A 3D ANALYTICAL MODEL FOR LINEAR ROCK CUTTING PROCESS

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- Analytical models from the past
- Experiments
- Data analysis
  - Determine failure mode
  - Compare results with model
  - Introduce 3 component model
- Conclusions and recommendations

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Introduction

Dredging: sand, clay and/or rock

‘Mining sediment from sea floor, transport and dump it’

Sand	Clay	Rock
Loose particles	Loose particles	Bonded grains
0.06mm<D<2mm	D<0,06mm	D>25cm

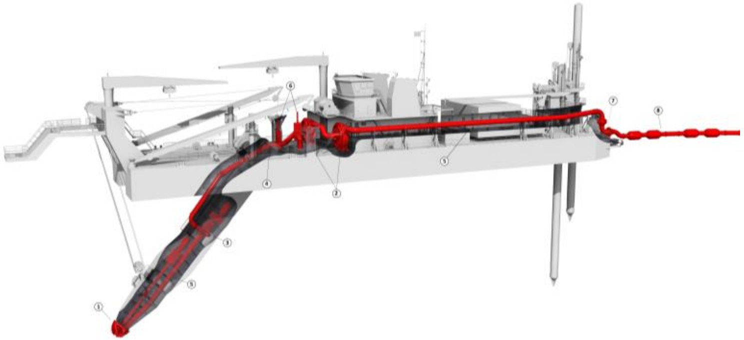
- Hard to predict cutting forces
  - Energy consumption (€ € €)
  - Dredging method (time = € € €)

http://escape.sg

https://beeldbank.rws.nl/

Introduction

- Dredging: how?



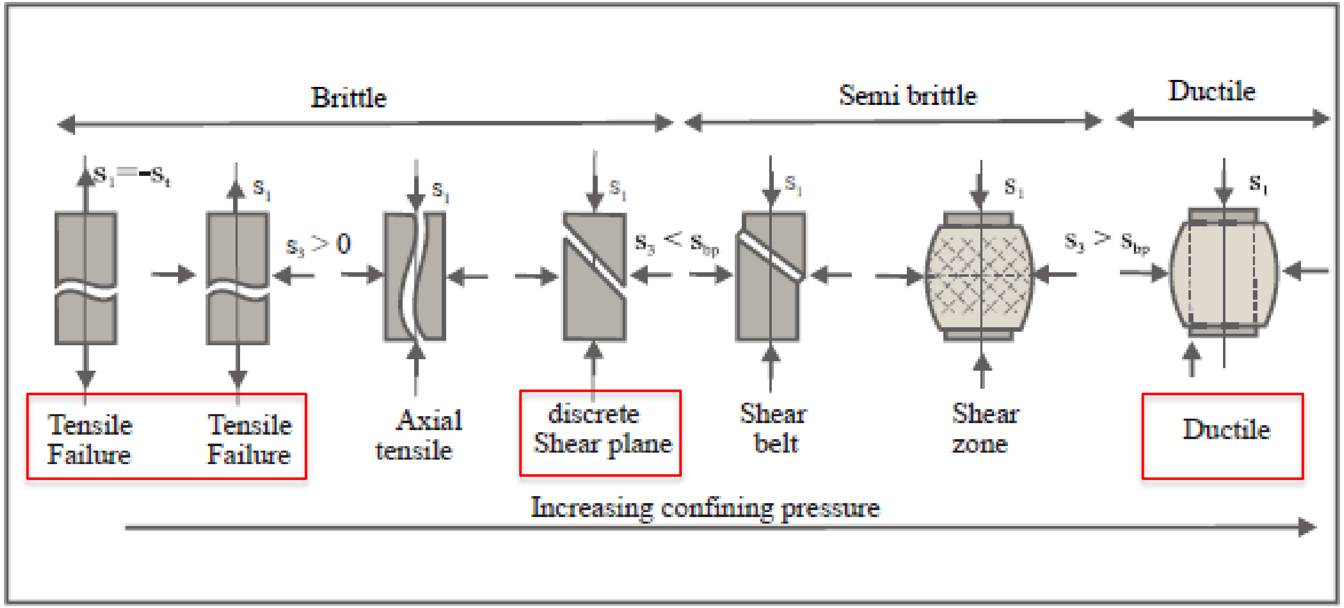
https://www.royalihc.com

https://www.royalihc.com

Let's see how rock cutting force is calculated

Cutting force prediction models

- Failure modes

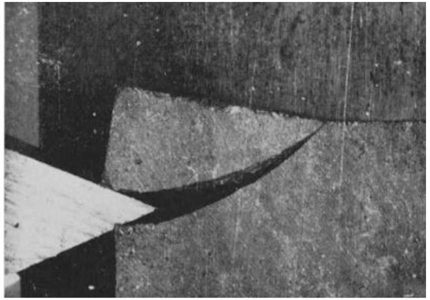


Cutting of rock, Vlasblom (2007)

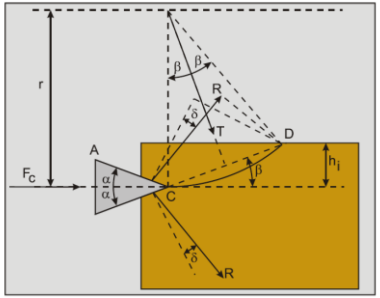
Cutting force prediction models

- The Evans Model (Tensile crack)
  - Sharp tool
  - 2D process
  - Brittle tensile → σ_t (=BTS)

    → β = crack angle (Tensile)



Evans (1964)

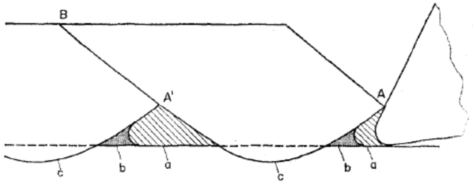


DSCRCM, Miedema (2014)

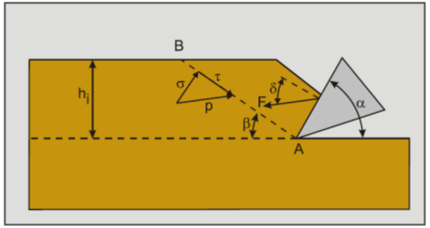
$$F_c = \sigma_T \cdot h_i \cdot w \cdot \frac{2 \cdot \sin(\alpha + \delta)}{1 - \sin(\alpha + \delta)}$$

Cutting force prediction models

- The Nishimatsu Model (Shear crack)
  - Sharp tool
  - 2D process
  - Brittle shear → *c*



Nishimatsu (1971)



