Contact mechanics and elements of tribology

Lecture 4.b

Contact and transport at small scales

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@ Centre des Matériaux (& virtually)
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Outline

1. **Two words about interfacial physics**
2. **True contact area**

   How does it grow with the squeezing force?
3. **Interfacial fluid flow**

   How does the permeability decay with the squeezing force?
4. **Conclusions & perspectives**

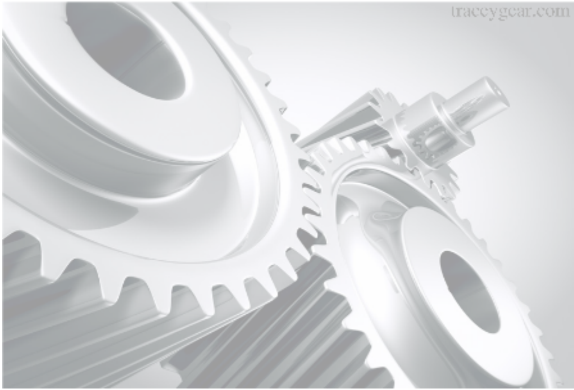
   How physical are the assumptions and results?

Objective:

link **roughness** parameters with the evolution of the true **contact area** and interface **permeability** with external pressure.

Contact between rough surfaces

Contact under microscope



Contact under microscope

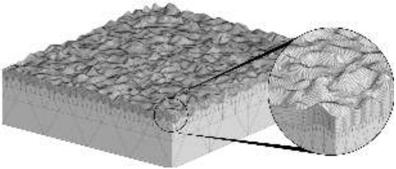
Problem statement & methods

Problem

- Solve contact problem for two elastic half-spaces E_1, ν_1 and E_2, ν_2
- With surface roughnesses $z_1(x,y)$ and $z_2(x,y)$
- Balance of momentum $\nabla \cdot \underline{\underline{\sigma}} = 0$,
- Boundary conditions $-\sigma_z^\infty = p_0$
- Contact constraints $g \ge 0, \quad p \ge 0, \quad g\,p = 0$,
  where $g(x,y)$ is the gap between surfaces,
  $p = -\underline{n} \cdot \underline{\underline{\sigma}} \cdot \underline{n}$ is the contact pressure.

Methods

- Finite element method

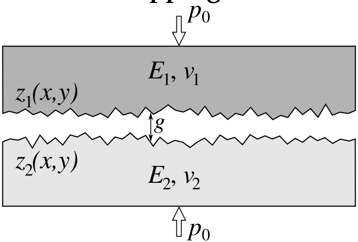


[1] Yastrebov, Wiley/ISTE (2013)

- Boundary element method

[2] Stanley & Kato, J Tribol 119 (1997)

Problem mapping



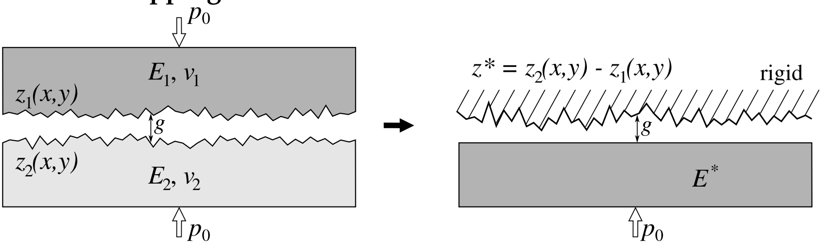
- **Flat** elastic[1] half-space with $E^* = \dfrac{E_1 E_2}{E_2(1-\nu_1^2) + E_1(1-\nu_2^2)}$
- **Rough** rigid[1] surface with $z^* = z_2 - z_1$
- Optimization problem[2]: $\min \mathcal{F}$

  under constraints $p \geq 0$ and $\frac{1}{A_0} \int\limits_A p dA = p_0$,

  with $\mathcal{F} = \int\limits_A p[u_z/2 + g] dA$

[1] Barber, Bounds on the electrical resistance between contacting elastic rough bodies, PRSL A 459 (2003)
[2] Kalker, Variational Principles of Contact Elastostatics, J Inst Maths Applics (1977)

Problem mapping



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Multi-asperity models

[1] Greenwood, Williamson. *P Roy Soc Lond A Mat* (1966)
[2] Bush, Gibson, Thomas. *Wear* (1975)
[3] Mc Cool. *Wear* (1986)
[4] Thomas. *Rough Surfaces* (1999)
[5] Greenwood. *Wear* (2006)
[6] Carbone. *J. Mech. Phys. Solids* (2009)
[7] Ciavarella, Greenwood, Paggi. *Wear* (2008)

Persson's model

[8] Persson. *J. Chem. Phys.* (2001)
[9] Persson. *Phys. Rev. Lett.* (2001)
[10] Persson, Bucher, Chiaia. *Phys. Rev. B* (2002)
[11] Müser. *Phys. Rev. Lett.* (2008)

Cross-link studies

[12] Manners, Greenwood. *Wear* (2006)
[13] Carbone, Bottiglione. *J. Mech. Phys. Solids* (2008)
[14] Paggi, Ciavarella. *Wear* (2010)

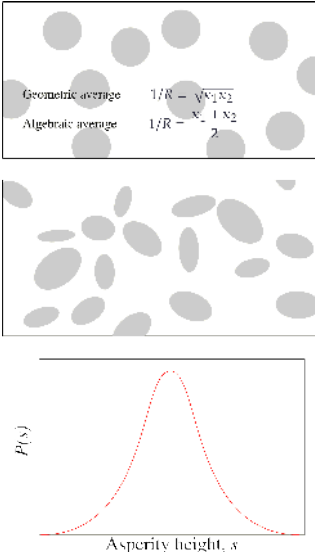

Fig. Multi-asperity models

Analytical models

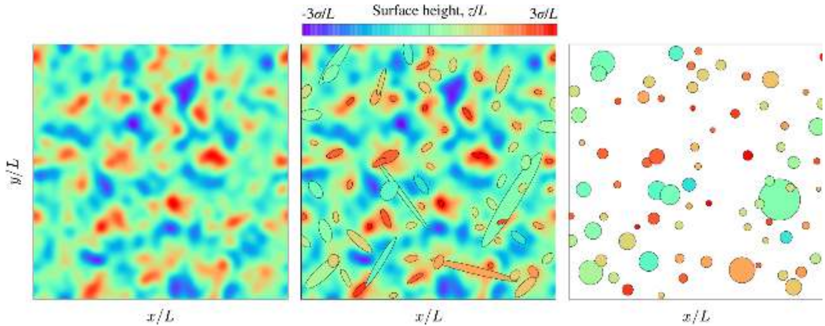

Fig. Roughness and detected asperities for $L/\lambda_l = 4$ and $L/\lambda_s = 16$

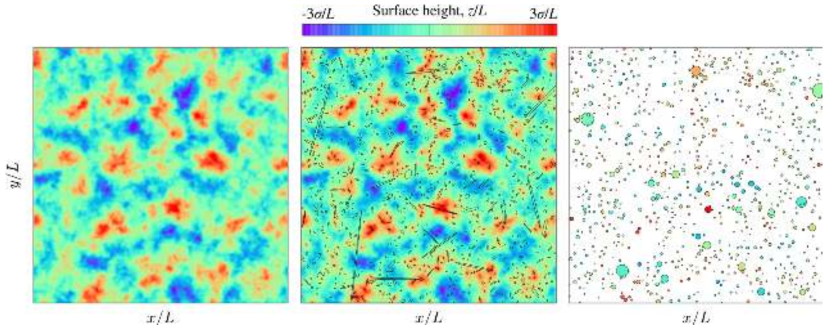

Fig. Roughness and detected asperities for $L/\lambda_l = 4$ and $L/\lambda_s = 64$

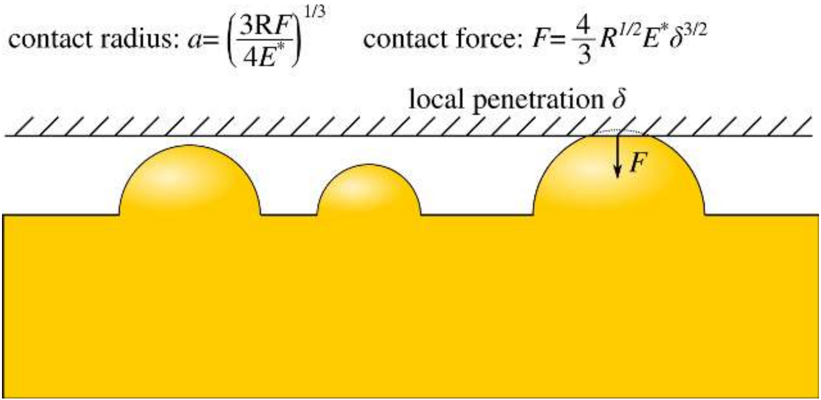

Fig. Hertz's theory of contact

Multi-asperity models

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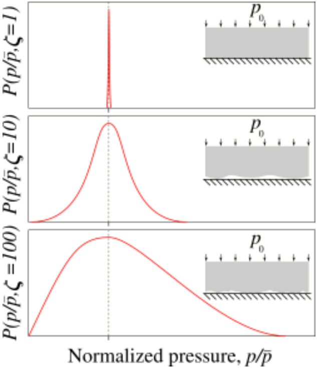

Fig. Persson's model

$$\frac{\partial P(p,\zeta)}{\partial V(\zeta)} = \frac{1}{2}\frac{\partial^2 P(p,\zeta)}{\partial p^2} \qquad P(0,\zeta) = 0$$

$$V(\zeta) = \frac{1}{2}E^* m_2(\zeta) = \frac{\pi E^*}{2}\int_{k_l}^{\zeta k_l} k^3 \Phi^p(k)dk$$

Why is the sky dark at night?

Why is the sky dark at night?

- Olbers' paradox or "dark night sky paradox"
- Two nominally-flat elastic half-spaces in contact
- At small scale they are rough with asperity density D
- Vertical displacement decay $u_z \sim 1/r$
- At every asperity, force F
- Sum up displacements induced by all forces*

$$u_z \sim \int\limits_0^{2\pi}\int\limits_{r_0}^{R} \frac{F}{r} r \, dr \, d\phi \xrightarrow[R\to\infty]{} \infty$$

---

*In case of light intensity I, it decays as $1/r^2$ but the integral is in volume for a constant start density the integral light intensity is:

$$\mathcal{I} \sim \int\limits_0^{2\pi}\int\limits_0^{\pi/2}\int\limits_{r_0}^{R} \frac{I}{r^2} \underbrace{r^2 \sin(\theta) \, dr \, d\phi d\theta}_{\text{Volume element}} \xrightarrow[R\to\infty]{} \infty$$

Comparison of models

Multi-asperity models | **Persson's model**

1. Evolution of the real contact area $A(p_0)$ for $A/A_0 \to 0$

$$\boxed{\frac{A}{A_0} = \frac{\kappa}{\sqrt{\langle|\nabla z|^2\rangle}}\frac{p_0}{E^*}}$$

$\kappa_{\mathrm{BGT}} = \sqrt{2\pi} \approx 2.5$ *according to* [2-5]

$\kappa_{\mathrm{P}} = \sqrt{8/\pi} \approx 1.6$ *according to* [6-7]

2. Evolution of the real contact area $A(p_0)$ for $\forall A/A_0$

$\frac{A}{A_0} = A(p_0, \alpha)/A_0$ *according to* [2-5]

$\frac{A}{A_0} = \mathrm{erf}\left(\sqrt{\frac{2}{\langle|\nabla z|^2\rangle}}\frac{p_0}{E^*}\right)$ *according to* [6-7]

[1] Greenwood, Williamson, P Roy Soc Lond A Mat 295 (1966)

[2] Bush, Gibson, Thomas, Wear 35 (1975)

[3] Mc Cool, Wear 107 (1986)

[4] Thomas, Rough Surfaces (1999)

[5] Greenwood, Wear 261 (2006)

