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Quantifying the accuracy of a radial approximation for pile heat exchangers.

Nick Woodman[1], Fleur Loveridge[2], Saqib Javed[3], Johann Claesson[3].

1. University of Southampton, 2. University of Leeds, 3. Lund University

GSHPA Technical Seminar, University of Leeds,24 May 2018

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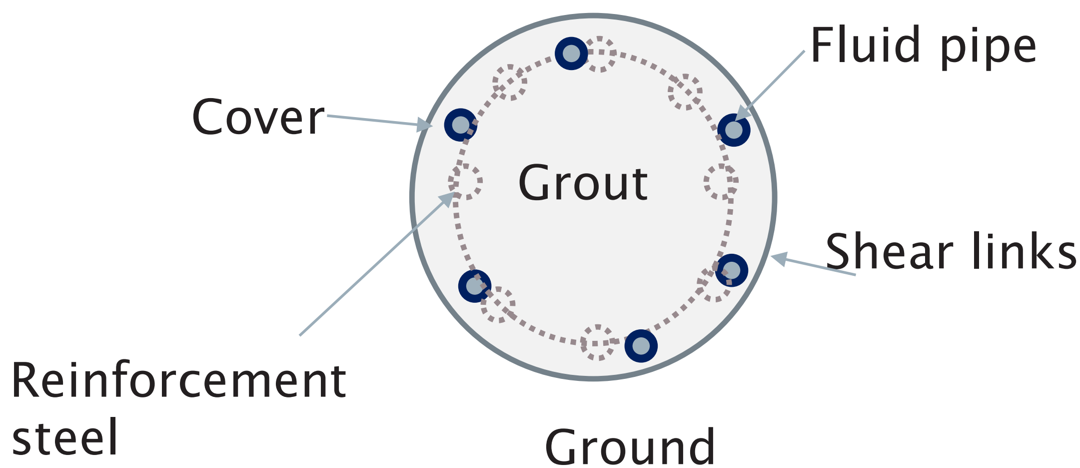
Introduction

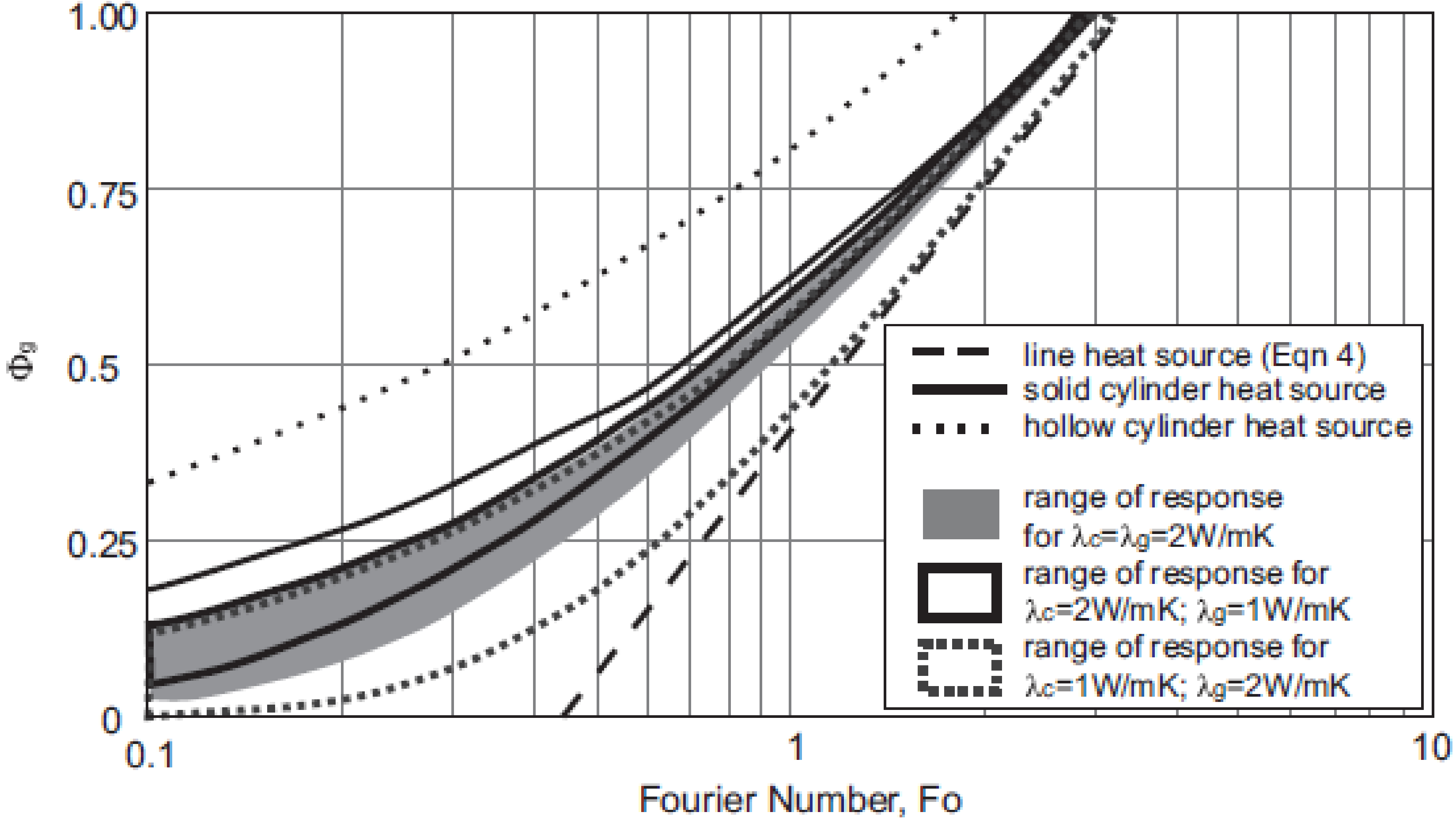
How to model thermal piles with sufficient accuracy?