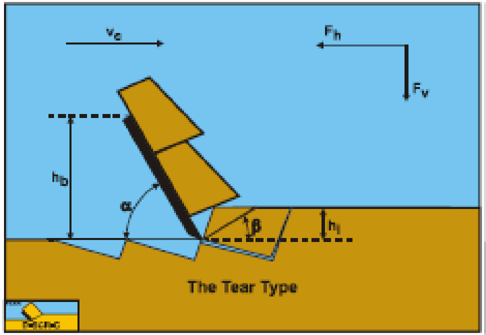
DSCRCM, Miedema (2014)

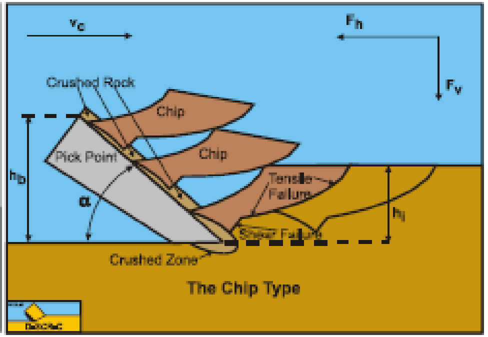
$$F_h = \frac{1}{(n+1)} \cdot \frac{c \cdot h_i \cdot w \cdot \cos(\varphi) \cdot \sin(\alpha + \delta)}{\sin(\beta) \cdot \sin(\alpha + \beta + \delta + \varphi)}$$

$$F_v = \frac{1}{(n+1)} \cdot \frac{c \cdot h_i \cdot w \cdot \cos(\varphi) \cdot \cos(\alpha + \delta)}{\sin(\beta) \cdot \sin(\alpha + \beta + \delta + \varphi)}$$

Cutting force prediction models

- The Tear/Chip Model
  - Sharp tool
  - 2D process
  - Brittle shear → *c*





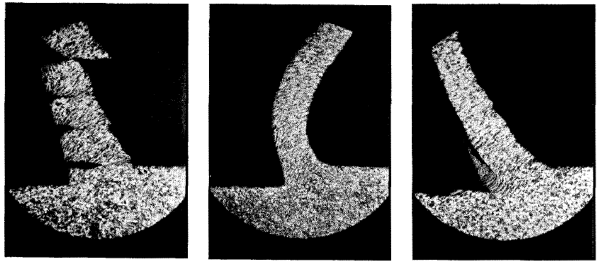
$$F_h = \frac{2 \cdot c_m \cdot h_i \cdot w \cdot \cos(\varphi) \cdot \sin(\alpha + \delta)}{1 + \cos(\alpha + \delta + \varphi)}$$

$$F_v = \frac{2 \cdot c_m \cdot h_i \cdot w \cdot \cos(\varphi) \cdot \cos(\alpha + \delta)}{1 + \cos(\alpha + \delta + \varphi)}$$

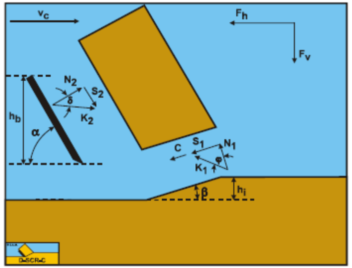
DSCRCM, Miedema (2014)

Cutting force prediction models

- The Flow Model
  - Sharp tool crushing the surface
  - 2D process
  - Ductile → c



Merchant (1945)



DSCRCM, Miedema (2014)

$$F_h = \frac{\lambda \cdot c \cdot h_i \cdot w \cdot \cos(\varphi) \cdot \sin(\alpha + \delta)}{\sin(\beta) \cdot \sin(\alpha + \beta + \delta + \varphi)}$$

$$F_v = \frac{\lambda \cdot c \cdot h_i \cdot w \cdot \cos(\varphi) \cdot \cos(\alpha + \delta)}{\sin(\beta) \cdot \sin(\alpha + \beta + \delta + \varphi)}$$

How good is the prediction?

- We can do some experiments
- Dredging: rock cutting with multiple rotating cutting teeth
  - Difficult: start from the beginning
    - Single pick point
    - Linear cutting

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Research Procedure

- Determine rock characteristics
- Conduct linear cutting experiments
- Validate existing calculation models
- Improve the calculation models

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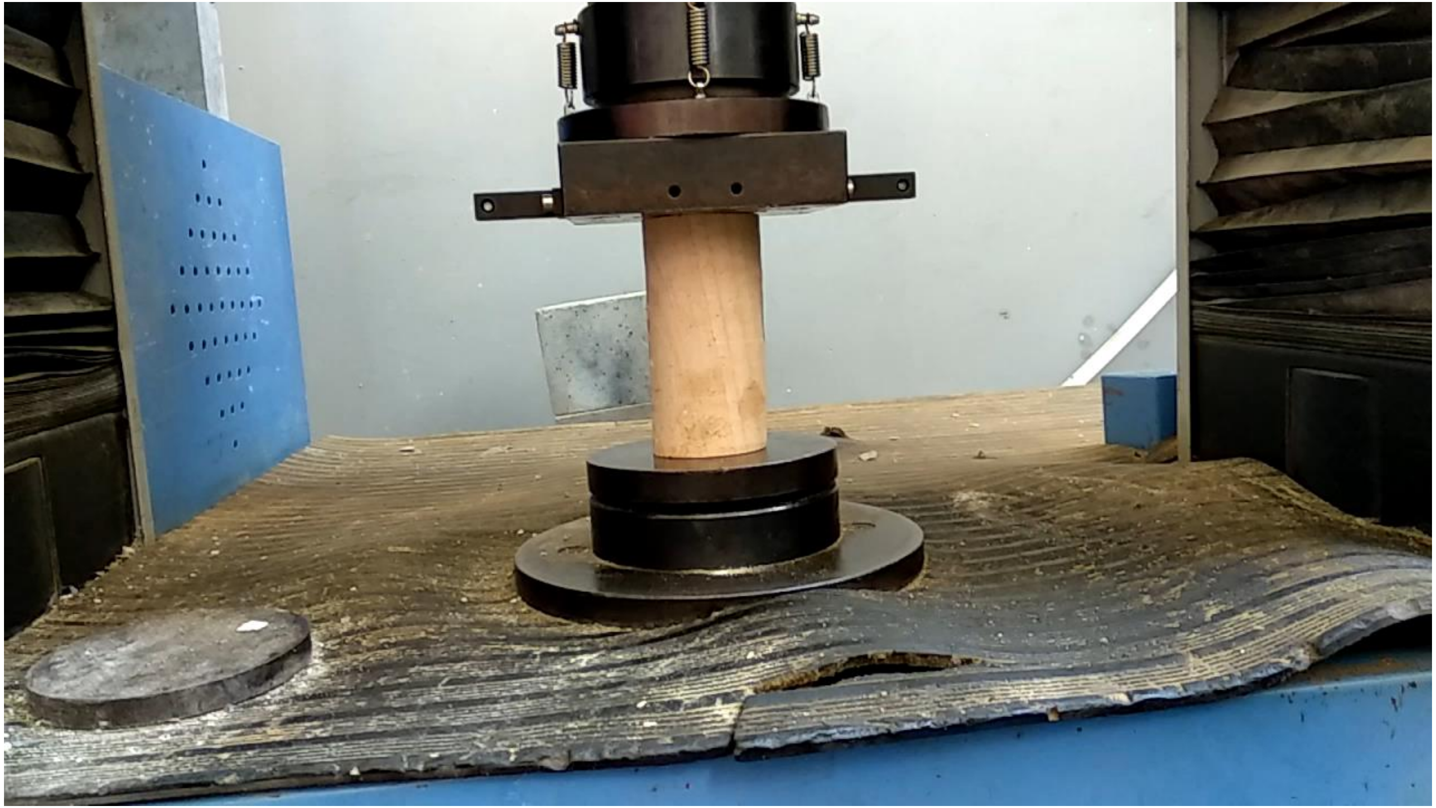
Rock characteristics

