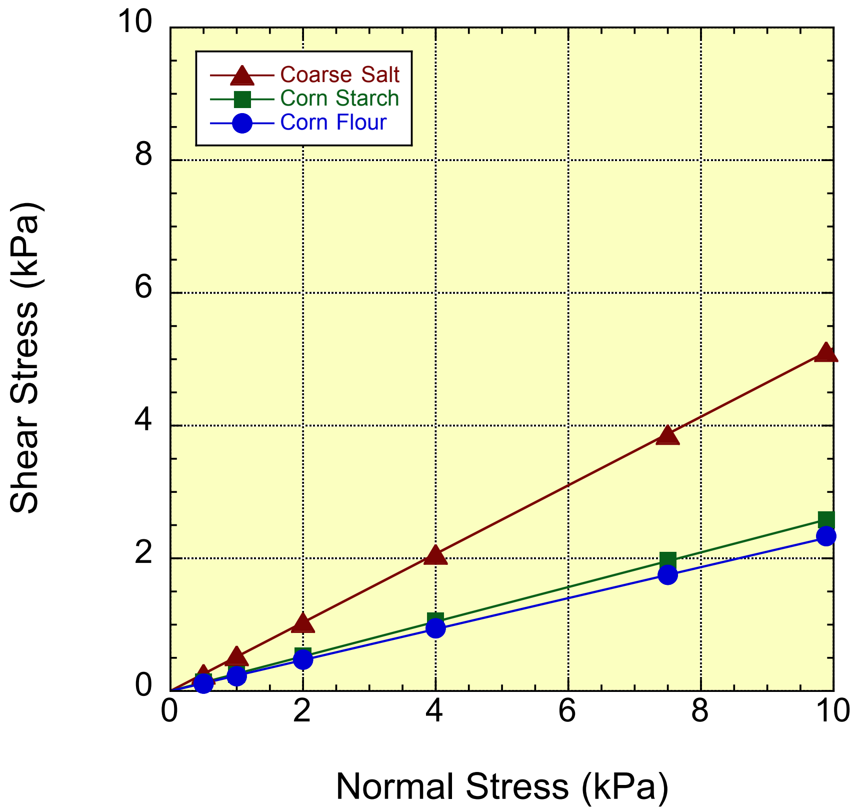
Cohesive Strength (kPa)
5
4
3
2
1
0
Coarse Salt
Corn Starch
Corn Flour
0
1
2
3
4
5
Consolidation Pressure (kPa)