...using simplest possible acceptable model ('fit for purpose')

...taking into account location of pipes, steel, diffusivity contrast between pile grout and ground?



Pile responses



Loveridge & Powrie, 2013


"Any arrangement"....
DFDP 2 being drilled 2014 Whataroa
Valley, Southern Alps, New Zealand
'Terminated' at 818 m. . .
Groundwater Heads reached 60m
Temperatures reached 110˚C

"Any arrangement"....

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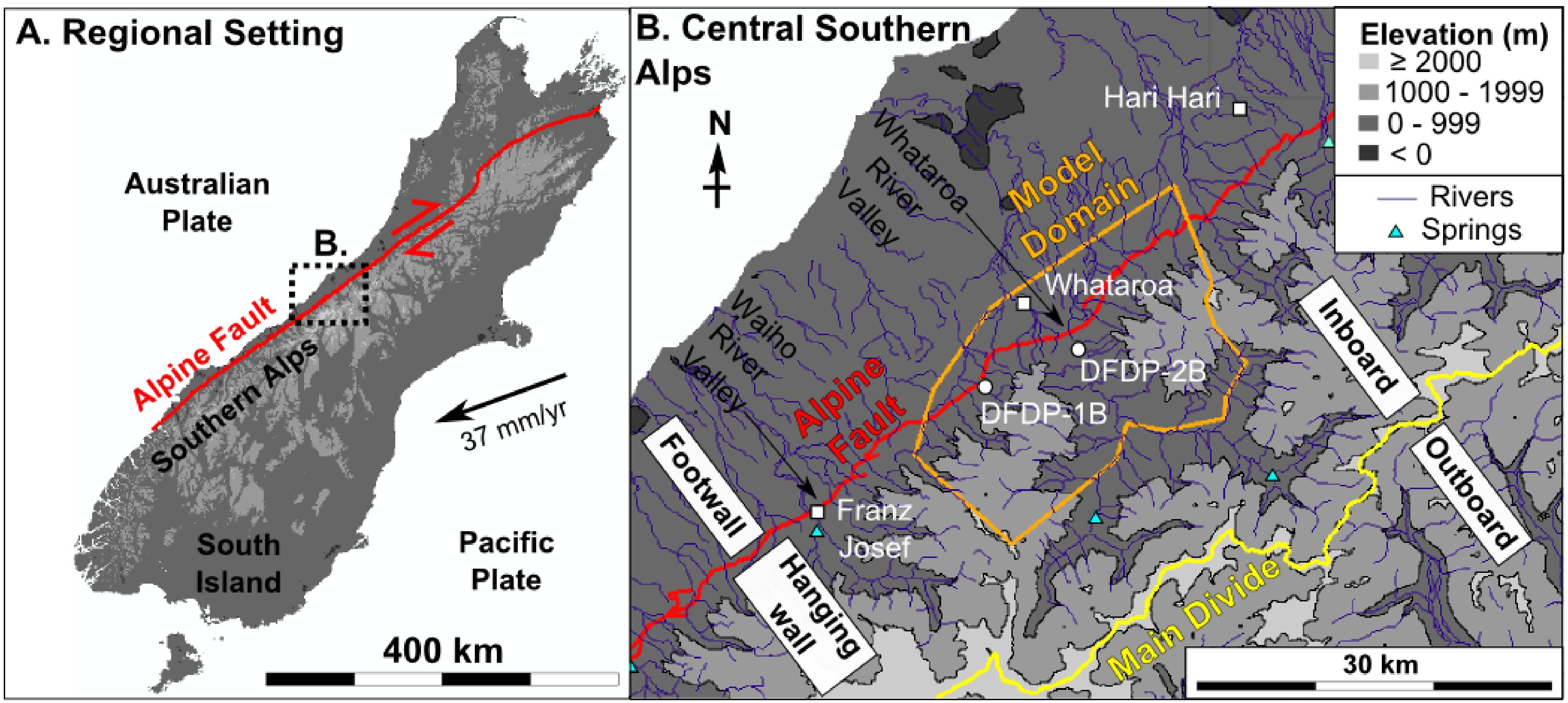
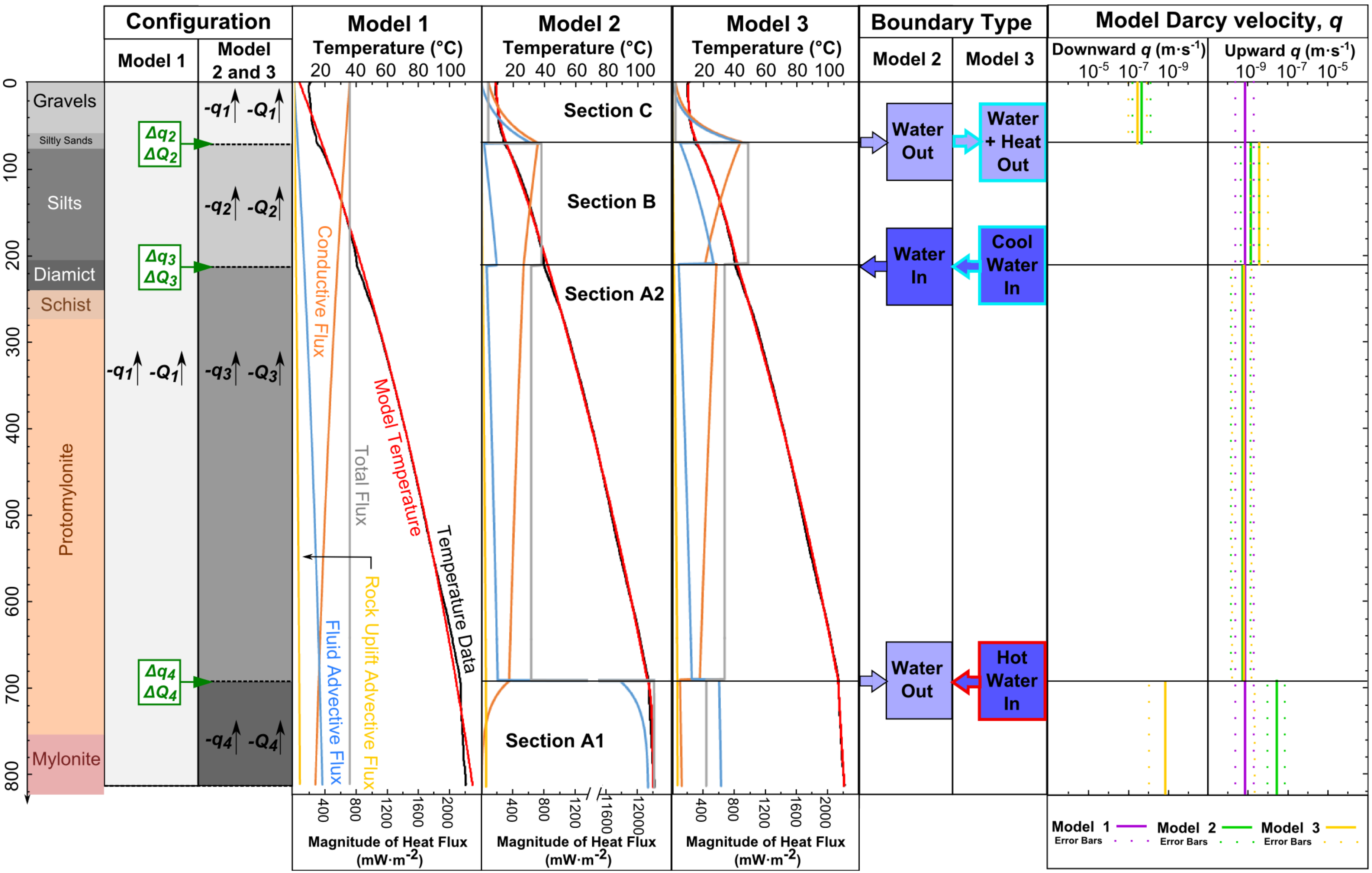
LETTER