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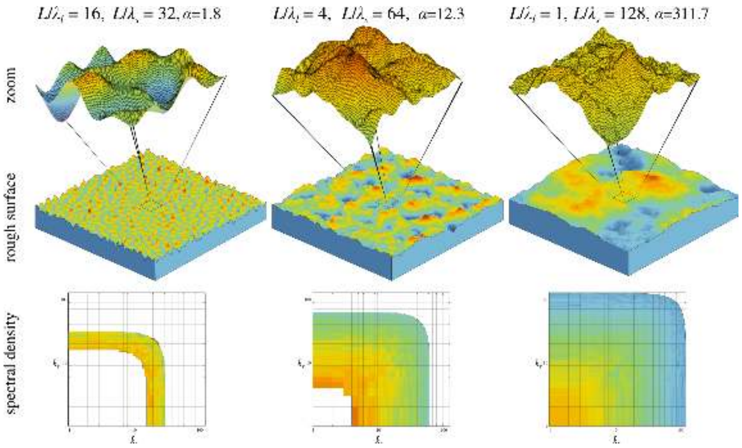
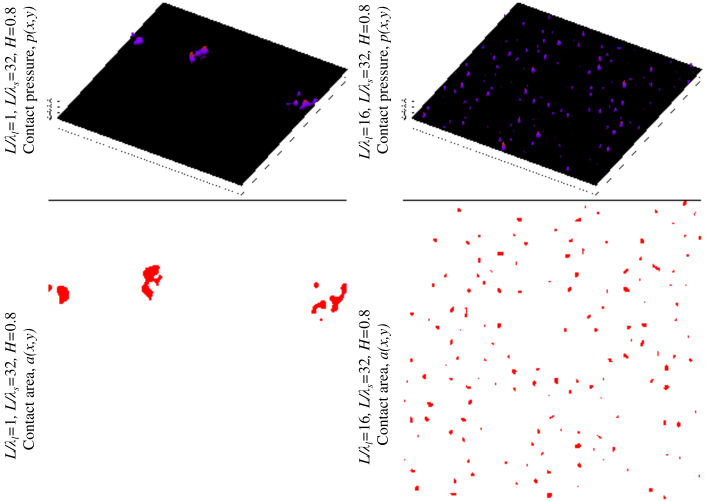
[9] Müser, Phys. Rev. Lett. 100, (2008)

Simulations set-up

- Cut-off parameters: $L/\lambda_l \otimes L/\lambda_s = \{1, 2, 4, 8, 16\} \otimes \{32, 64, 128, 256, 512\}$
- Hurst exponent $H = \{0.4, 0.8\}$
- 10 random surface realizations per combination of parameters
- Discretization: $\{L/\Delta x\} \times \{L/\Delta x\} = 2048 \times 2048$
- Search for contact area A', gap field $g(x, y)$ and gap PDF $P(g)$



Contact area and contact pressure evolution



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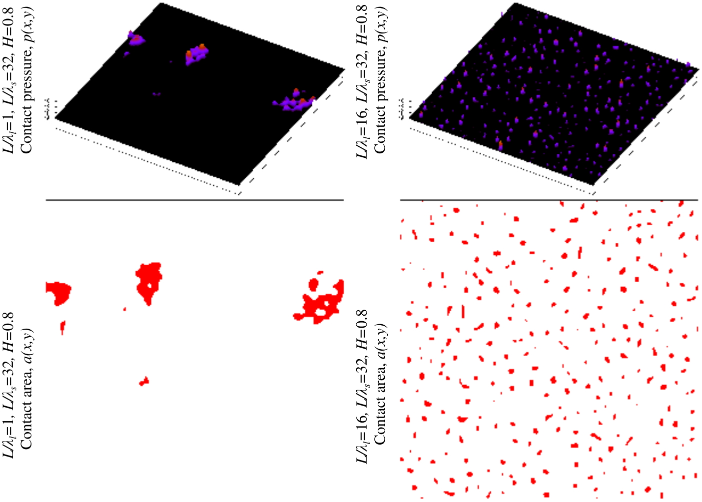

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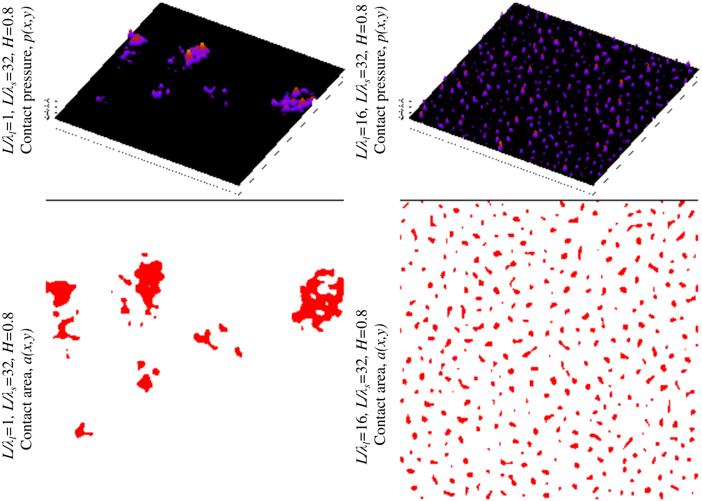
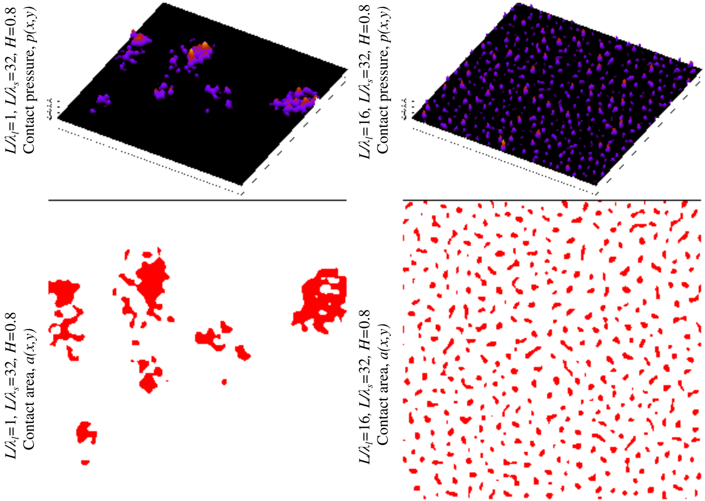
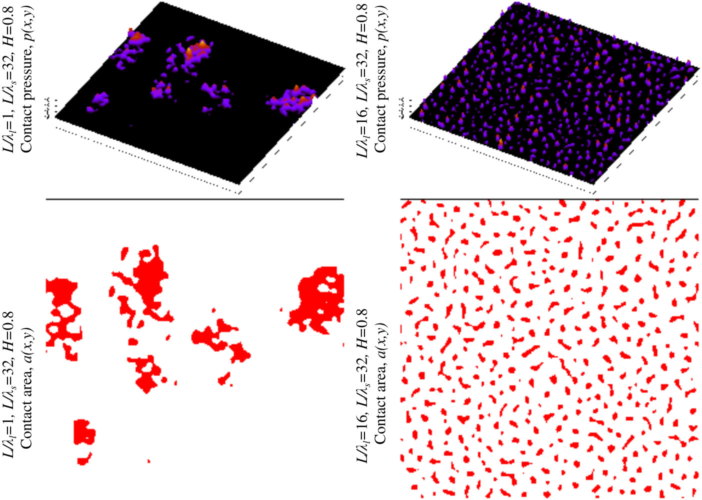
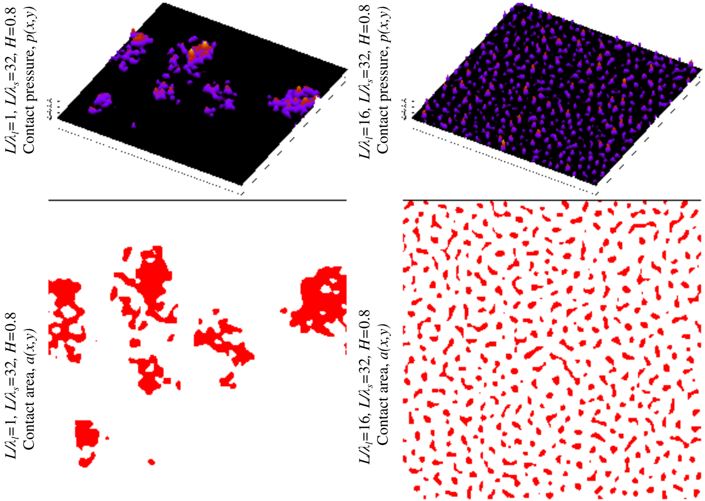



L/λl=1, L/λs=32, H=0.8
Contact pressure, p(x,y)
L/λl=16, L/λs=32, H=0.8
Contact pressure, p(x,y)
L/λl=1, L/λs=32, H=0.8
Contact area, a(x,y)
L/λl=16, L/λs=32, H=0.8
Contact area, a(x,y)

Contact area and contact pressure evolution




L/λ_l=1, L/λ_s=32, H=0.8
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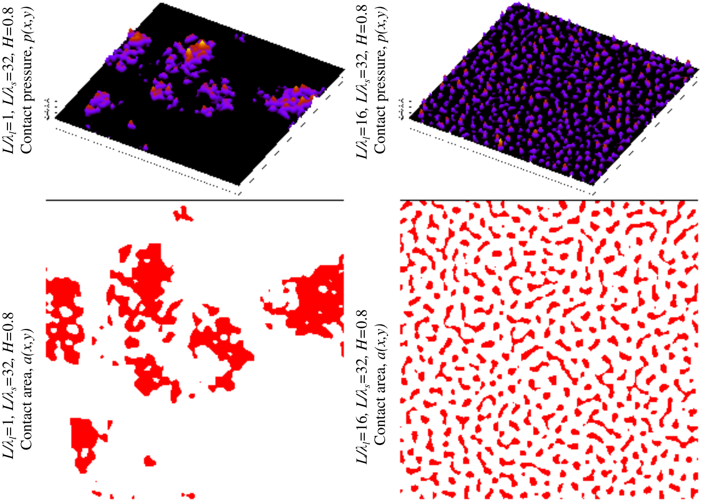
Contact area, $a(x,y)$

Contact area and contact pressure evolution



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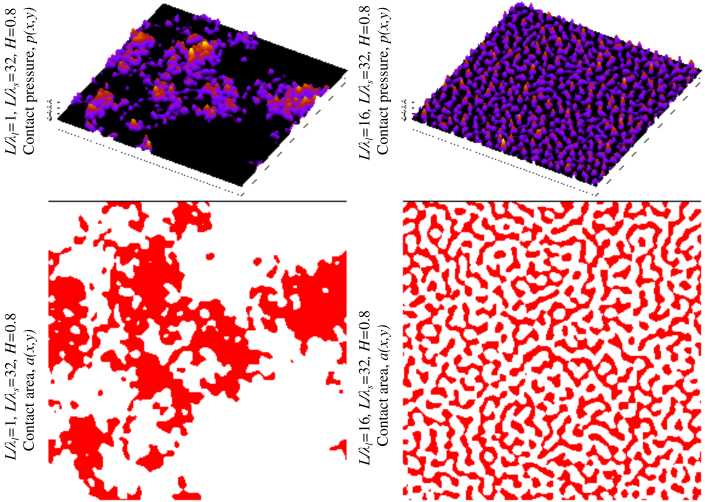

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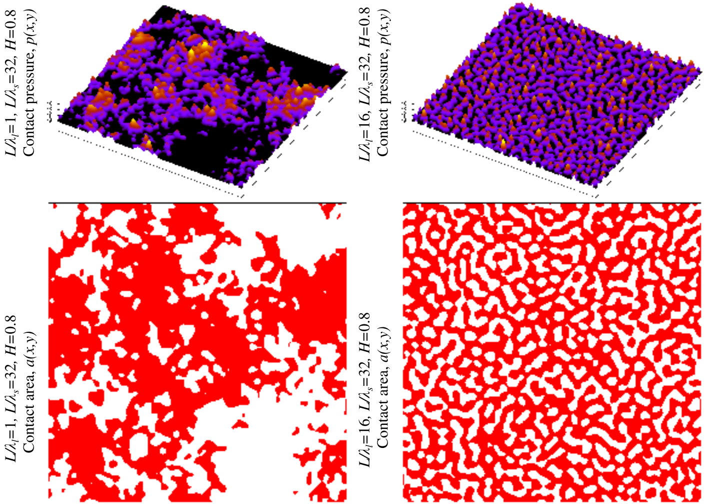