Critical Arching Diameter (in.)
10
8
6
4
2
0
Coarse Salt
Corn Starch
Corn Flour

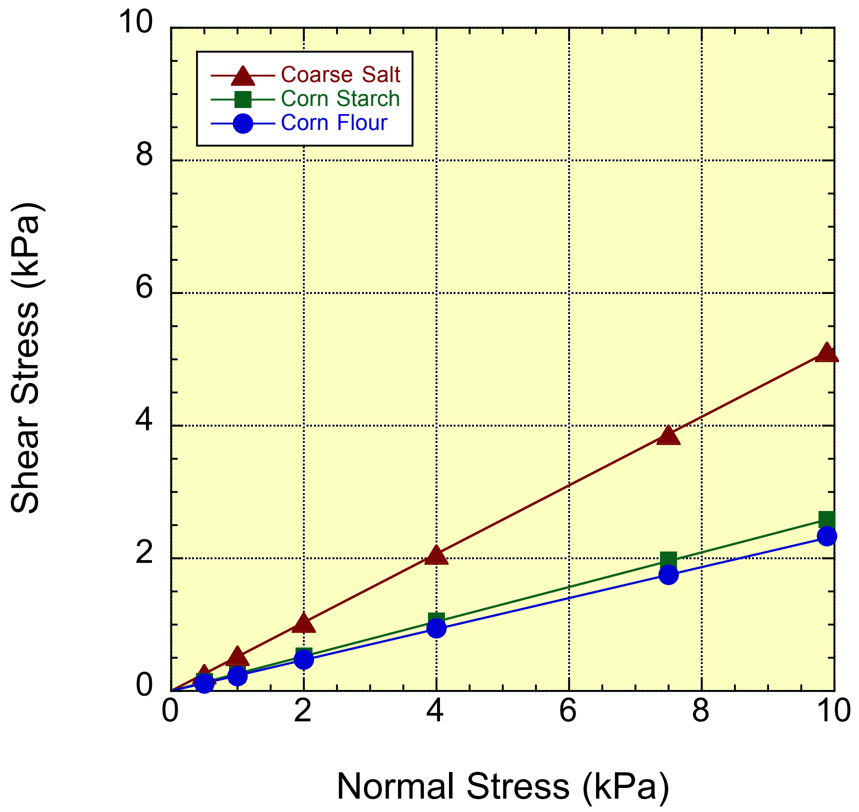
GM&A

Example

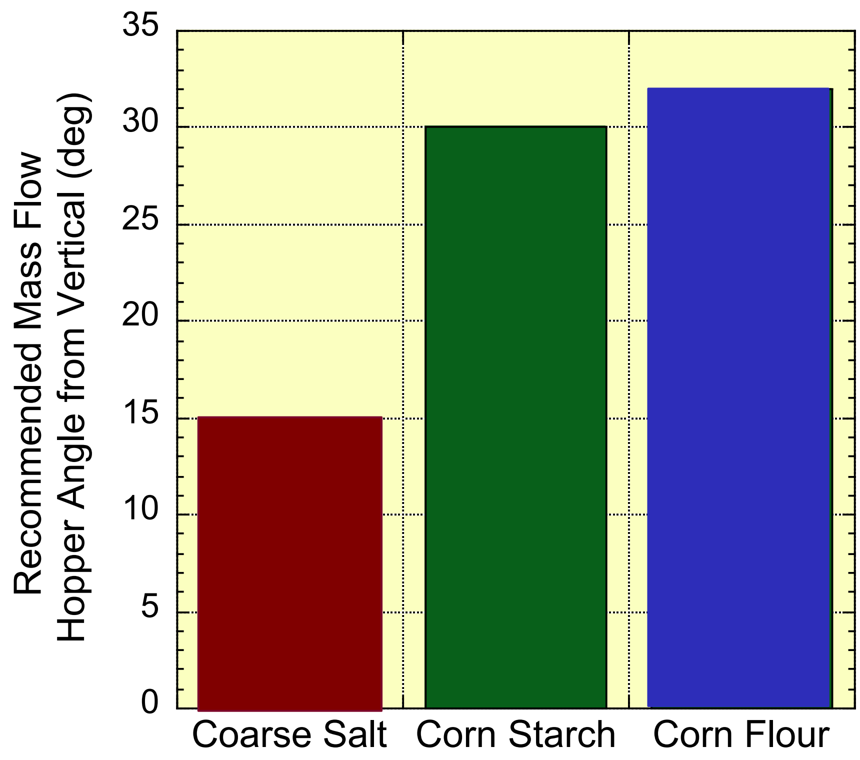


Coarse Salt
Corn Starch
Corn Flour
Shear Stress (kPa)
Normal Stress (kPa)
0
2
4
6
8
10

Example



10
8
6
4
2
0
0
2
4
6
8
10
Coarse Salt
Corn Starch
Corn Flour
Shear Stress (kPa)
Normal Stress (kPa)



35
30
25
20
15
10
5
0
Recommended Mass Flow
Hopper Angle from Vertical (deg)
Coarse Salt
Corn Starch
Corn Flour

Complications

- Bulk density, cohesive strength, wall friction, and internal friction depend on solids stress
- Choice of regression model affects outcome
- Stresses at outlet are important
- Major principal stress is not equal to wall stress
- Mass flow hopper angle depends on outlet size
- Feeder selection is important
- There is always more than one answer

2002 Albuturol recall

- Schering-Plough
  - 59 million asthma inhalers recalled
  - Unknown number contained no AI (albuterol)
  - $500,000,000 fine

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- WSJ September 9, 2003:

  "The pharmaceutical industry has a little secret: Even as it invents futuristic new drugs, its manufacturing techniques lag far behind those of potato-chip and laundry-soap makers."

Flow and Storage of Powders

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