doi:10.1038/nature22355

Extreme hydrothermal conditions at an active plate-bounding fault



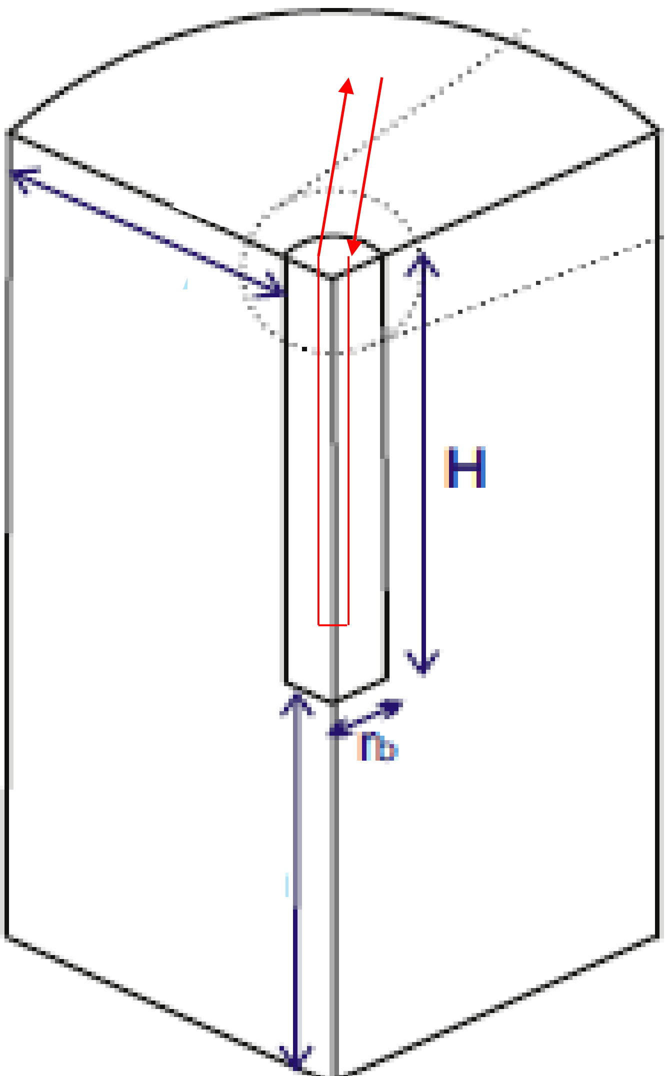
1D insights



Configuration
Model 1
Model 2 and 3
Model 1
Temperature (°C)
Model 2
Temperature (°C)
Model 3
Temperature (°C)
Boundary Type
Model 2
Model 3
Model Darcy velocity, q
Downward q (m·s-1)
Upward q (m·s-1)
Gravels
Siltly Sands
Silts
Diamict
Schist
Protomylonite
Mylonite
Section C
Section B
Section A2
Section A1
Conductive Flux
Total Flux
Model Temperature
Temperature Data
Rock Uplift Advective Flux
Fluid Advective Flux
Water Out
Water + Heat Out
Water In
Cool Water In
Water Out
Hot Water In
Magnitude of Heat Flux (mW·m-2)
Model 1
Error Bars
Model 2
Error Bars
Model 3
Error Bars

Pile Geometry

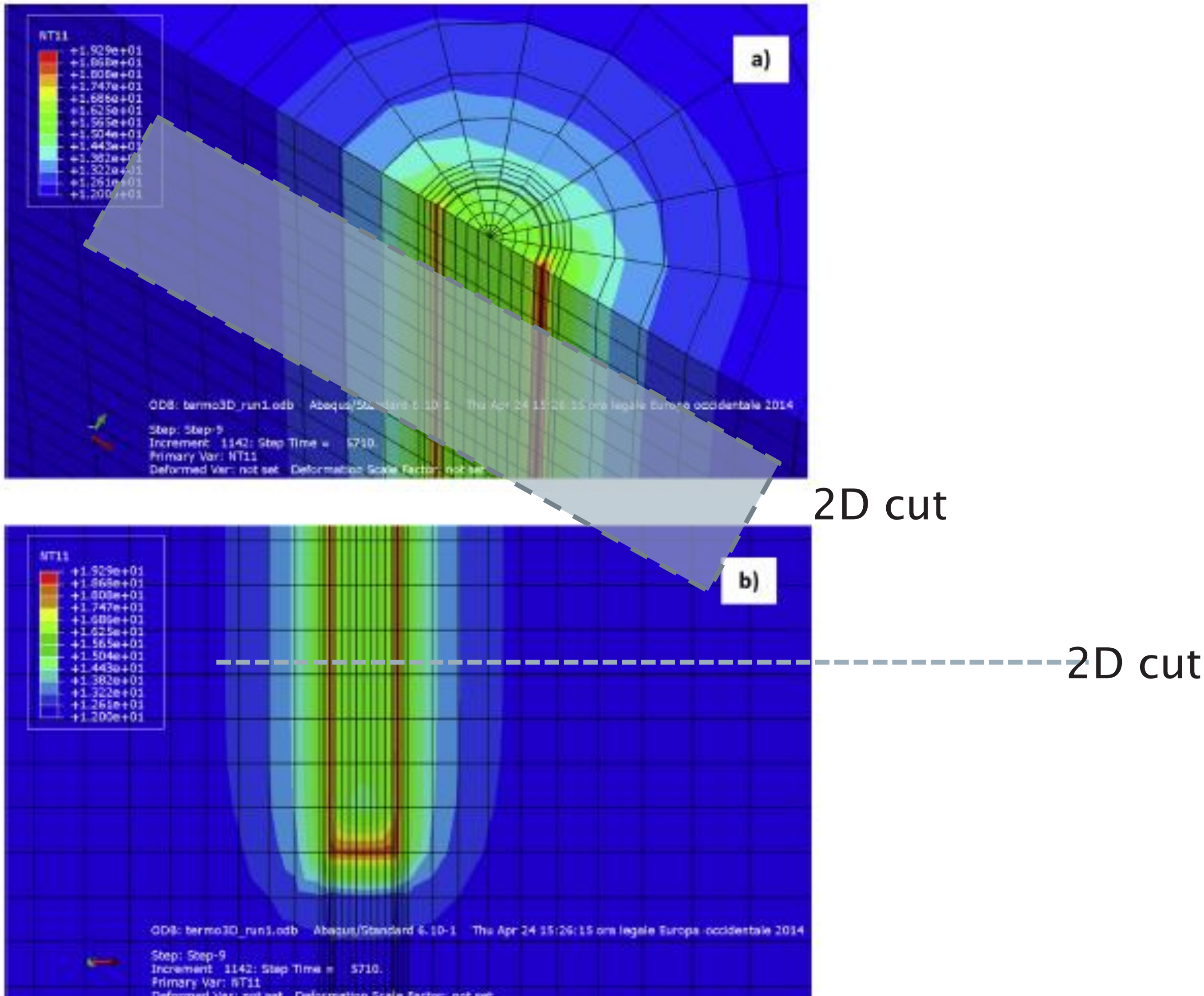
Aspect Ratio, $AR=H/(2r_b)$



Hemmingway, Phil; Long, Michael (Michael M.)