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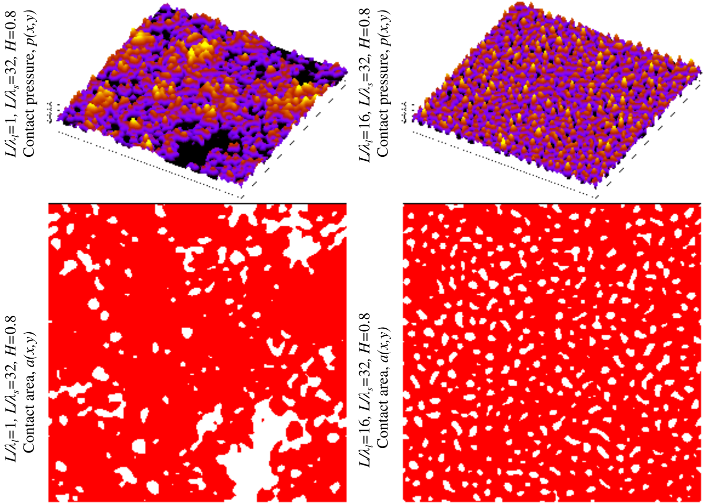

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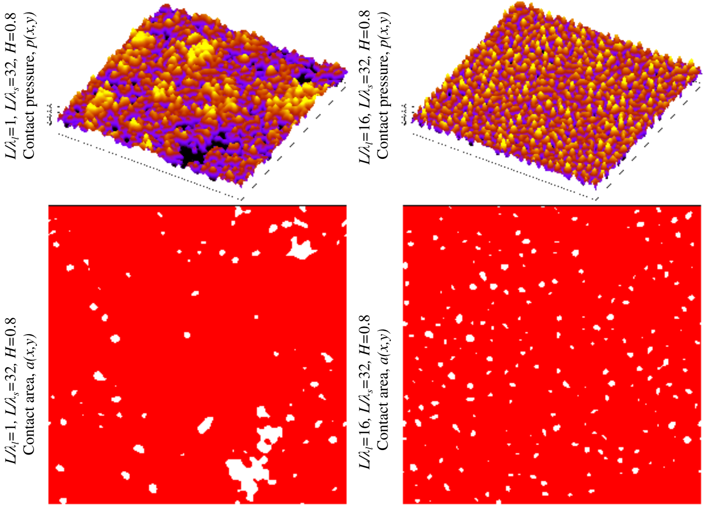

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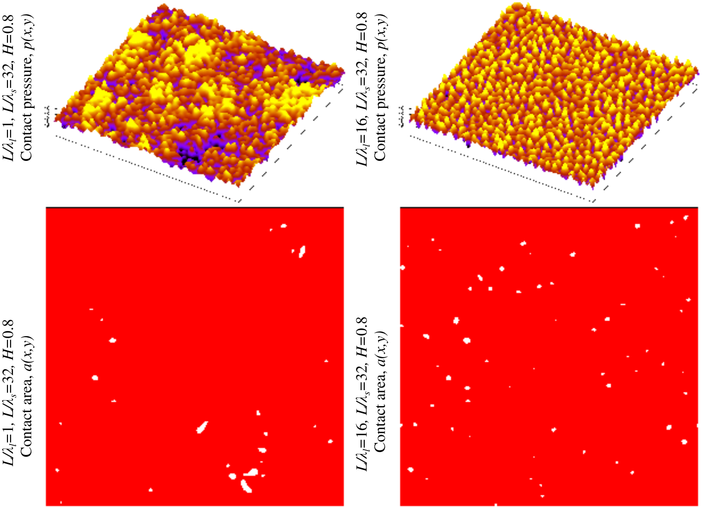

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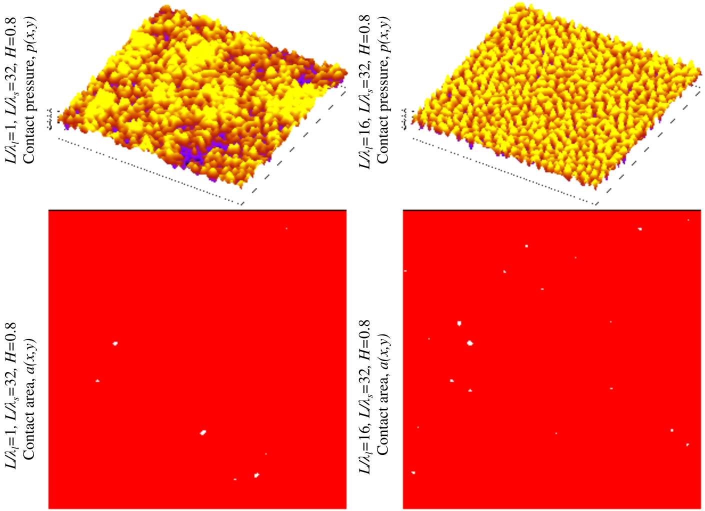

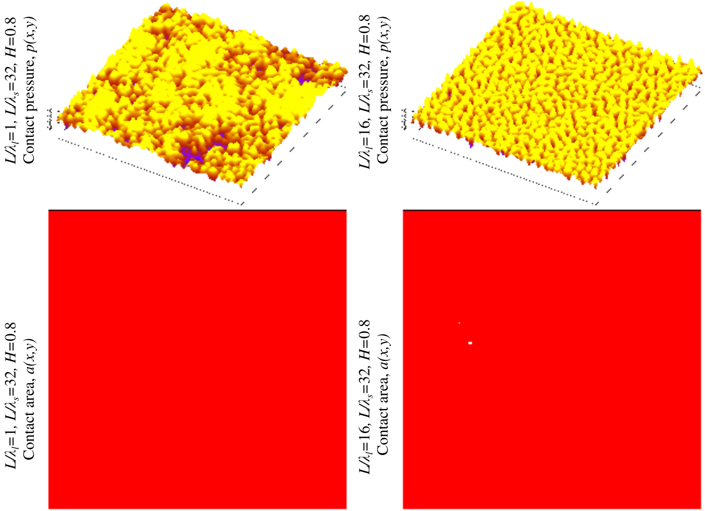
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Contact area, $a(x,y)$
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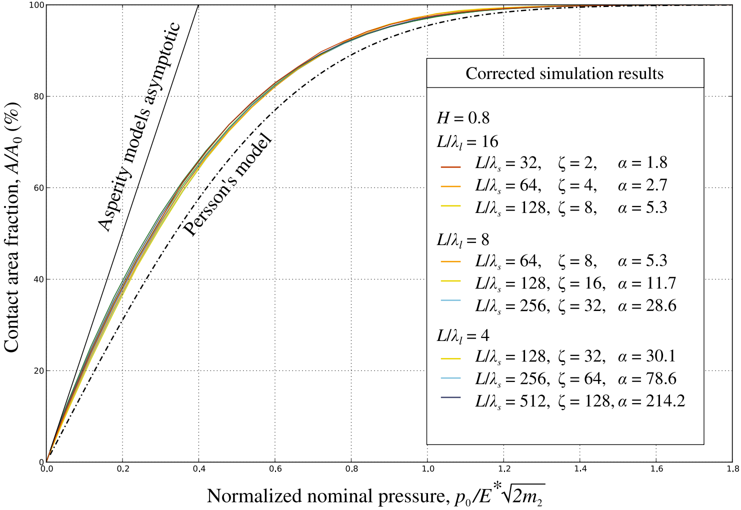
Contact area, $a(x,y)$

Results: contact area



Multi-asperity models asymptotic[1,2], Persson's model[3]

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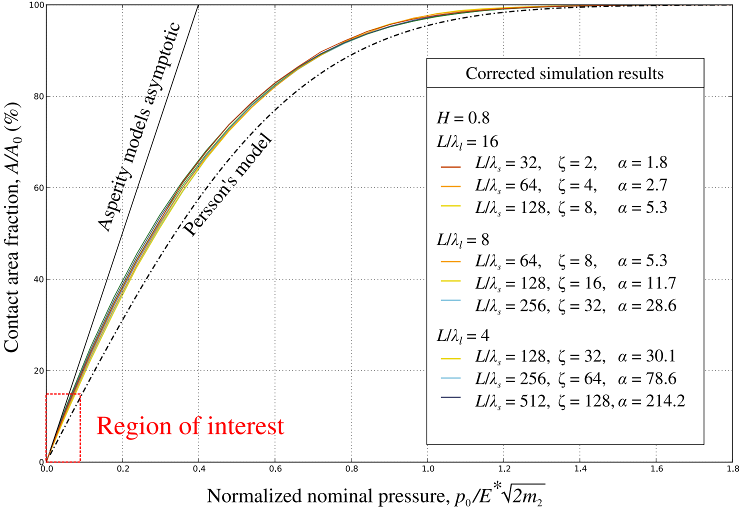

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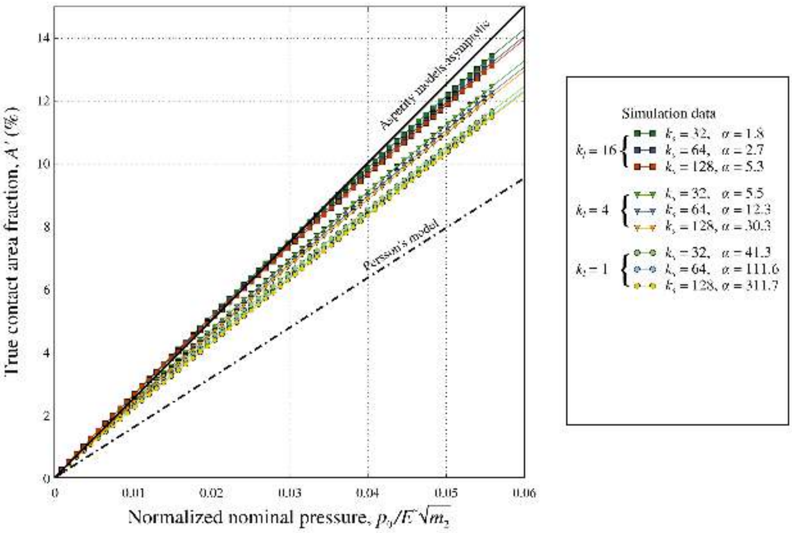
Real contact area: interpretation of results?



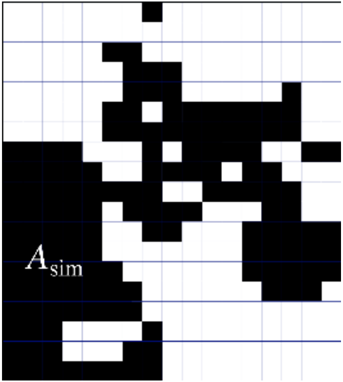
Raw data

[1] Yastrebov, Anciaux, Molinari, Int J Solids Struct 52 (2015)

Numerical error correction

- Contact area is overestimated in simulations:

$$A_{\text{sim}} > A_*$$



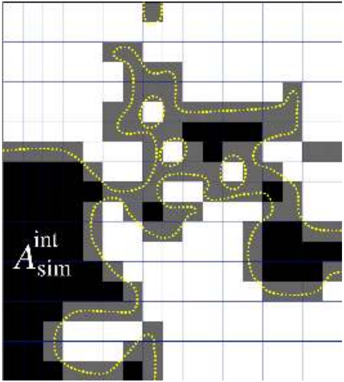
Numerical error correction

- Contact area is overestimated in simulations:

  $$A_{\mathrm{sim}} > A_*$$

- The overestimation is localized at boundary nodes:

  $$A_{\mathrm{sim}} > A_* > A_{\mathrm{sim}}^{\mathrm{int}}$$



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- The overestimation is localized at boundary nodes:

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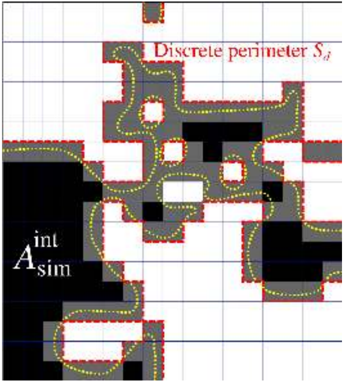
- Boundary area ~ perimeter S_d:

  $$A_{\rm sim} - A_{\rm sim}^{\rm int} = S_d \Delta x$$



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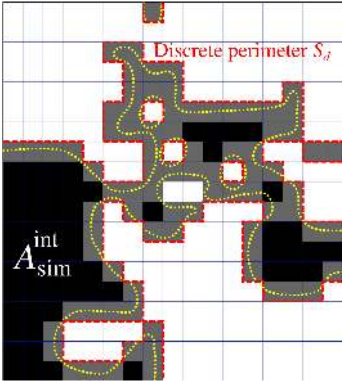
- Manhattan S_d vs Euclidean metric S:

$$\langle S \rangle = \frac{\pi}{4} \langle S_d \rangle$$



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- Boundary area ~ perimeter S_d:

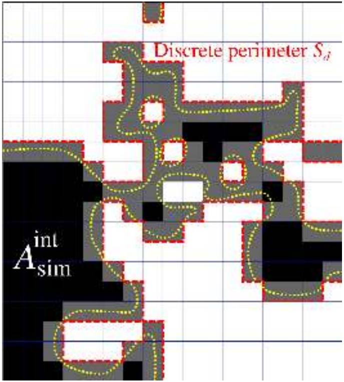
  $$A_{\text{sim}} - A^{\text{int}}_{\text{sim}} = S_d \Delta x$$

- Manhattan S_d vs Euclidean metric S:

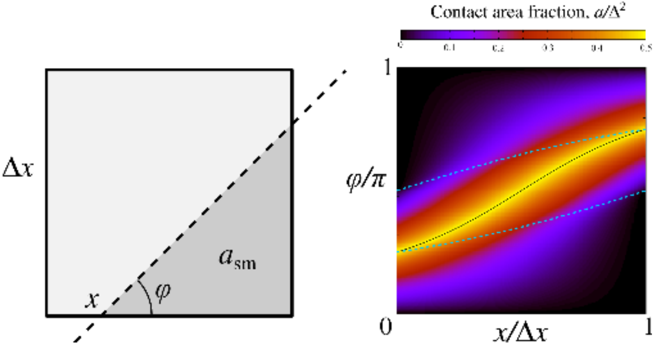
  $$\langle S \rangle = \frac{\pi}{4} \langle S_d \rangle$$

- True contact area estimation:

  $$\boxed{A_* \approx A_{\text{sim}} - \beta \frac{\pi}{4} S_d \Delta x}$$



Numerical error correction: corrective factor

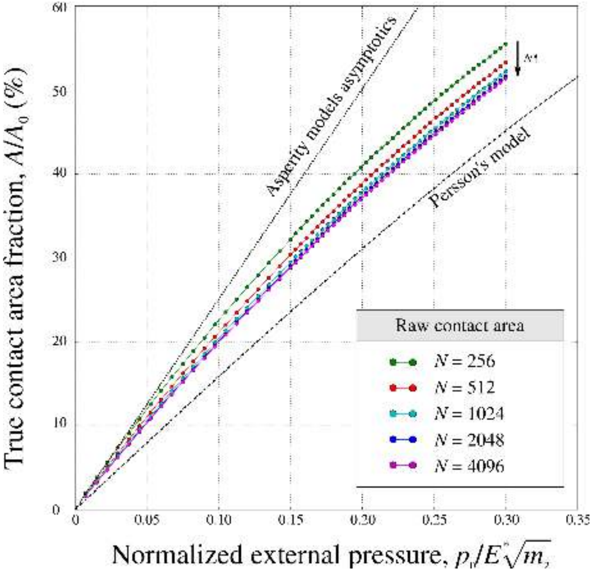


Corrective factor $\beta = \dfrac{\langle a_{\text{sm}} \rangle}{\Delta x^2} = \dfrac{1}{\Delta x^2} \int\limits_0^h \int\limits_0^\pi a_{\text{sm}} P(x,\phi)\, dx d\phi = \dfrac{\pi - 1 + \ln 2}{6\pi}$

$$\beta = 0.150387618994810151606955\dots$$

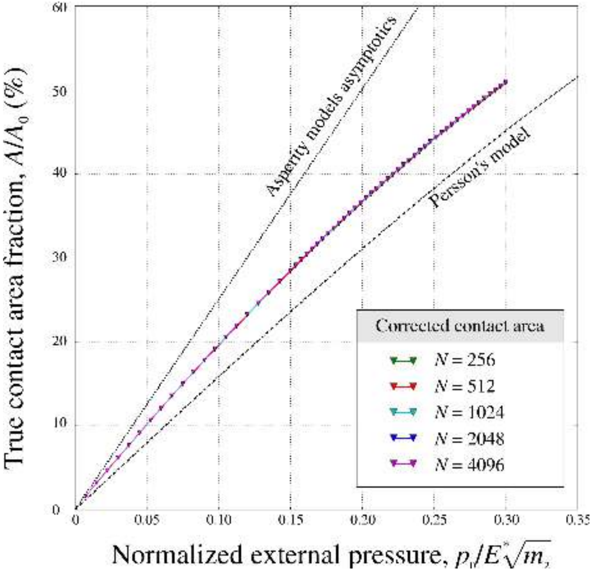
True area estimation: $\boxed{A_* \approx A_{\text{sim}} - \dfrac{\pi - 1 + \ln 2}{24} S_d \Delta x}$

Numerical error correction: convergence study



[1] Yastrebov, Anciaux, Molinari, Tribol Int 114 (2017)

Numerical error correction: convergence study



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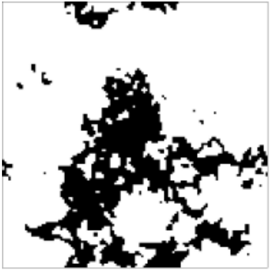
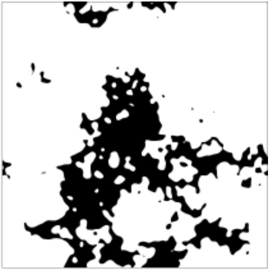
Morphological correction

- Morphology of contact clusters



N=128, raw



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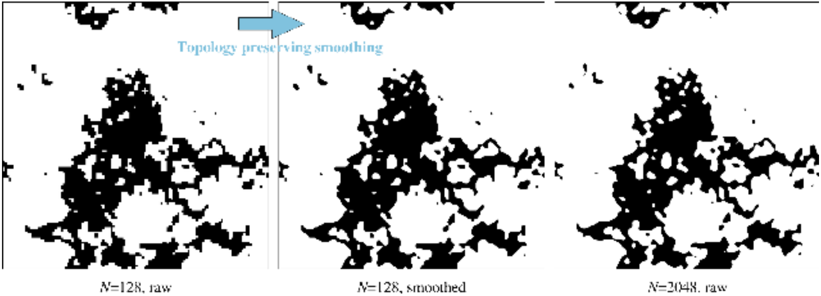
Morphological correction

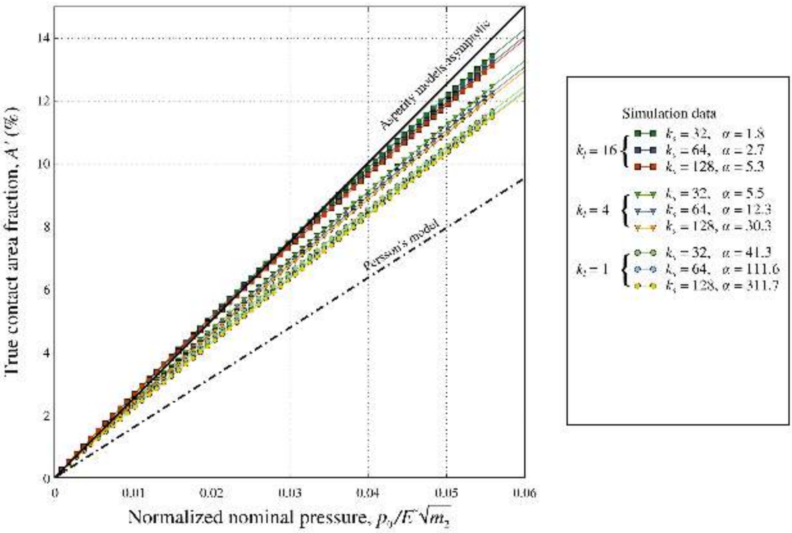
- Morphology of contact clusters



Topologically preserving smoothing results in realistic cluster geometry

[1] Couprie & Bertrand, *J Electr Imag* 13 (2004)

Real contact area: accurate results



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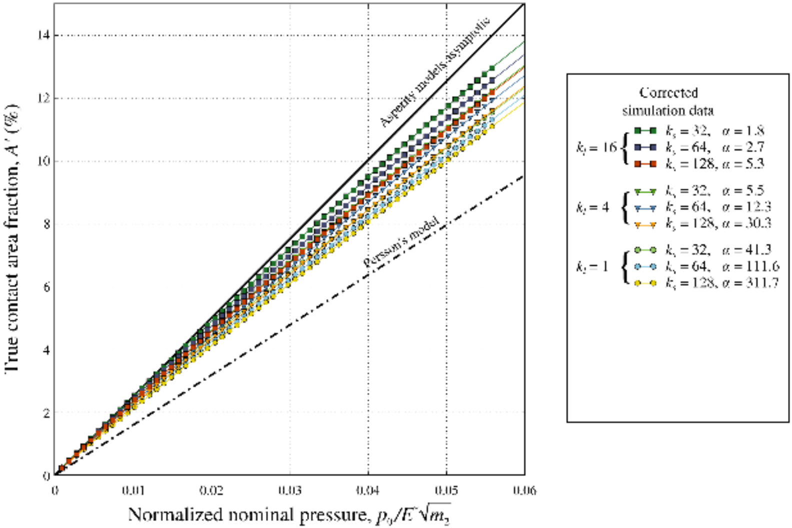
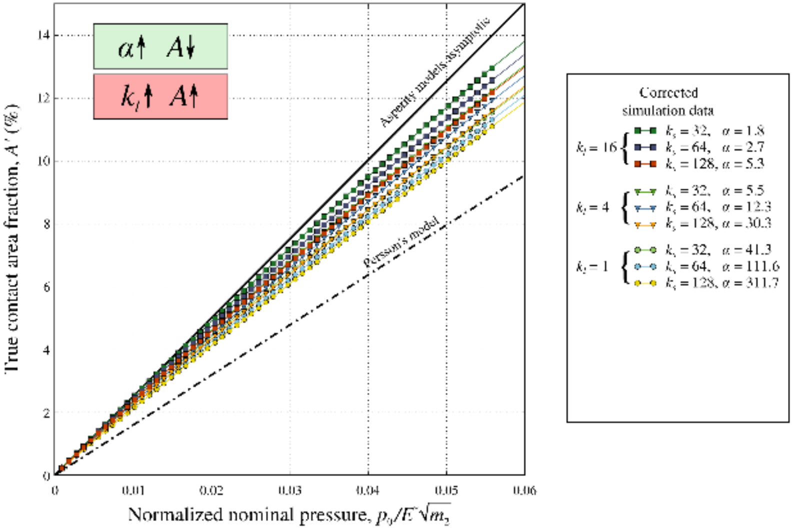
[1] Yastrebov, Anciaux, Molinari, Int J Solids Struct 52 (2015)



Corrected data

[2] Yastrebov, Anciaux, Molinari, *J Mech Phys Solids* 107 (2017)

Real contact area: accurate results



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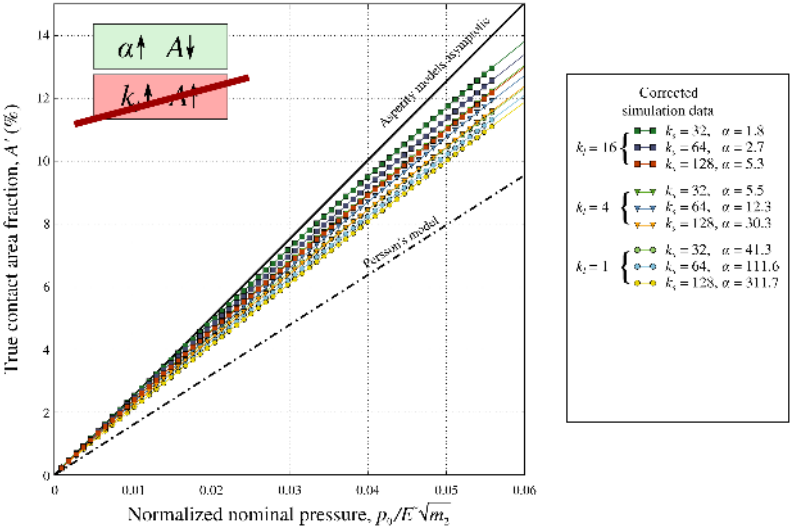
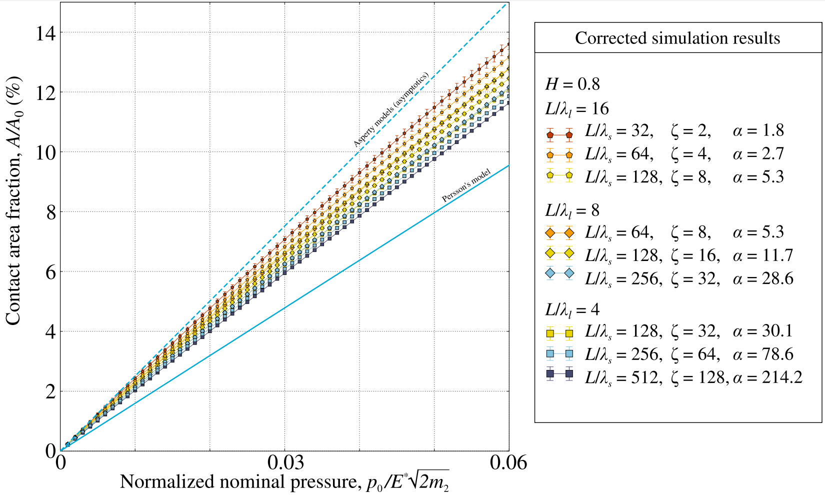


Corrected data

[2] Yastrebov, Anciaux, Molinari, *J Mech Phys Solids* 107 (2017)

Results: contact area



Corrected contact area (discretization independent): "magic" formula[1,2]

$$A_* \approx A_{\text{sim}} - \frac{\pi-1+\ln 2}{24} S_d \Delta x,$$

where S_d is the integral **perimeter** of the contact zones.