- Sandstone
- 210x53x12 cm

Uniaxial compression tests



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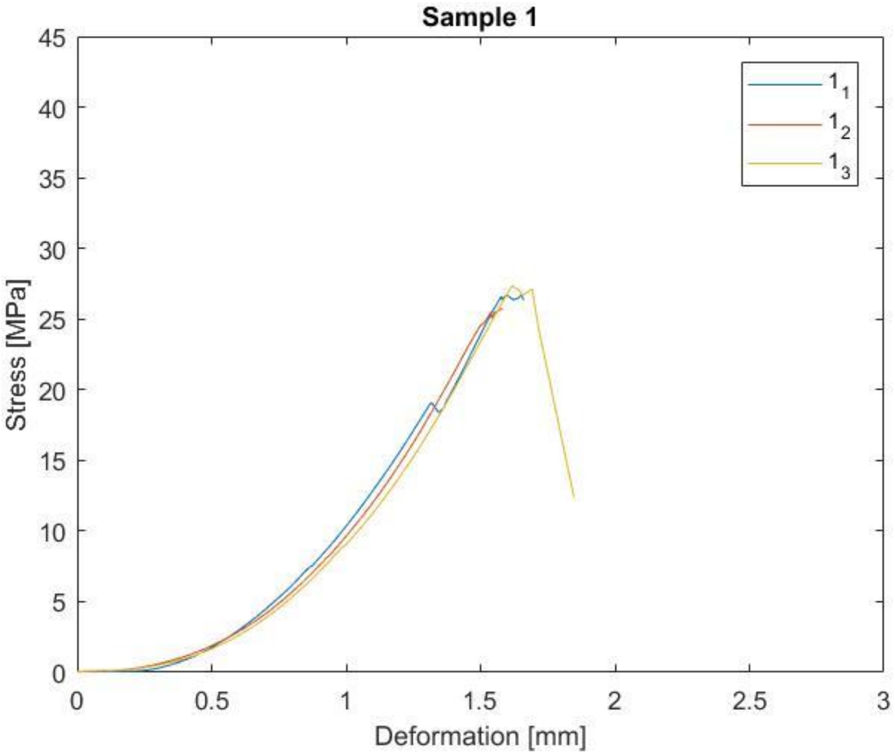
Uniaxial compression tests