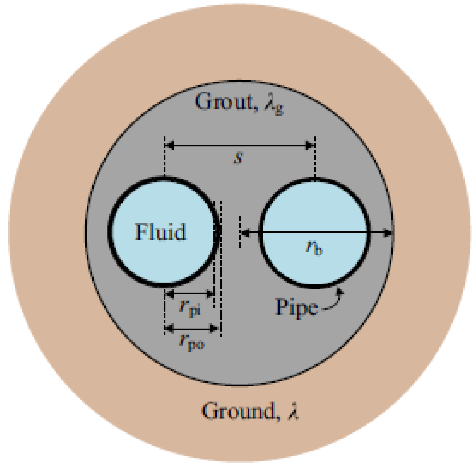
Explicit 3D

F. Cecinato, F.A. Loveridge / Energy 82 (2015) 1021–1033



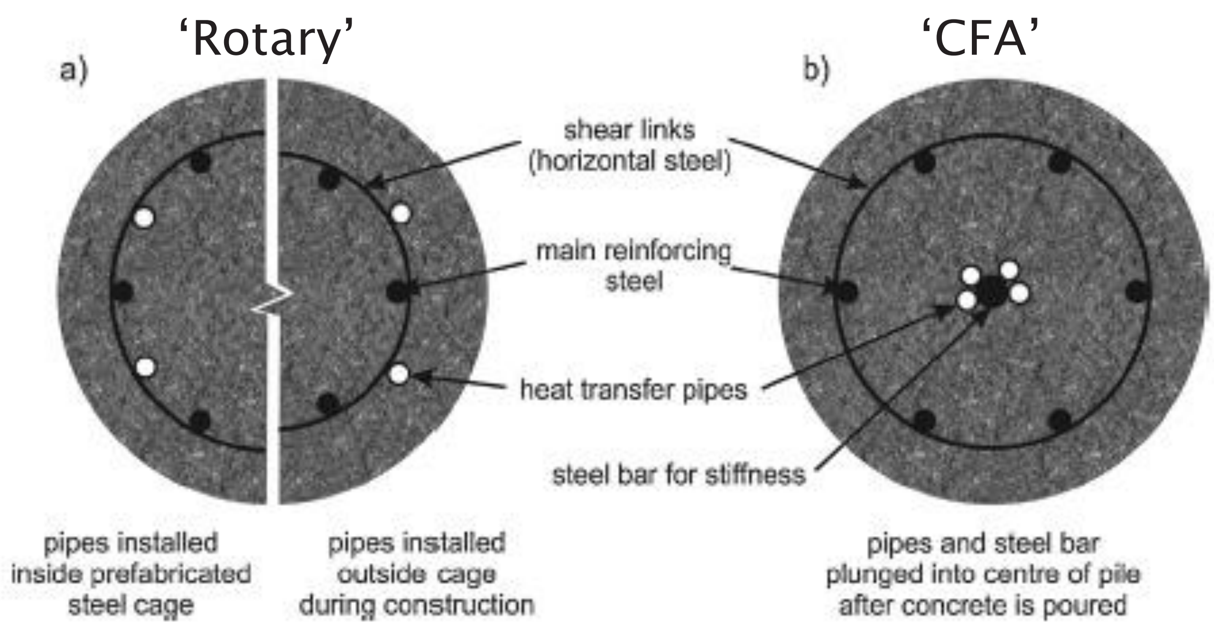
Cecinato & Loveridge, 2015

Borehole Heat Exchanger



- r_b~0.1m
- H~10-100m
- AR~100 (*neglect axial heat-flow)*
- Relatively small thermal mass of grout (*assume steady-state resistance for grout*)

Pile Heat Exchanger



- r_b~1m
- AR~10 (*axial heat-flow*)
- Significant thermal mass (*non-steady-state temperatures in grout except at late-time*)
- More U-tubes

2D model assumptions

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Well-mixed (isothermal) fluid, constant uniform power

Neglect convective resistance (easily added)

Steady-state pipe resistance

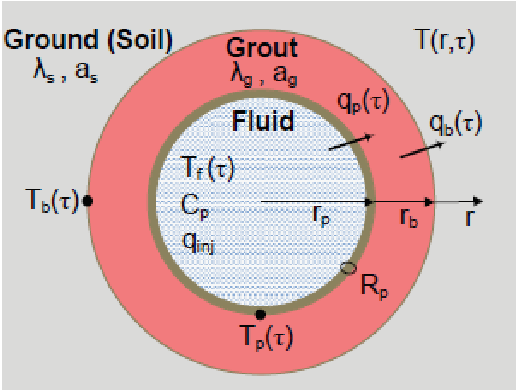
2D-axially symmetric heat flow:

- stationary groundwater
- homogeneous
- initial steady-state
- neglect axial heat flow

No other interactions or constitutive relationships

LV-11-C001

New Analytical and Numerical Solutions for the Short-term Analysis of Vertical Ground Heat Exchangers



Saqib Javed, P.E.
Student Member ASHRAE

Johan Claesson, Ph.D.