[1] Yastrebov, Anciaux, Molinari, *Tribol. Int.* 114 (2017)
[2] Yastrebov, Anciaux, Molinari, *J Mech Phys Solids* 107 (2017)

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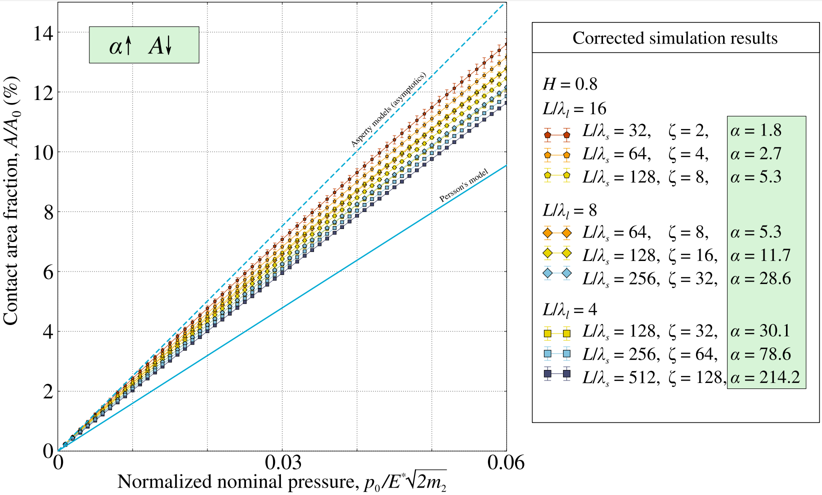

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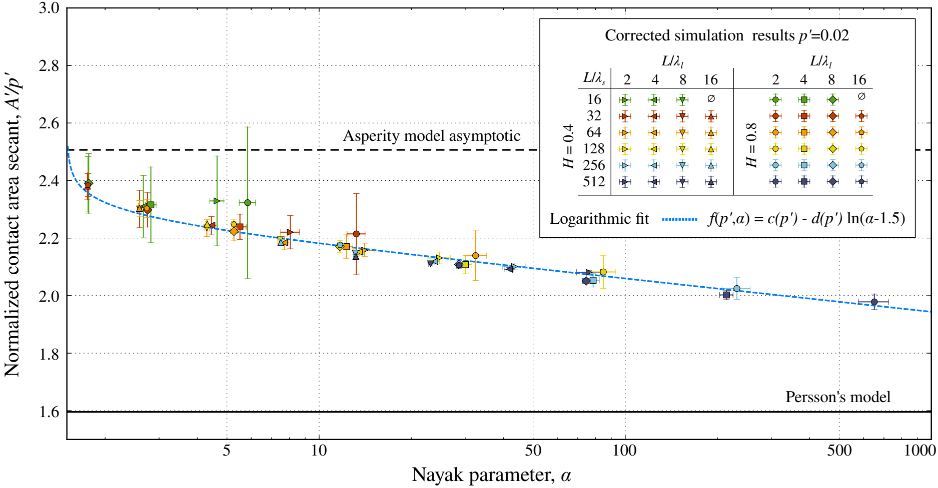
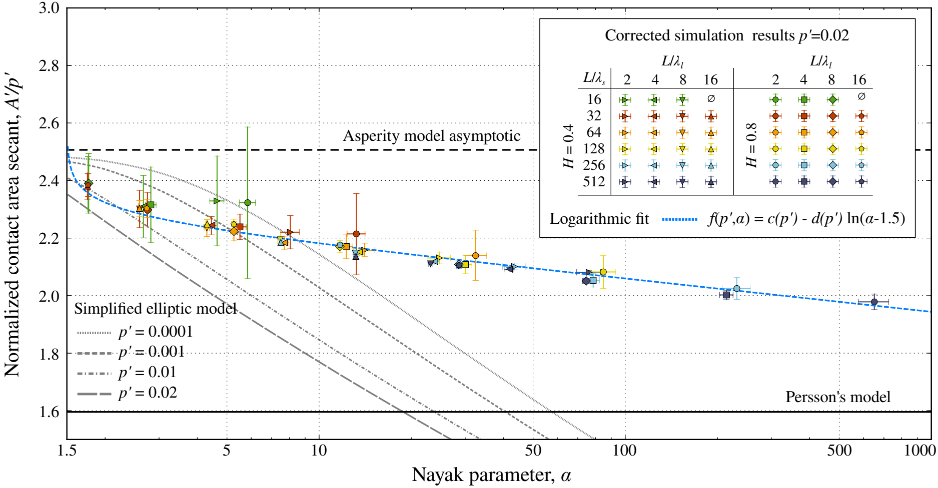
Role of Nayak parameter α



Numerical results: [1] Yastrebov, Anciaux, Molinari, J Mech Phys Solids 107 (2017)

Role of Nayak parameter α



Numerical results: [1] Yastrebov, Anciaux, Molinari, J Mech Phys Solids 107 (2017)

Simplified elliptic model: [2] Greenwood, Wear (2006)

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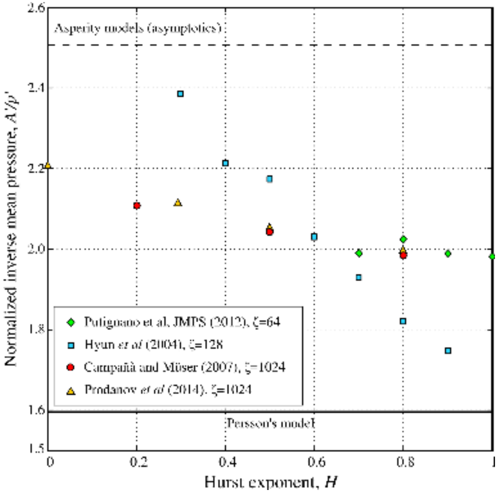
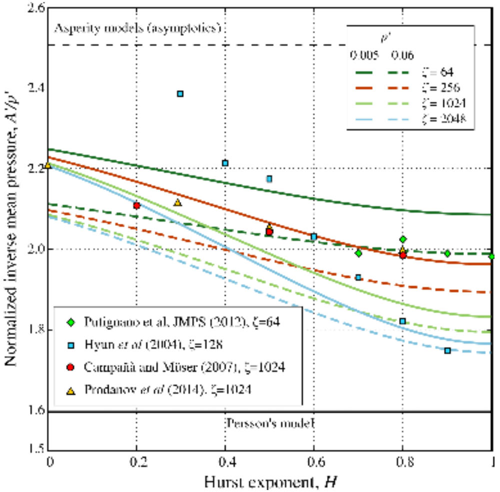


Comparison with other numerical studies
Nayak-Hurst relationship

$$\alpha(H,\zeta) = \frac{3}{2}\,\frac{(1-H)^2}{H(H-2)}\,\frac{(\zeta^{-2H}-1)(\zeta^{4-2H}-1)}{(\zeta^{2-2H}-1)^2}$$

Role of Nayak parameter α



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Phenomenological relationship

- Contact area A grows with applied pressure p_0 as

$$\frac{A}{A_0} = a(\alpha)\frac{p_0}{E^*\sqrt{2m_2}} - b(\alpha)\left[\frac{p_0}{E^*\sqrt{2m_2}}\right]^2$$

- Contact area fraction $A' = A/A_0$ grows with normalized applied pressure $p' = p_0/E^*\sqrt{2m_2}$

$$\boxed{A' = a(\alpha)p' - b(\alpha)p'^2}$$

- With ≈universal adimensional constants:

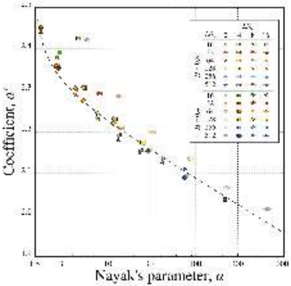
$$a(\alpha) = 2.35 - 0.057\ln(\alpha - 1.5)$$

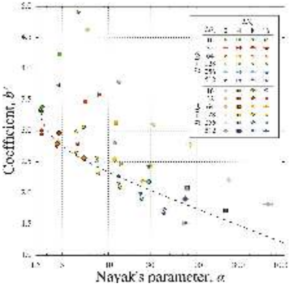
$$b(\alpha) = 2.85 - 0.24\ln(\alpha - 1.5)$$

- Pressure dependent friction coefficient:

$$\mu(p') = \mu_0\left[1 - \frac{b(\alpha)}{a(\alpha)}p'\right]$$

with $\mu_0 = a(\alpha)\tau_{\max}/E^*\sqrt{2m_2}$,
$\tau_{\max}$ is the maximum shear traction the contact interface can bear.





Conclusions

- Contact area growth almost linearly for small pressures and saturates at bigger pressure
- The key parameter of the contact area growth is the RMS slope or its variance $2m_2$
- Contact area depends weakly on Nayak parameter $\alpha = m_0 m_4 / m_2^2$

$$\boxed{A' = a(\alpha)p' - b(\alpha){p'}^2}$$

with $a(\alpha) = 2.35 - 0.057\ln(\alpha - 1.5)$, $\quad b(\alpha) = 2.85 - 0.24\ln(\alpha - 1.5)$

- No effect of fractal dimension D_f *per se* on the contact area
  it affects the contact area only through the Nayak parameter

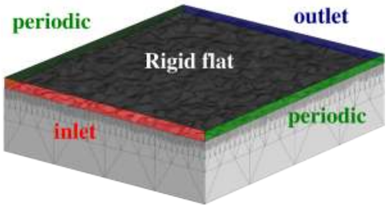
Flow through the contact interface

Problem

- **Thin creeping** flow in contact interface:
  Navier-Stokes → Stokes → Reynolds equation
- In addition: incompressible fluid, immobile walls:

$$\nabla \cdot \underline{q} = 0, \quad \underline{q} = -\frac{g^3}{12\mu}\nabla p_f$$

$\underline{q}(x,y)$ is the fluid flux,
$g(x,y)$ is the gap (opening) fields,
$p_f(x,y)$ hydrostatic fluid pressure,
μ is the dynamic viscosity.



- Gap profile $g(x,y)$ for $x,y \in (0,L)$
- At inlet: $p_f = p_{\text{in}}$
- At outlet: $p_f = p_{\text{out}}$
- At lateral sides: periodic
  $q_n(y=L) = -q_n(y=0)$
- Linear problem: use FEM

Analytical approach

Effective flow estimation

- Averaging over surface $\langle x \rangle = 1/A_0 \int_{A_0} x\,dA$ gives:

$$\langle \underline{q} \rangle = -\underline{\underline{K}}_{\text{eff}} \cdot \langle \nabla p_f \rangle$$

- For isotropic case, normalized scalar **effective transmissivity** along pressure drop OX:

$$K'_{\text{eff}} = -\frac{12\mu\langle q_x \rangle L}{m_0^{3/2}(p_{\text{in}} - p_{\text{out}})}$$

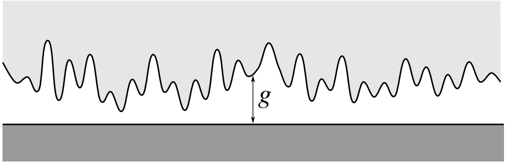
- Using effective medium[1,2] approach

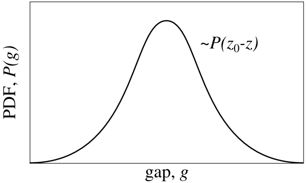
$$(1 - A')\int\limits_0^\infty \frac{g^3 P(g)}{g^3 + K'_{\text{eff}} m_0^{3/2}}\,dg = \frac{1}{2}$$

$A' = A/A_0$ is the contact area fraction, $P(g)$ is the gap probability density.