$\sigma = F/A$

$\sigma_{max} = UCS$

$UCS1_1 = 26.7$ MPa

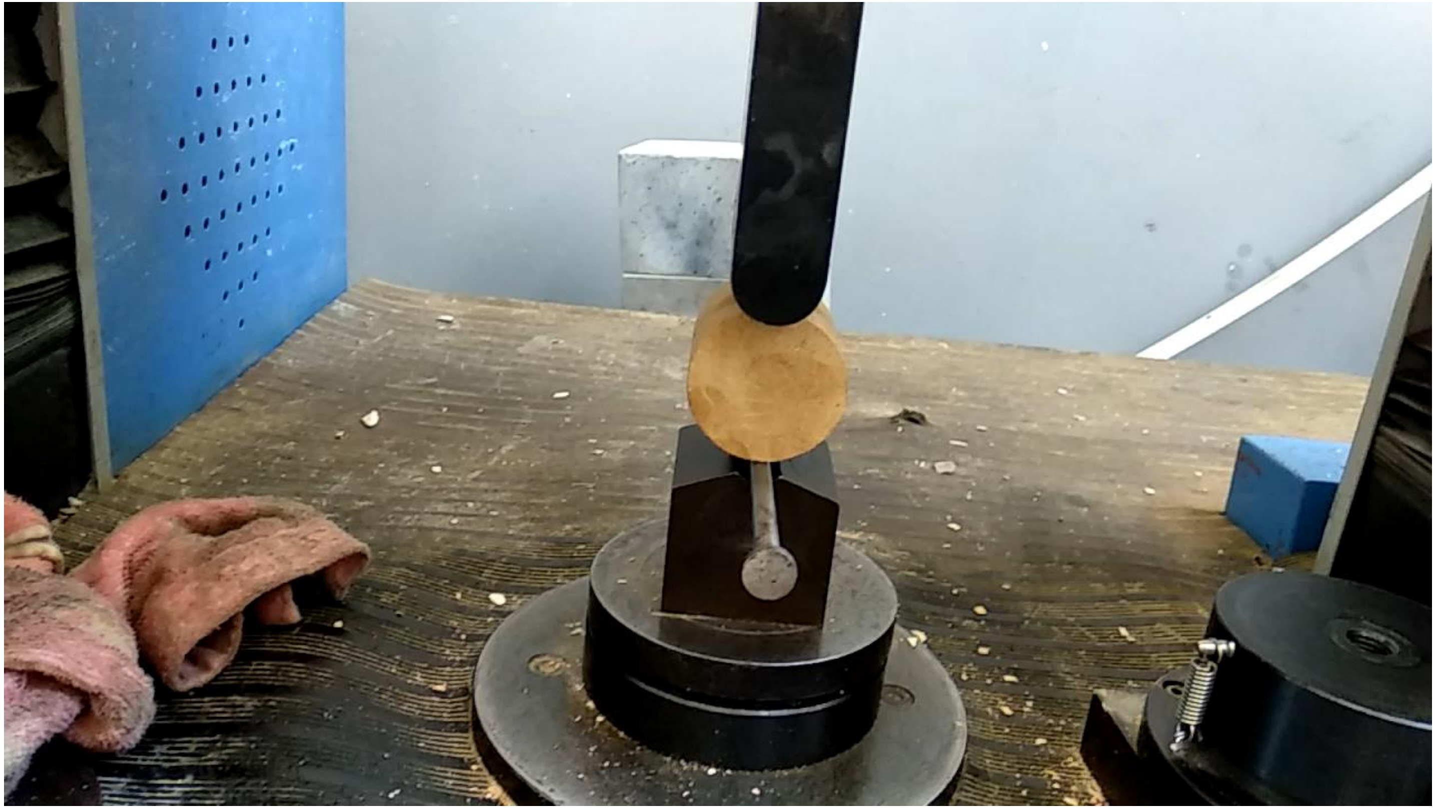
$UCS1_2 = 25.7$ MPa

$UCS1_3 = 27.3$ MPa

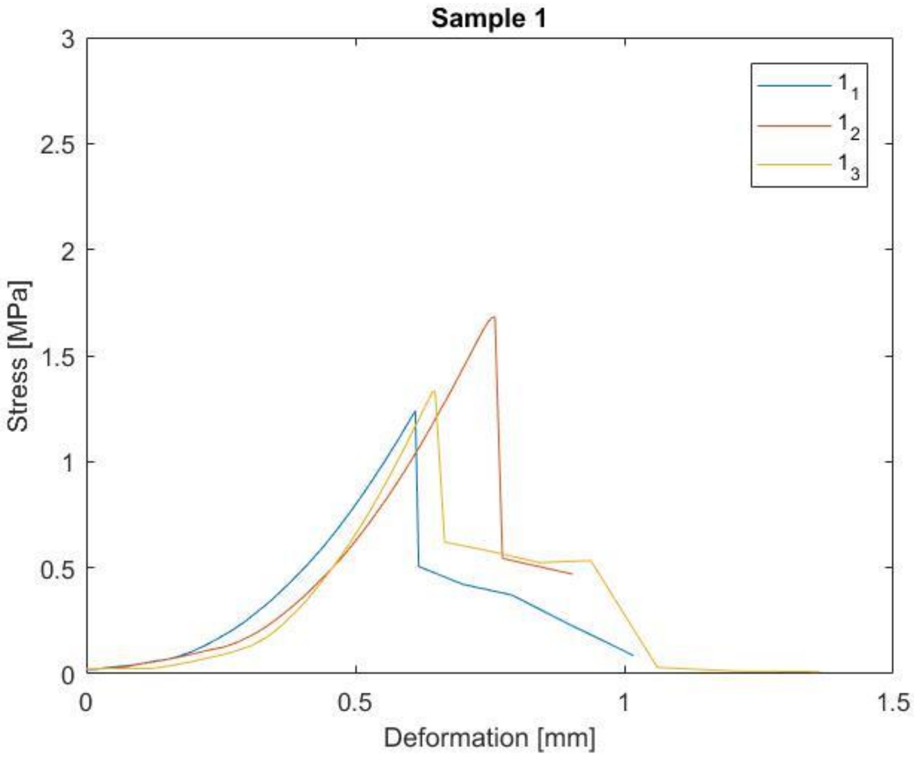
Average:

UCS1 = 26.6 MPa

Brazilian Tensile tests



Brazilian Tensile tests



$\sigma = (2*F)/(\pi*D*L)$
$\sigma_{max} = BTS$

$BTS1_1 = 1.2$ MPa
$BTS1_2 = 1.7$ MPa
$BTS1_3 = 1.3$ MPa

Average:
BTS1 = 1.4 MPa

Hoek-Brown Failure Criterion

- Internal friction angle (*φ'*)

$$\phi' = \sin^{-1}\left(\frac{6am_b(s+m_b\sigma_{3n})^{\,a-1}}{2(1+a)(2+a)+6am_b(s+m_b\sigma'_{3n})^{\,a-1}}\right)$$

- External friction angle (*δ'*)

$$\delta' = \frac{2}{3}\phi'$$

- Cohesion (*c'*)

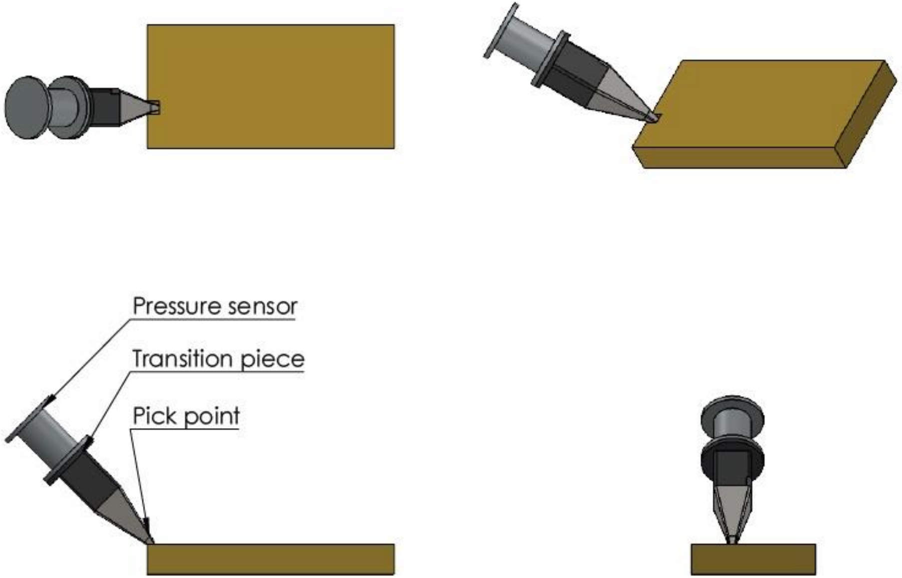
$$c' = \frac{\sigma_{ci}((a+2a)s+(1-a)m_b\sigma_{3n})(s+m_b\sigma_{3n})^{\,a-1}}{(1+a)(2+a)\sqrt{\frac{a+(6am_b(s+m_b\sigma_{3n})^{\,a-1}}{(1+a)(2+a)}}}$$

Rock characteristics

Sample	UCS MPa	BTS MPa	m_i [-]	c' MPa	ϕ' °	δ' °
1	18.9	1.7	11	3.7	44	29
2	26.6	1.1	24	4.7	52	35
3*	20.4	1.7	12	4.0	45	30
4	17.6	1.3	14	3.3	46	31
5	18.7	1.6	12	3.6	45	30

$m_i<9$ ductile failure
$9<m_i<15$ brittle-ductile transition
$m_i>15$ brittle failure

Test setup



The pickpoint has a total length of 30cm,
with a tip angle of 26º.