Call this "Claesson-Javed Radial Model - CJRM"

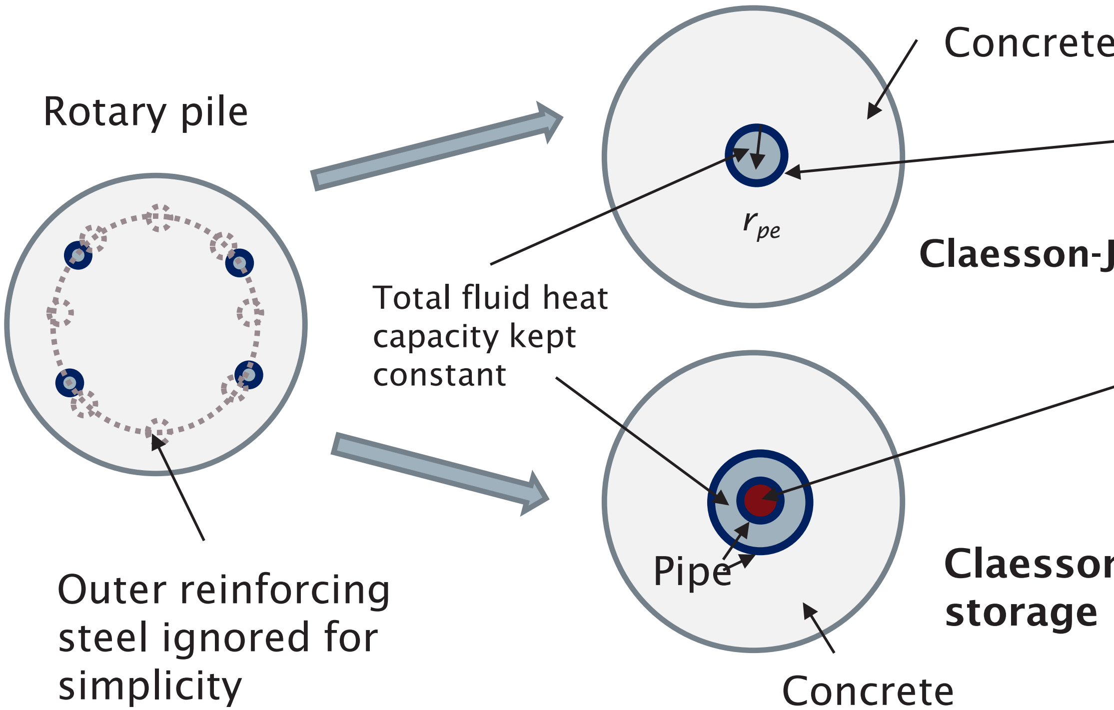
Model equivalence (rotary)

Explicit Geometry (EGM)

Numerical model

Equivalent Radial Geometry

Semi-analytical model



Pipe modelled as steady-state resistance, $R_{pe}=R_P/4$

Claesson-Javed Radial Model - CJRM

Isothermal store,
Heat capacity varied to capture ‘enclosed’ part of pile

Claesson-Javed Radial Model with storage - CJRMS

Keep the ground and concrete properties the same

Model equivalence (CFA)

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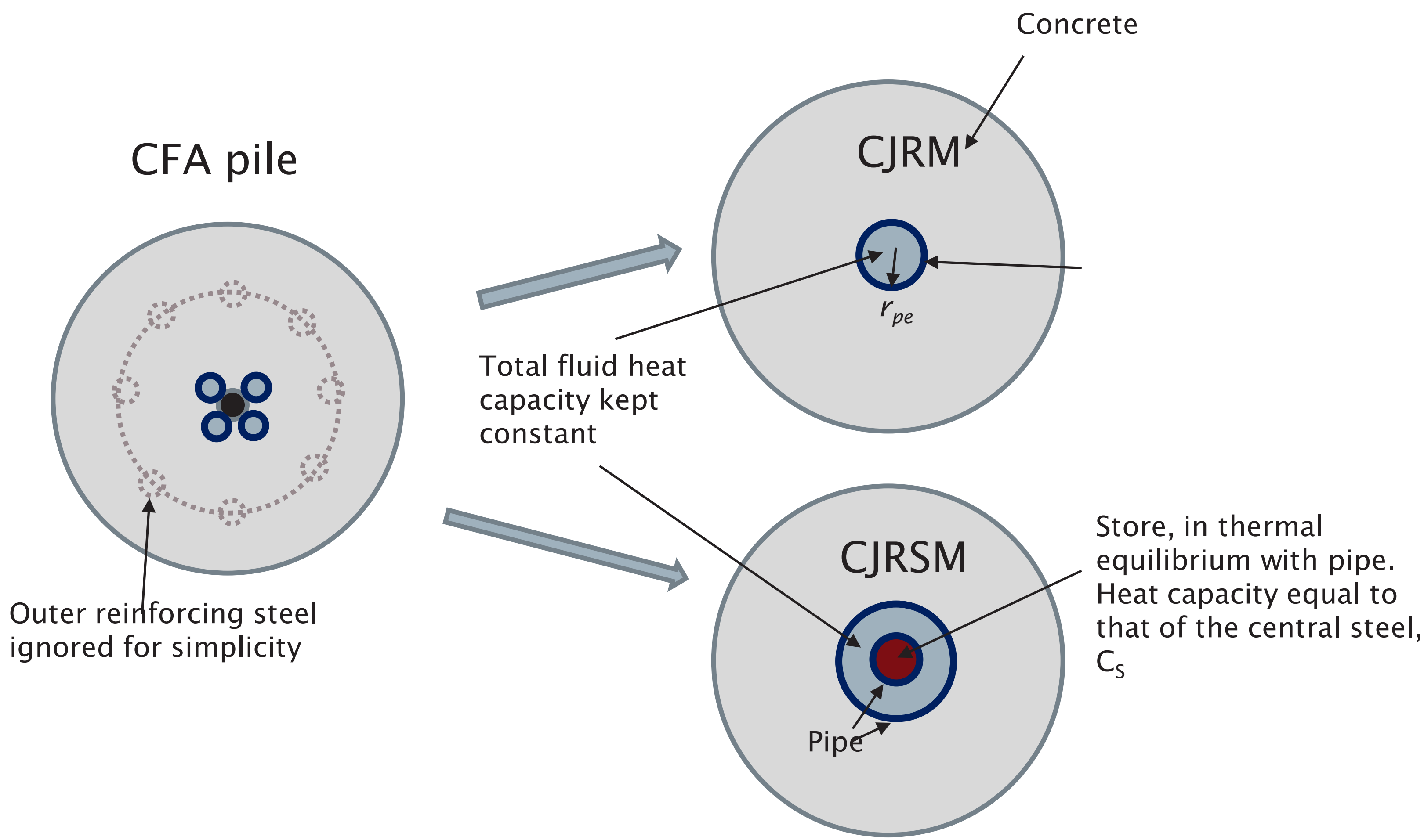
Explicit Geometry (EGM) | Equivalent Radial Geometry