[1] Kirkpatrick. Rev Modern Phys, 45 (1973)
[2] Lorenz & Persson. Europ Phys J E: Soft Matter, 31 (2010)

- Geometrical overlap model is highly inaccurate





Danger: geometrical overlap

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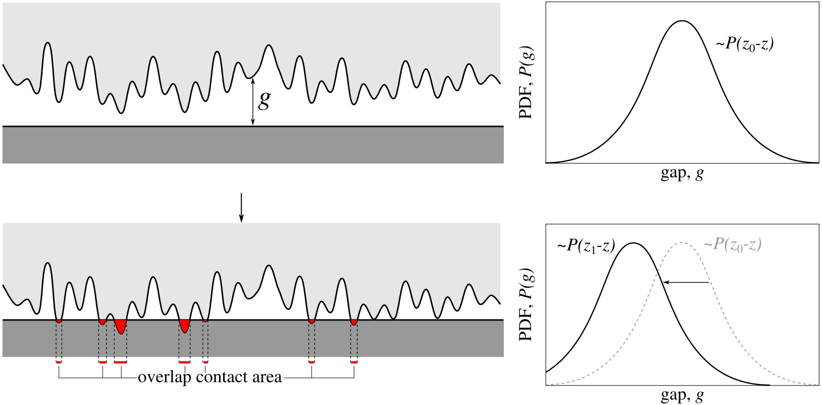
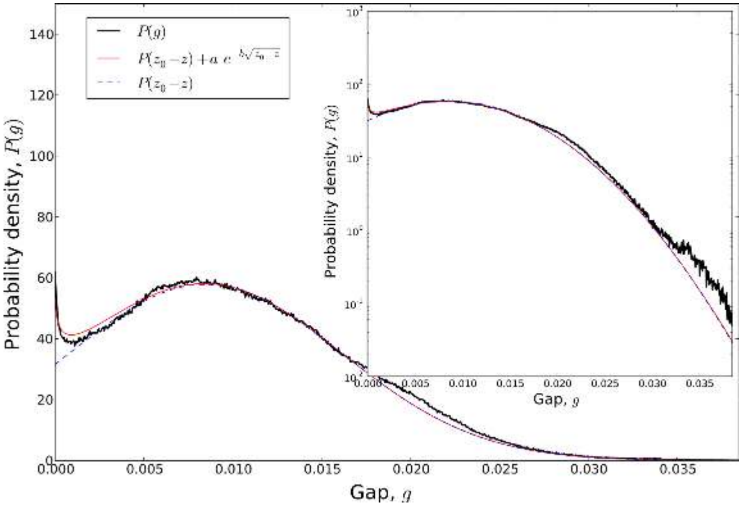


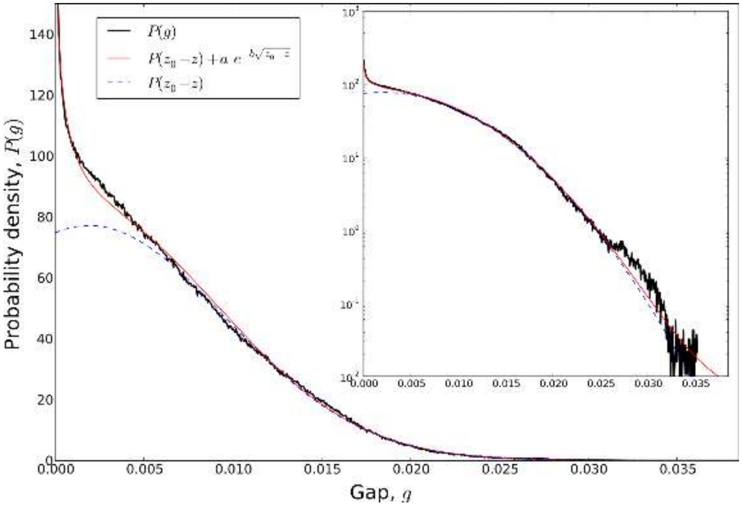
Solid contact results: gap distribution



Area fraction $A' = 1.6\%$

Gap probability density VS geometrical overlap model (dashed line)
Near contact interface $P(g) \sim P(z_0 - z) + a \exp(-b\sqrt{z_0 - z})$

Solid contact results: gap distribution



Area fraction $A' = 9.5\%$

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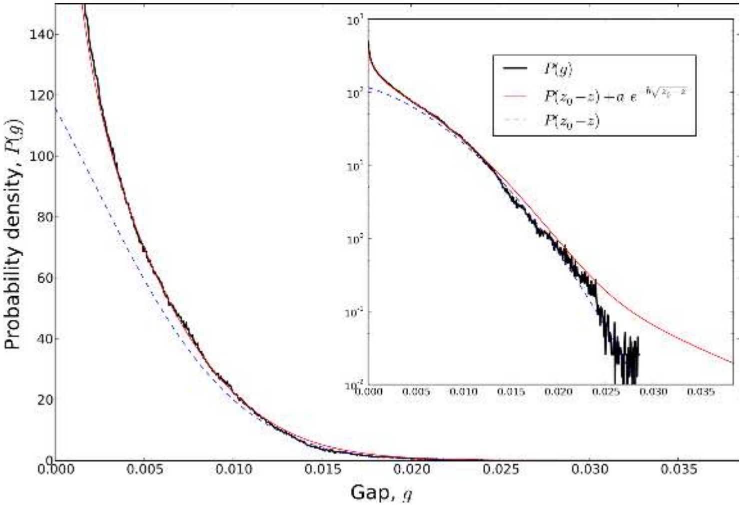
Solid contact results: gap distribution



Area fraction $A' = 24\%$

Gap probability density VS geometrical overlap model (dashed line)
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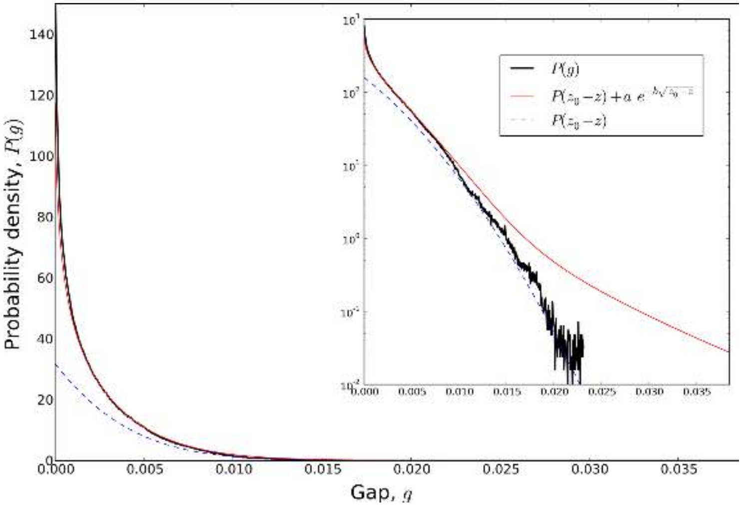

Area fraction $A' = 39\%$

Gap probability density VS geometrical overlap model (dashed line)
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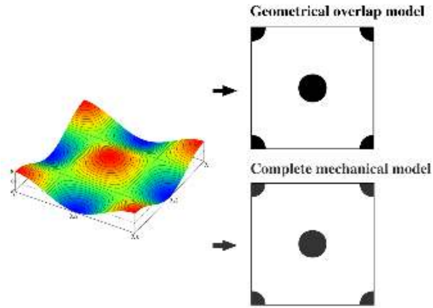
Geometrical overlap: morphology and percolation

- Geometrical overlap model is highly inaccurate[1,2]



[1] Dapp, Lücke, Persson, Müser, *Phys. Rev. Lett.* 108 (2012)

[2] Yastrebov, Anciaux, Molinari. *Tribol Lett*, 56 (2014)

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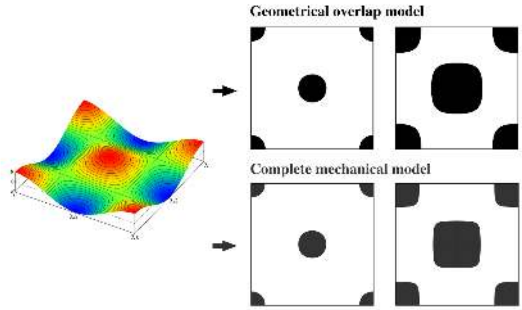

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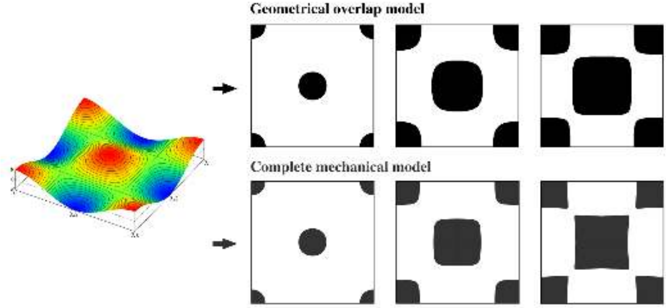

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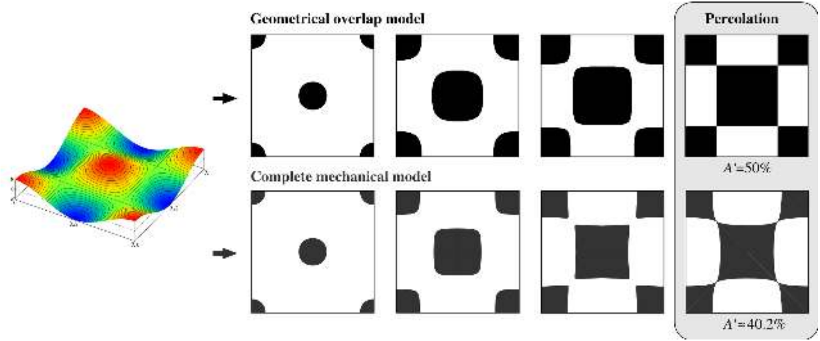

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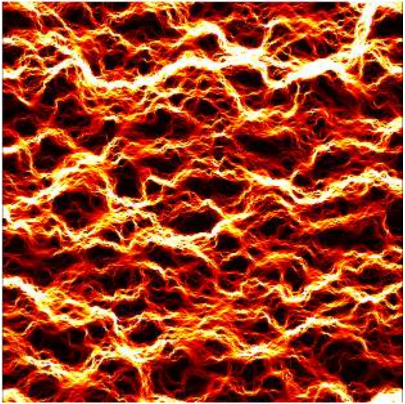
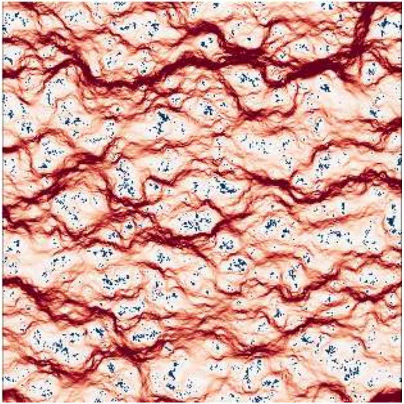
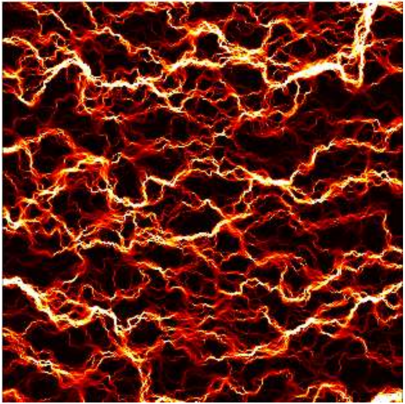
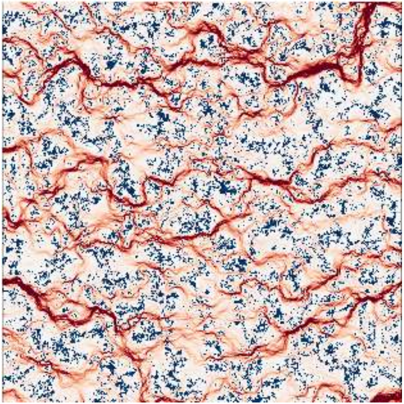