Test setup

- Settings:
  - Cutting angles
    - 40-70 degrees
  - Cutting speed
    - 5 cm/s
  - Depths
    - 0.5-1.5cm
    - (Limited by sensor)
  - Without water
    - No cavitation
    - No hyperbaric conditions

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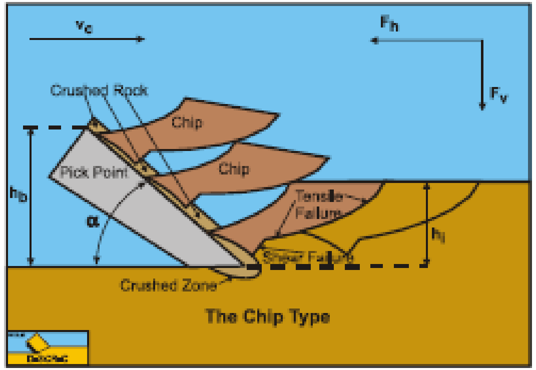
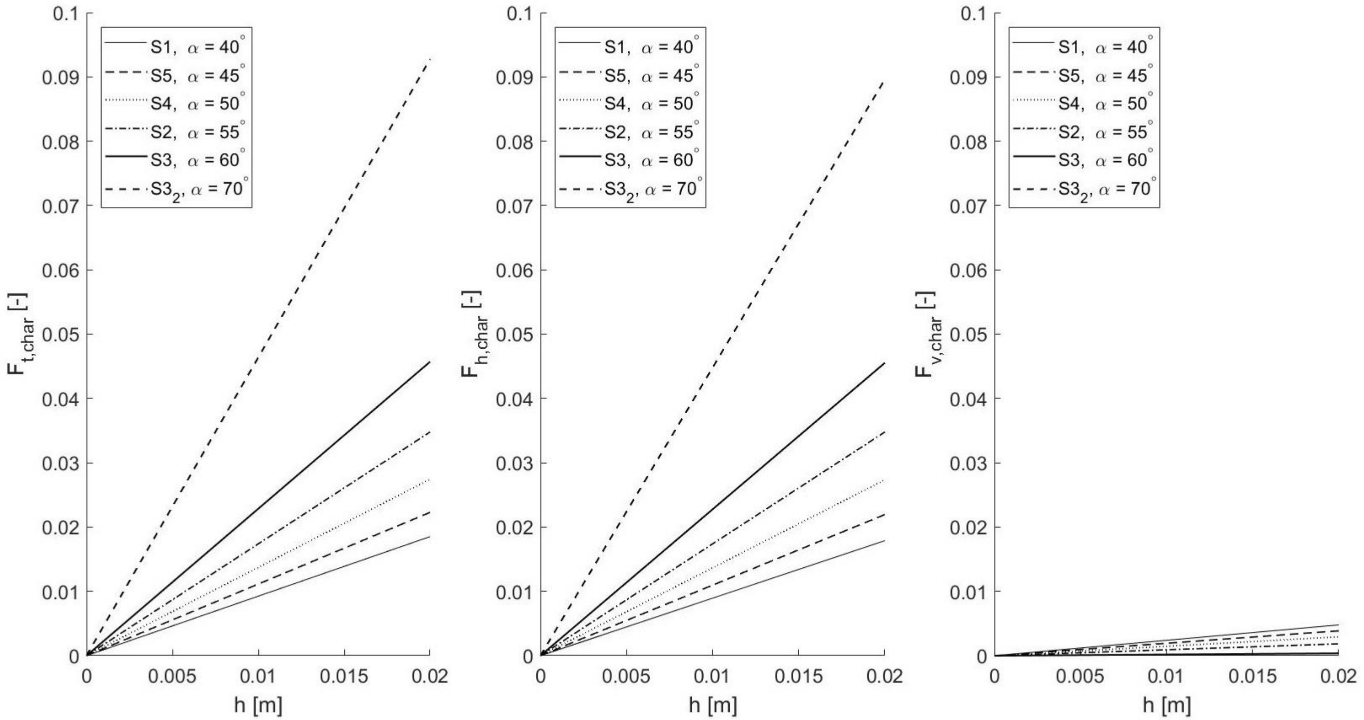
Determine failure mode

- Failure mode:
  - Brittle or ductile?
    - No plastic deformation → brittle
  - Tensile or shear?
    - Insufficient depth for tensile crack → shear
  - Nishimatu or Tear/Chip?
    - Tear model limited with cutting angles → Nishimatsu



DSCRCM, Miedema (2014)

The Nishimatsu Model



F_{total}, $F_{horizontal}$, $F_{vertical}$: linear increase vs. cutting depth

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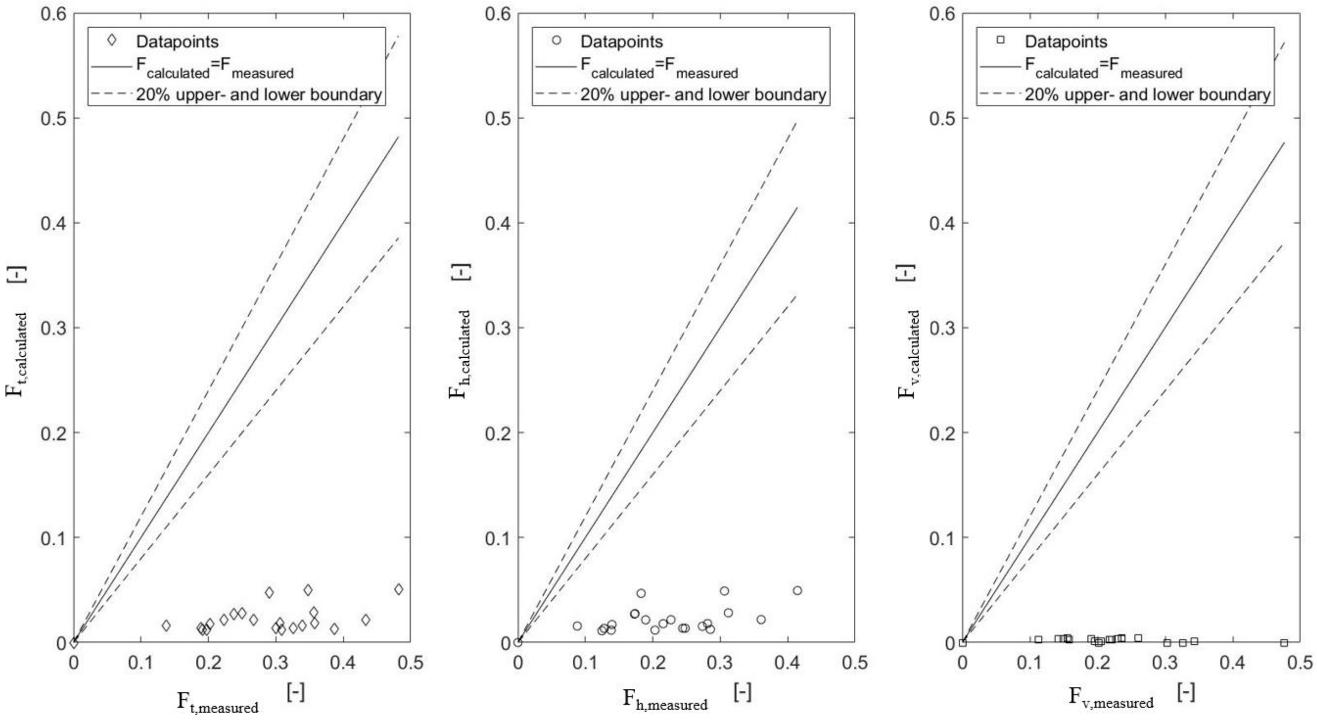
Nishimatsu vs. Measurements