Borehole resistance (steady-state)

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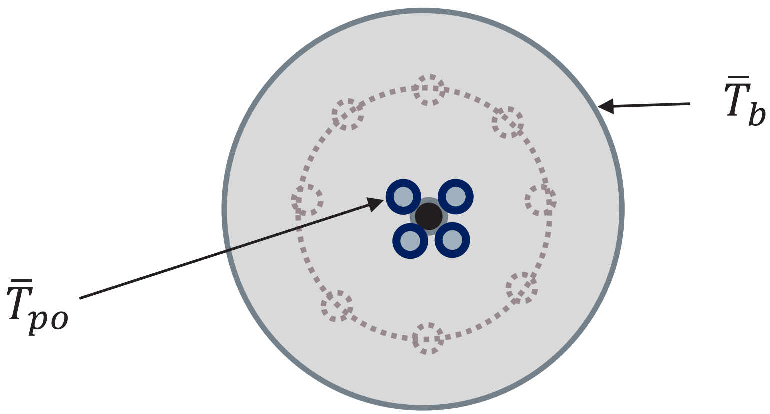
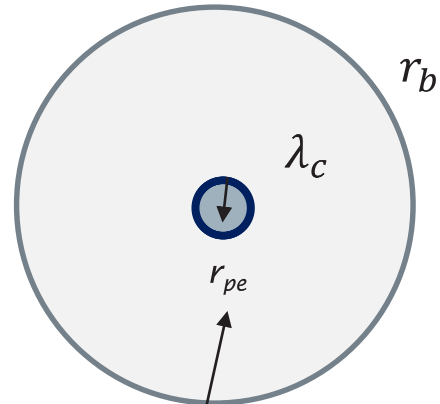
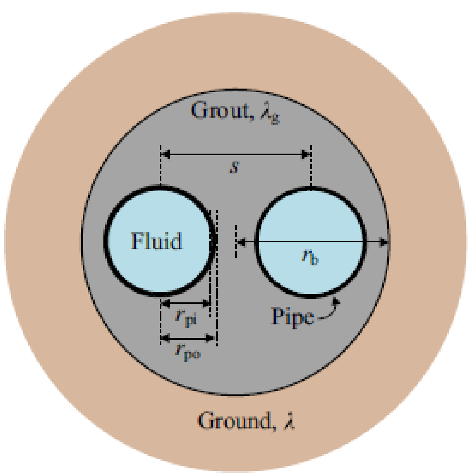
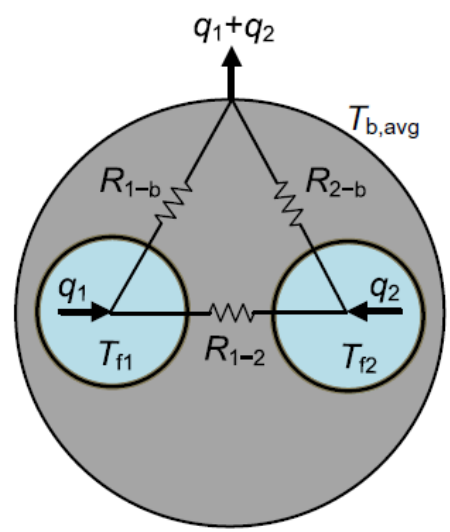




$$\bar{T}_{po} - \bar{T}_b = qR_b = \frac{q}{2\pi\lambda_c}\ln\left(\frac{r_b}{r_{pe}}\right)$$

Javed & Spitler (2017) 10 methods vs. 10th order multi-pole.





Claesson-Javed Radial model ('CJRM')

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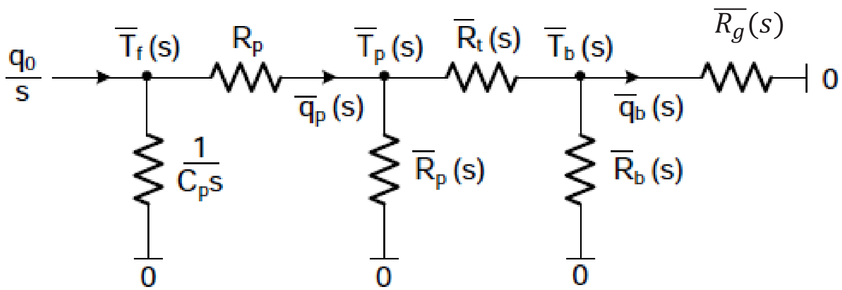
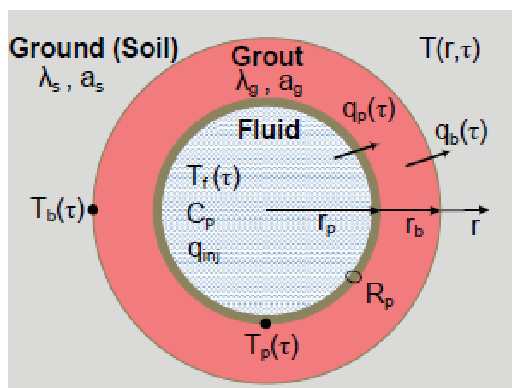