Creeping fluid transport





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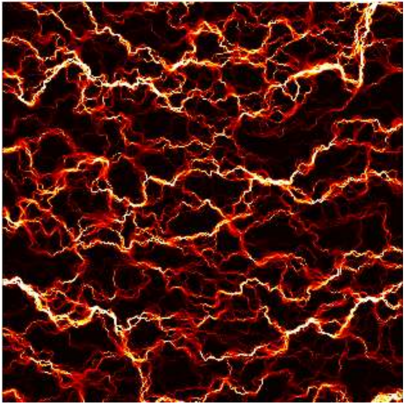

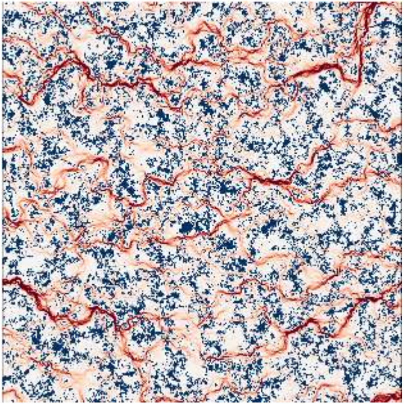

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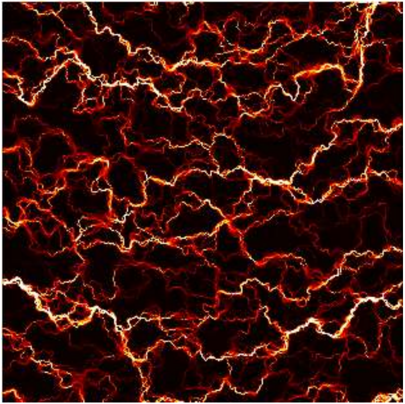 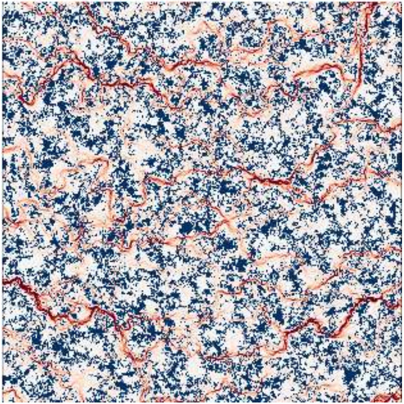

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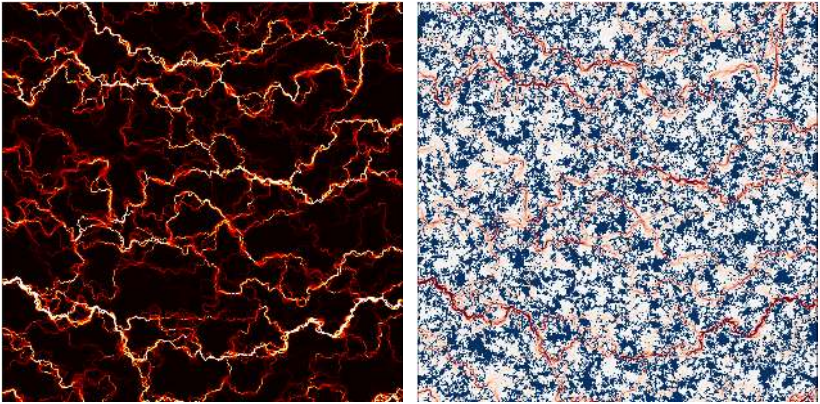

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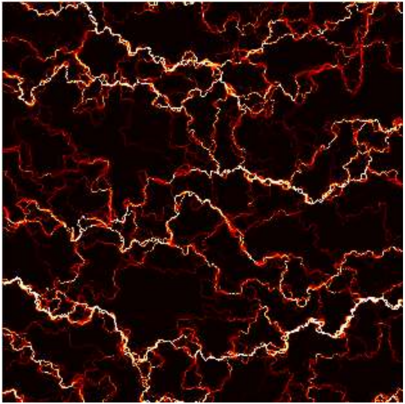 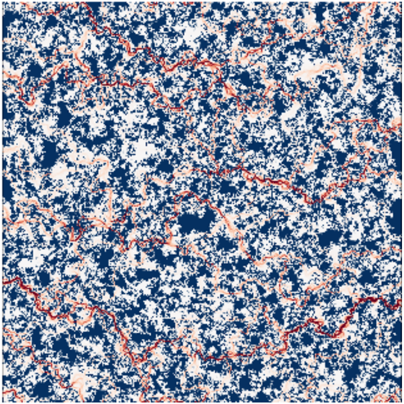

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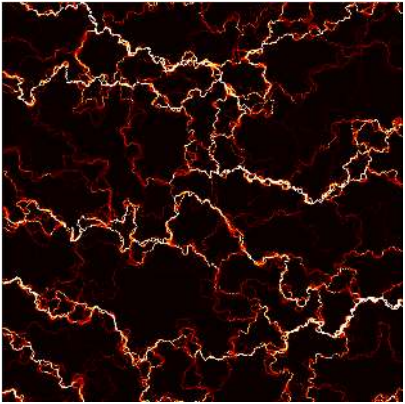

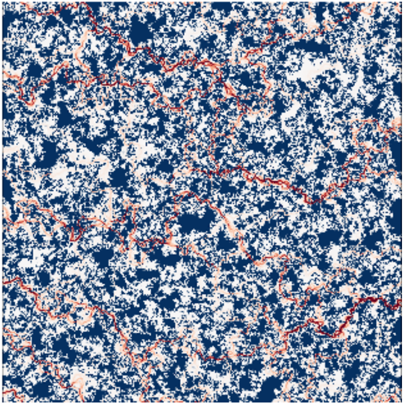

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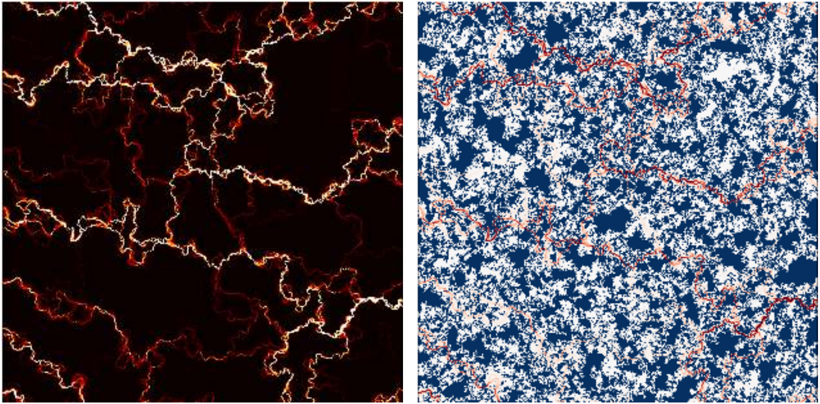

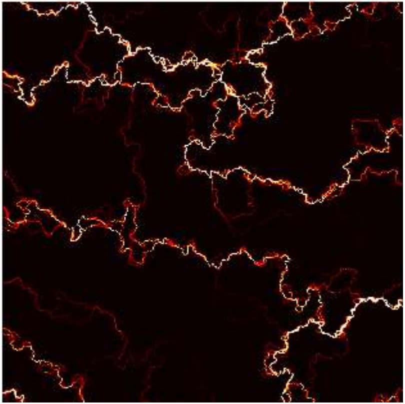

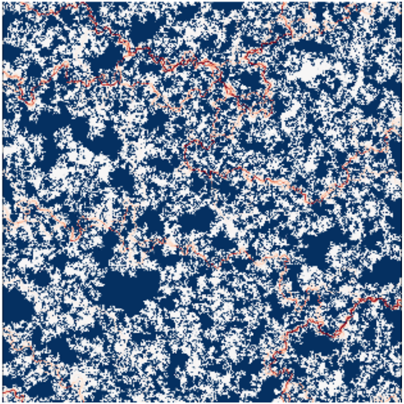

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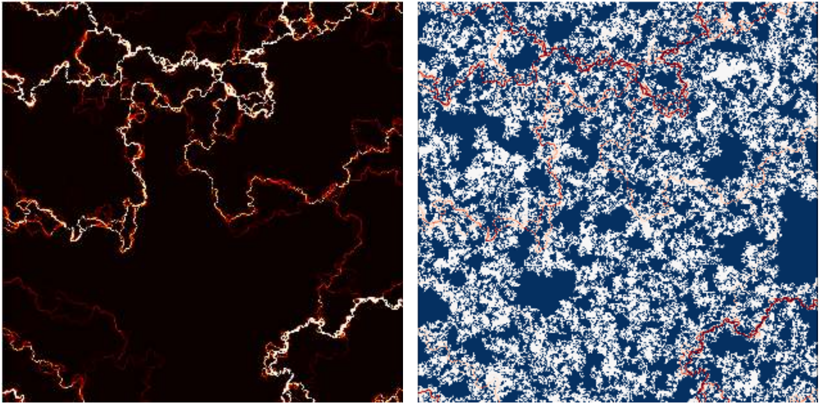

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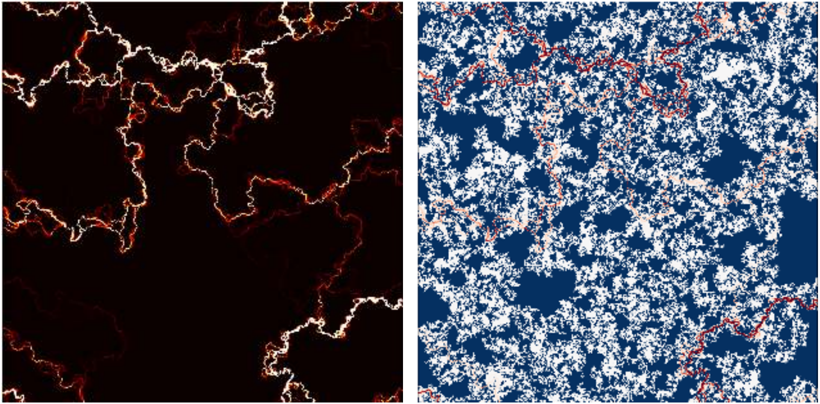

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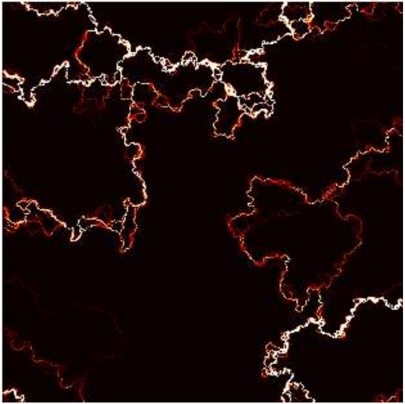

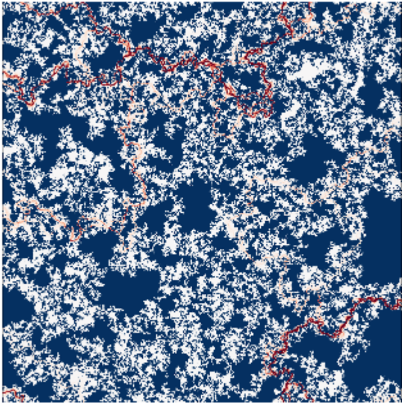

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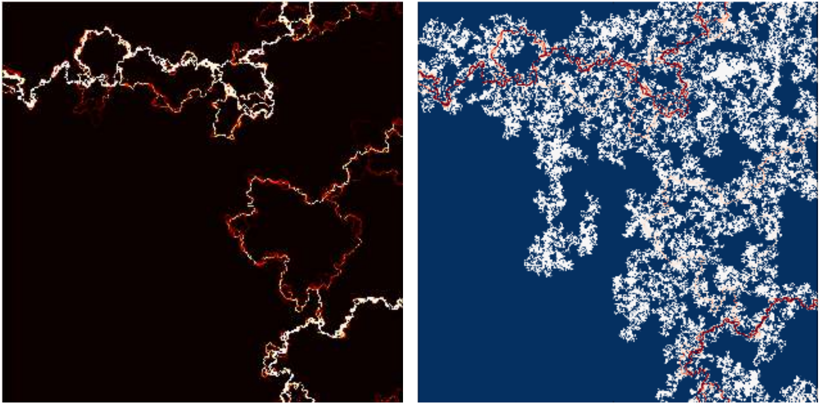