Measured cutting forces are 10~20 times of the Nishimatsu calculations

Component model

‘Is the Nishimatsu model limited by its assumptions?’

- Assume model is correct, but limited by:
  - Sharp tool assumption
  - 2D assumption
- Measured force = Model + bluntness effect + 3D effect

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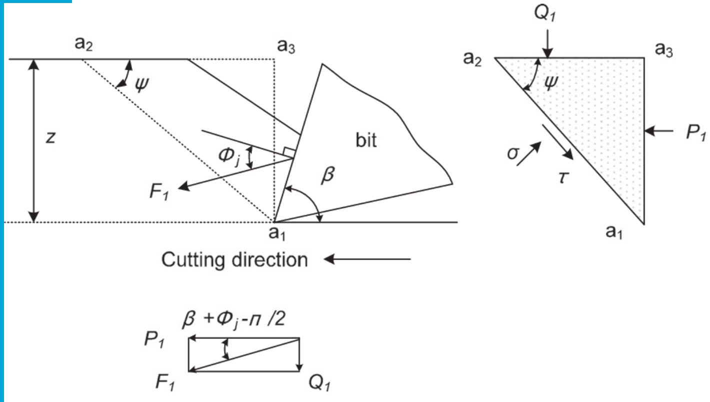
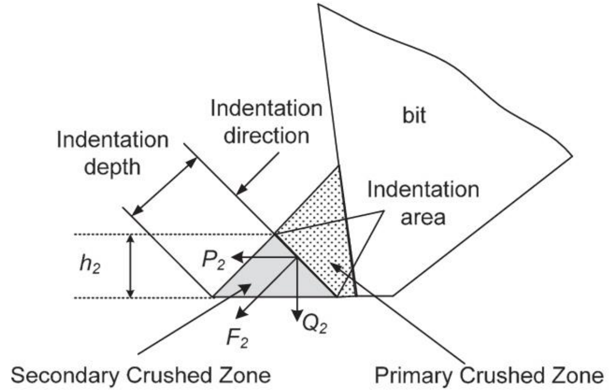
Component model

- Blunt tool → secondary crushed zone



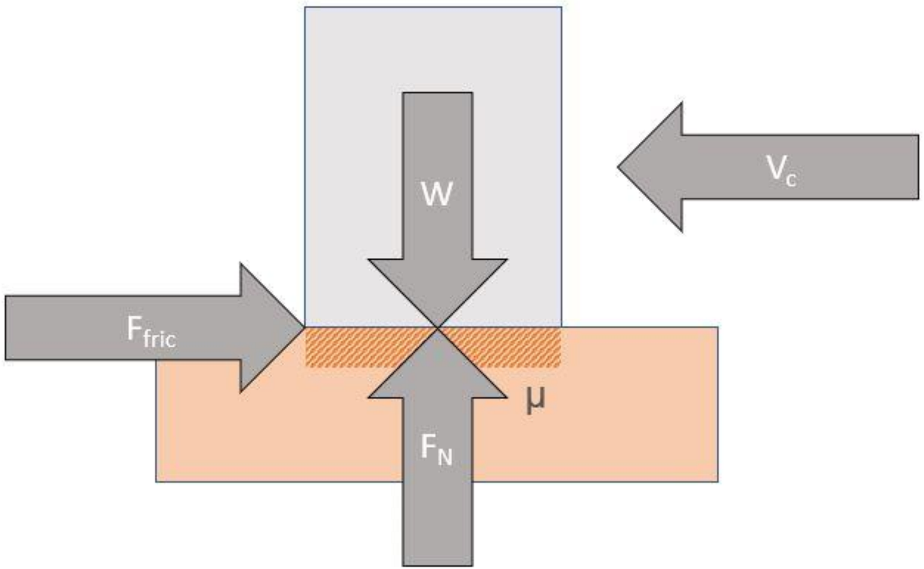


Zhantao Li (2012)

‘P2 is equal to dynamic friction’

Component model

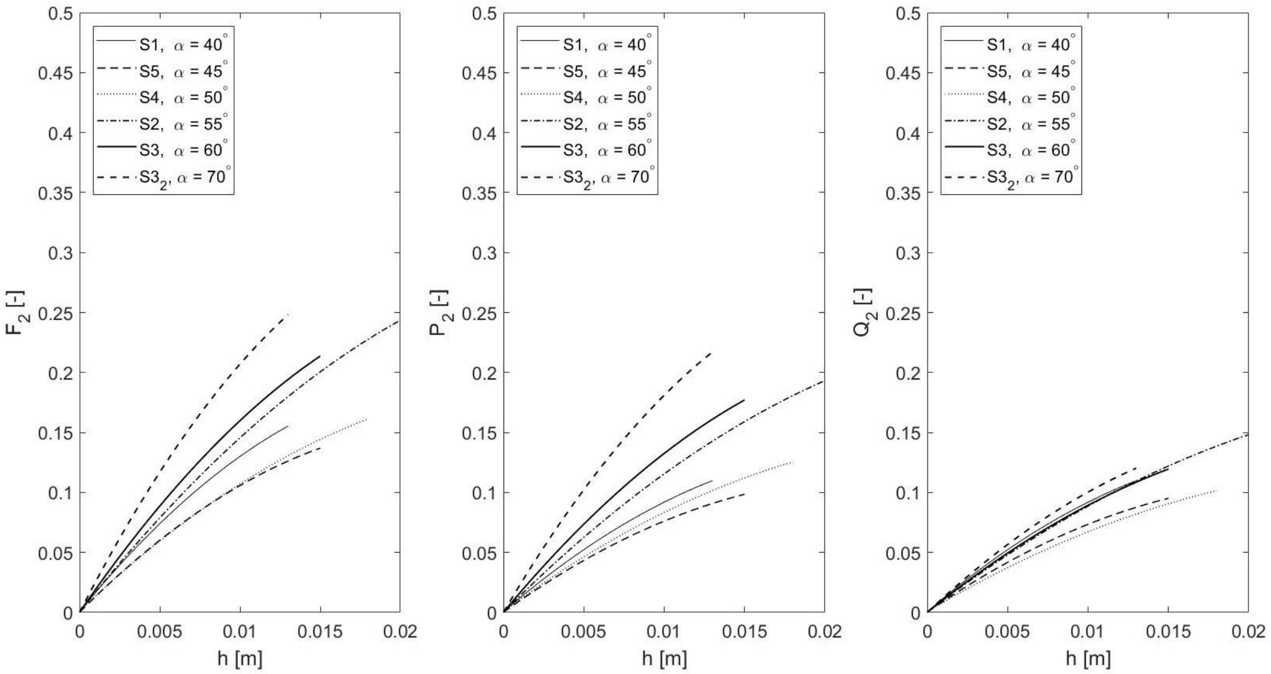
- Dynamic friction



General:
$F_n = W$
$F_{fric} = F_n * \mu$

This case:
$W = F_v$ (experiment)
$F_n = F_v$
$\mu = 0.39$
$F_{fric} = F_v * 0.39$