Contact area & trapped fluid

- Contact area does not conduct flow

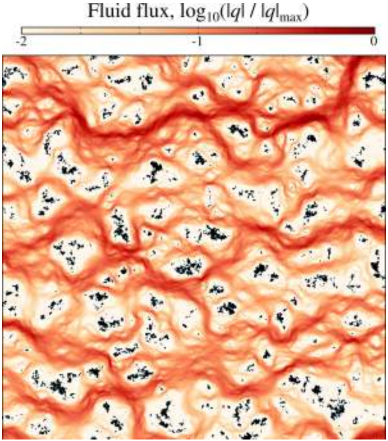

Fig. Fluid flux

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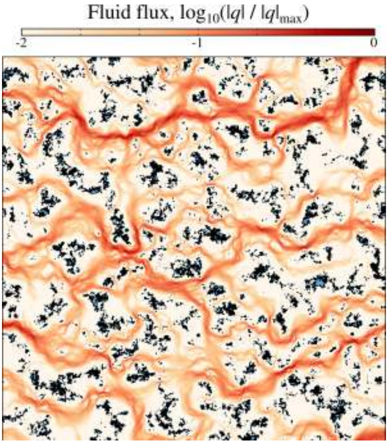

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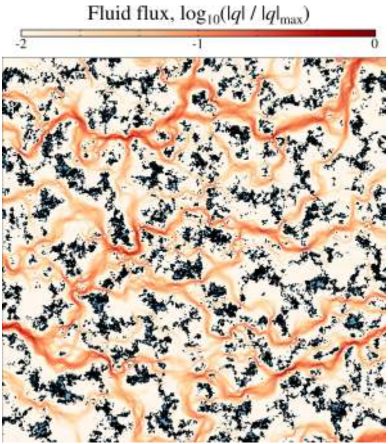

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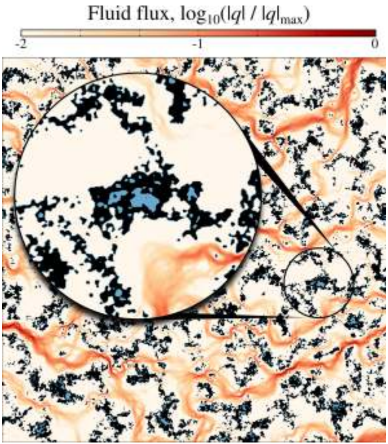


Fig. Fluid flux (zoom)

Contact area & trapped fluid

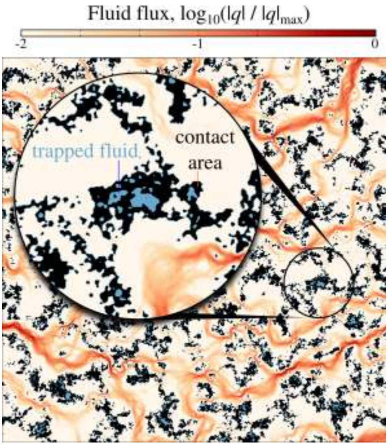
- Contact area does not conduct flow
- Islands of trapped fluid ≡ non-simply connected contact spots do not contribute to conduction
- Thus the effective transmissivity depends on the **effective contact area**:

$$A'_{\text{eff}} = A' + A'_t$$

A' is the contact area fraction
A'_t is the area of trapped fluid

- Effective medium transmissivity:

$$(1 - A' \;) \int\limits_0^\infty \frac{g^3 P(g)}{g^3 + K'_{\text{eff}} m_0^{3/2}}\, dg = \frac{1}{2}$$



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[1] Shvarts, Yastrebov. *Trapped Fluid in the Contact Interface*, JMPS:119 (2018)

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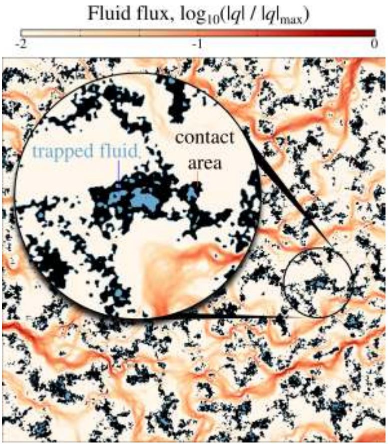

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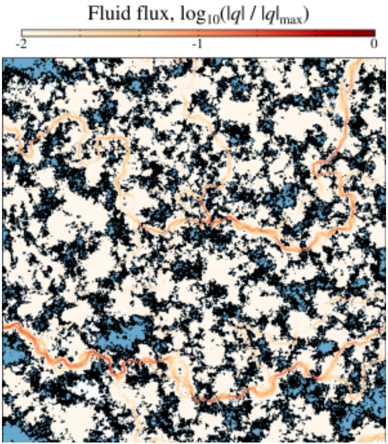

Fig. Fluid flux

[1] Shvarts, Yastrebov. *Trapped Fluid in the Contact Interface*, JMPS:119 (2018)

Contact area & trapped fluid

- Contact area does not conduct flow
- Islands of trapped fluid ≡ non-simply connected contact spots do not contribute to conduction
- Thus the effective transmissivity depends on the **effective contact area**:

$$A'_{\text{eff}} = A' + A'_t$$

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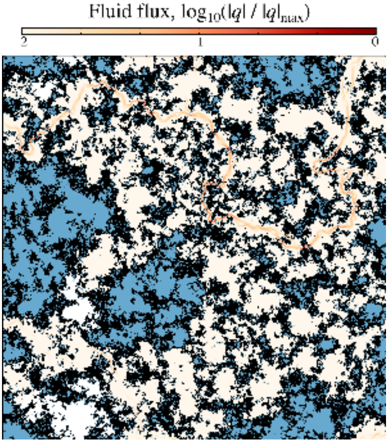

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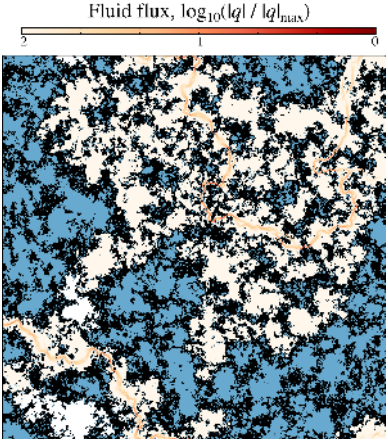

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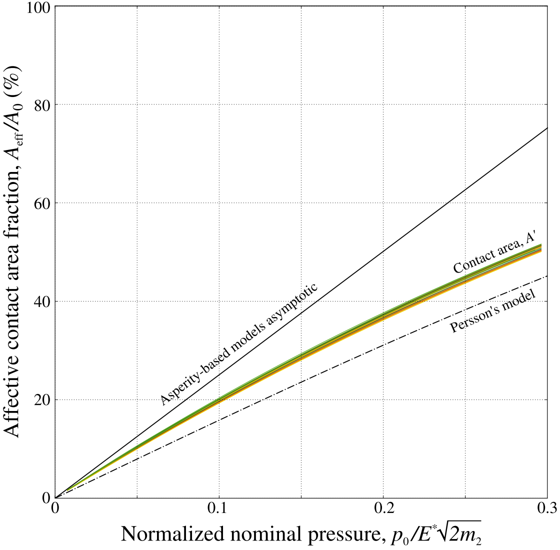

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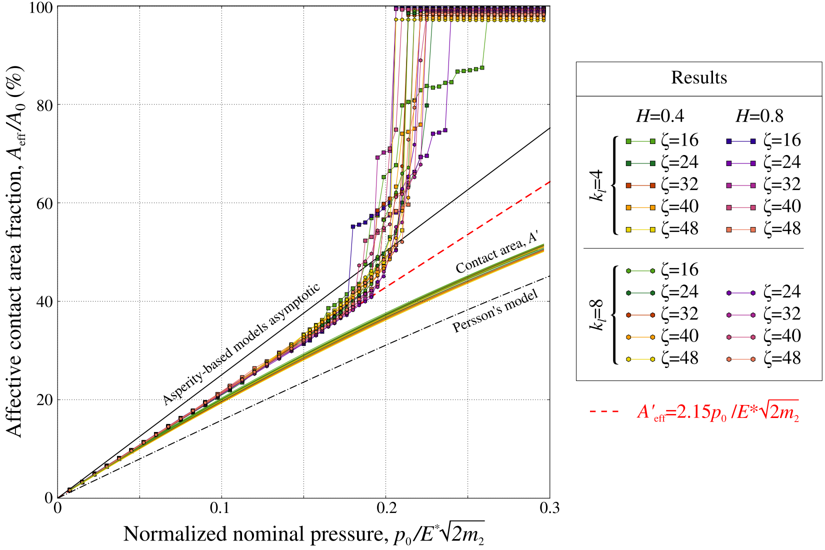
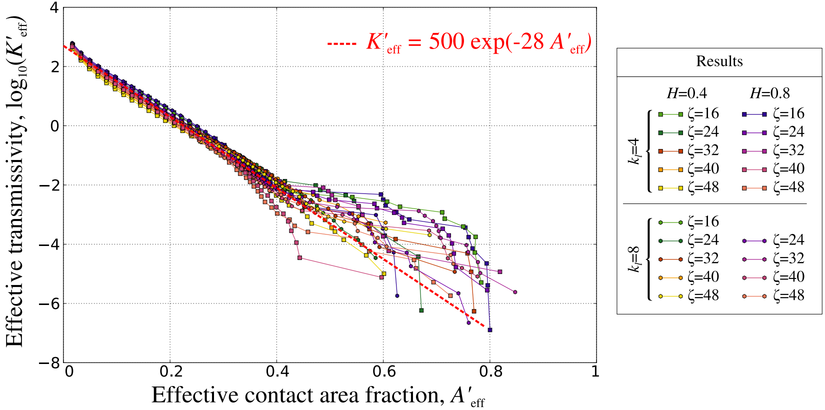




~ normalized nominal pressure p'

Fig. Evolution of the effective transmissivity

Effective transmissivity

- Effective area wrt load:

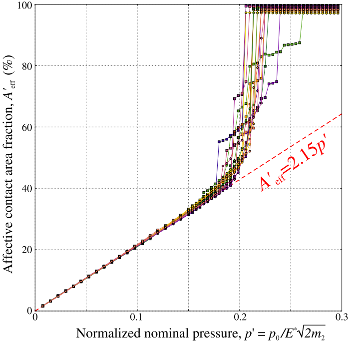
$$A'_{\text{eff}} \approx 2.15p'$$

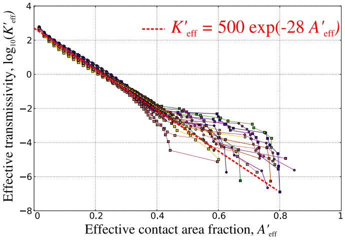
- Normalized load:

$$p' = p_0/E^* \sqrt{2m_2}$$

- Normalized effective transmissivity wrt effective area:

$$K'_{\text{eff}} \approx 500\exp(-28A'_{\text{eff}})$$





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- Recall:

$$K'_{\text{eff}} = -\frac{12\mu \langle\, q_x \,\rangle L}{m_0^{3/2} \Delta P_f}$$

- Express the mean flow:

$$\langle\, q_x \,\rangle = -\frac{K'_{\text{eff}} m_0^{3/2} \Delta P_f}{12 \mu L}$$

- Finally:

$$\boxed{\langle\, q_x \,\rangle \approx -\frac{41.7 \exp(-42.57 p_0 / E^* \sqrt{m_2}) m_0^{3/2} \Delta P_f}{\mu L}}$$

Main result:

Mean flow (far from the percolation) through contact of nominal area $L \times L$:

$$\langle\, q_x \,\rangle \approx -\frac{41.7 m_0{}^{3/2} \Delta P_f}{\mu L} \cdot \exp\left(-42.57 \frac{p_0}{E^* \sqrt{m_2}}\right)$$

u is dynamic viscosity,
ΔP_f is the pressure drop between the inlet and the outlet,
p_0 is the nominal applied pressure,
E^* is the effective elastic modulus.
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m_0 is the variance of roughness,
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Conclusion & current work

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Beyond the one-way coupling:

- Monolithic two-way FEM[1] framework coupling solid and fluid equations (thin flow, Reynolds equation) with contacts including islands of non-linear compressible fluid

[1] A.G. Shvarts, J. Vignollet, V.A. Yastrebov. "Computational framework for monolithic coupling for thin fluid flow in contact interfaces". Computer Methods in Applied Mechanics and Engineering, 379:113738 (2021).

General conclusion

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- But, at Å-scales, continuum mechanics and especially continuum contact[1] do not work.
- Search for relevant physics that could justify $\lambda_s \gg$ Å.
- Candidates: plasticity (scale dependent), surface energy and adhesion, interaction potential.

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☺ Thank you for your attention!