The Bluntness effect

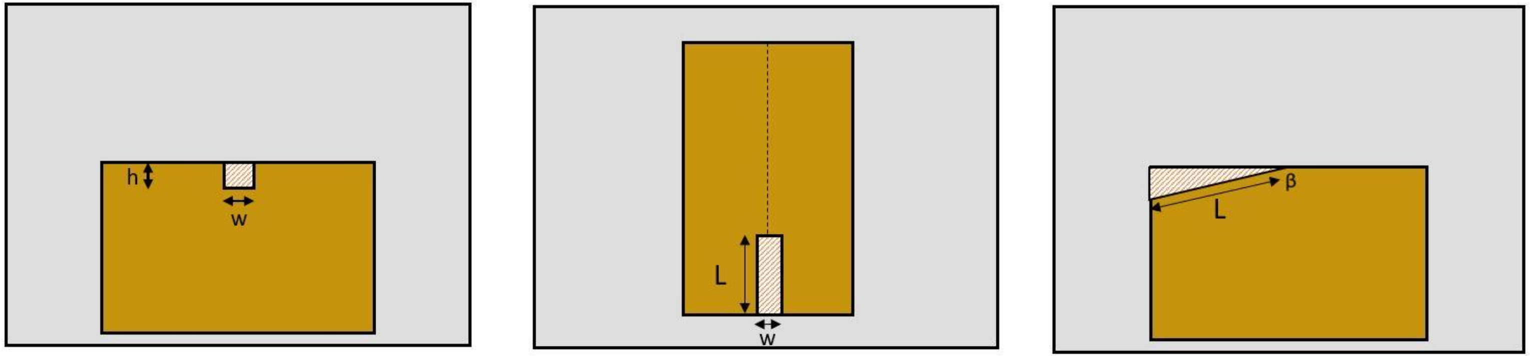


F2 – resultant force
p2 – horizontal force
Q2 – vertical force

Force to remove secondary crushed zone converges over depth

Component model

- 2D assumption

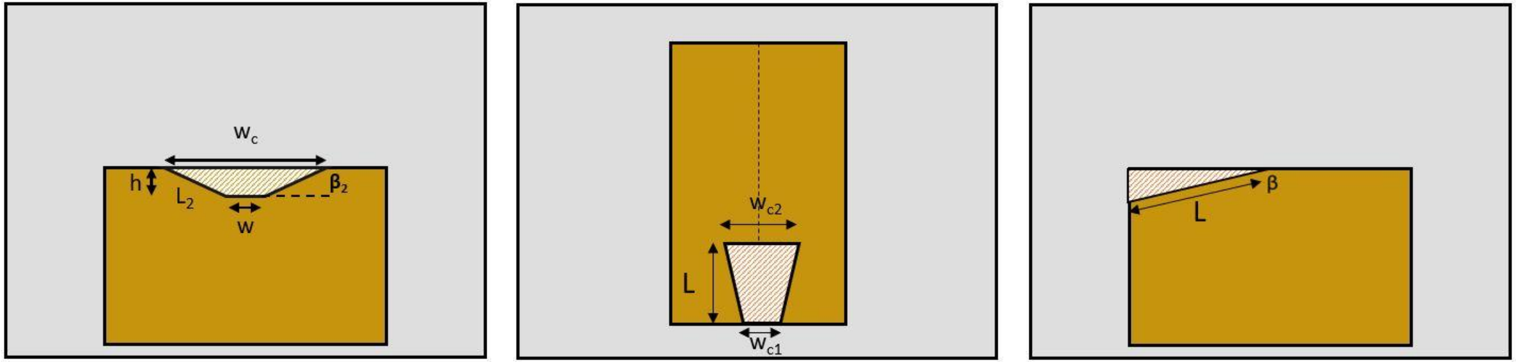


Component model

- However…

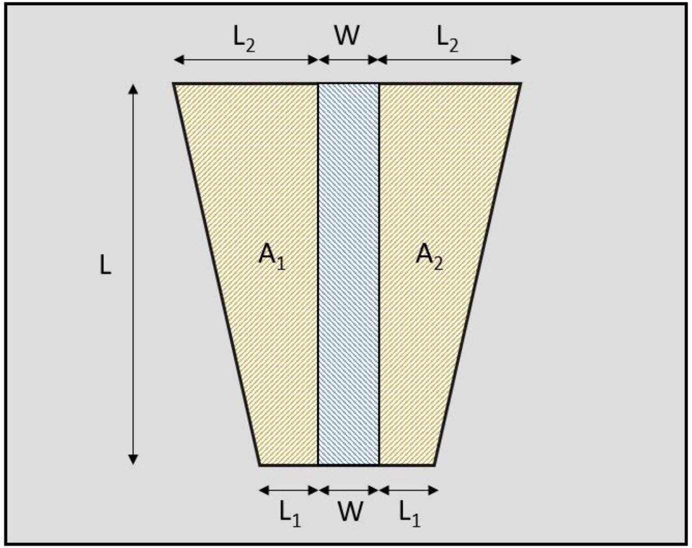
Component model

- 3D problem
  - Larger shear area



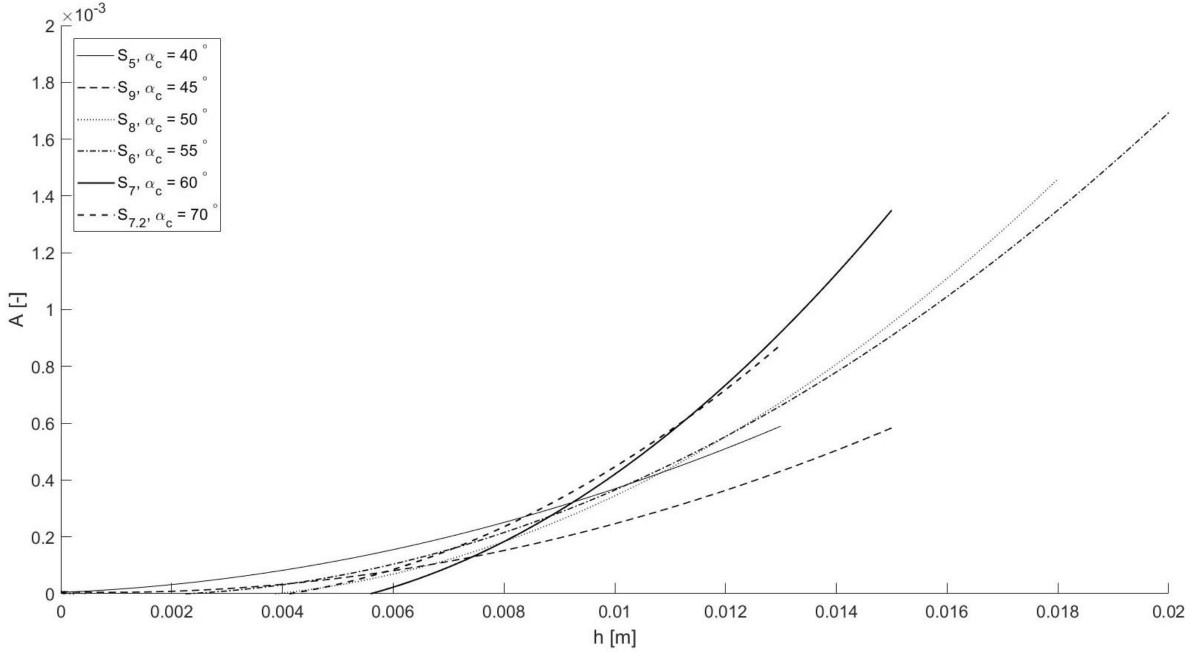
Component model

- 3D problem
  - Measure area from samples



$$F_3 = A * C$$

The outbreaking shear effect



- A – the ourbreaking shear surface area
- Quadratically increasing the shear component

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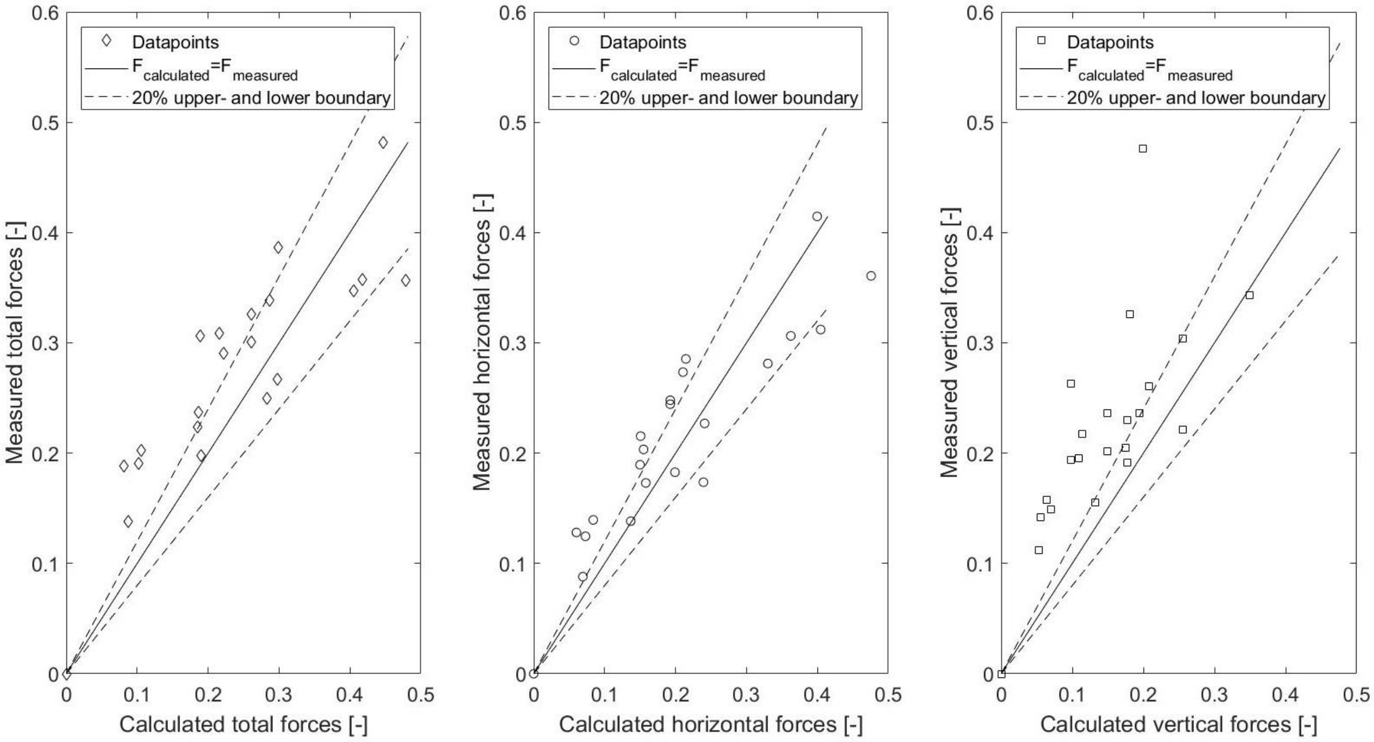
Combination of the three components



Overall trend: LINEAR

horizontal force: matches relatively well
vertical force: shows significant underestimation
total force: matches much better than pure Nishimatsu

Conclusions

- Proposed component model
  - Increases accuracy
  - Sharp tool + 2D assumption limiting factors
  - Still not perfect…
    - Vertical forces still inaccurate

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Conclusions

- Maximum forces linear over depth
  - Linear model component
  - Converging indentation component
  - Quadratically increasing shear component

Recommendations

- Conduct indentation tests
  - To get more real stress level in the crushed zone
- More experiments to enable the component model into a mature prediction model
- Try to get a cutting process which is dominated by indentation forces (check force over depth)
- Try to get a cutting process which is dominated by shear forces (check force over depth)

Thank you

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