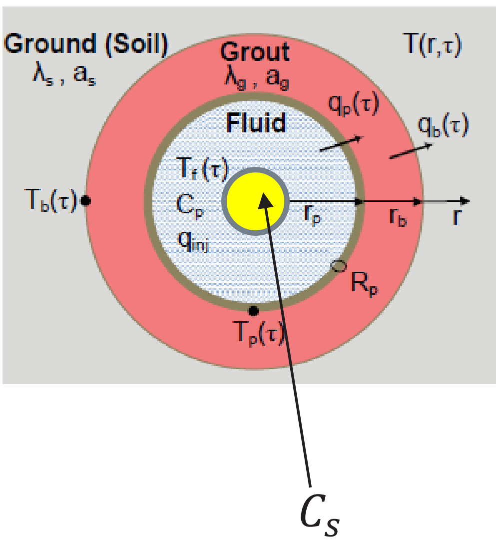
$$\overline{T_f} = \frac{q_0}{s}\frac{1}{C_p s + \cfrac{1}{R_p + \cfrac{1}{\overline{K_p} + \cfrac{1}{\cfrac{1}{\overline{K_t}} + \cfrac{1}{\overline{K_b} + \overline{K_g}}}}}}$$

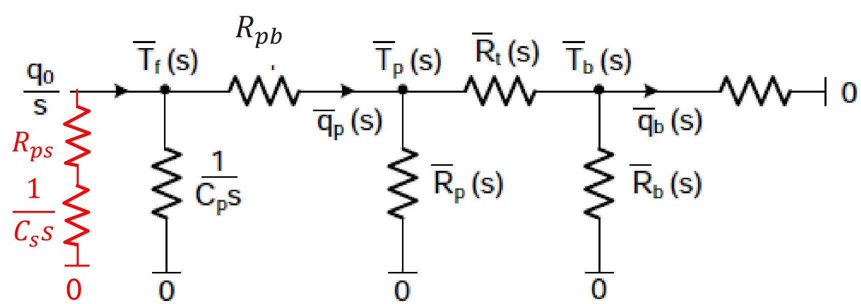


$$\overline{K_g} = \frac{1}{\overline{R_g}} = 2\pi\lambda \frac{\tau_g u\left[J_1(\tau_g u) - iY_1(\tau_g u)\right]}{J_0(\tau_g u) - iY_0(\tau_g u)} \quad \text{etc}$$

Claesson-Javed Radial model with Storage (‘CJRMS’)

$$\overline{T}_f = \frac{q_0}{s}\,\frac{1}{C_p s + \dfrac{1}{R_{ps} + \dfrac{1}{C_s s}} + \dfrac{1}{R_{pb} + \dfrac{1}{\overline{K}_p + \dfrac{1}{\dfrac{1}{\overline{\overline{K}}_t} + \dfrac{1}{\overline{\overline{K}}_b + \overline{\overline{K}}_g}}}}}$$





Validation (radial diffusion)

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WATER RESOURCES RESEARCH, VOL. 24, NO. 10, PAGES 1796–1804, OCTOBER 1988

A Generalized Radial Flow Model for Hydraulic Tests in Fractured Rock

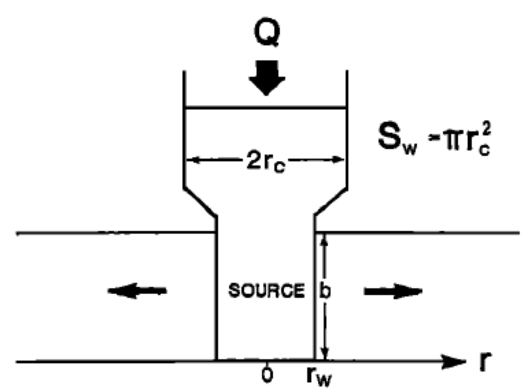
J. A. Barker

British Geological Survey, Wallingford, Oxfordshire, United Kingdom

$$\bar{Q}(p)/\bar{H}(p) = pS_w + K_f b^{3-n} \alpha_n r_w^{n-2} \Phi_\nu(\mu)/[1 + s_f \Phi_\nu(\mu)] \qquad (21)$$

where the function $\Phi_\nu(z)$ is defined by

$$\Phi_\nu(z) = zK_{\nu-1}(z)/K_\nu(z)$$



Aside – useful commonality

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Modelling doublets and double porosity

J.A. Barker

School of Civil Engineering and the Environment, University of Southampton, Highfield, Southampton SO17 1BJ, UK
(e-mail: j.a.barker@soton.ac.uk)

Abstract: A simple model has been developed as a scoping tool for transport between an injection well and an abstraction well pumping at the same rate (i.e. a doublet) in a fractured porous rock. This model is aimed primarily at the planning and preliminary interpretation of tracer tests and trial heat exchange using thermal doublets in the Chalk aquifer. The model is essentially a particular case of transport along

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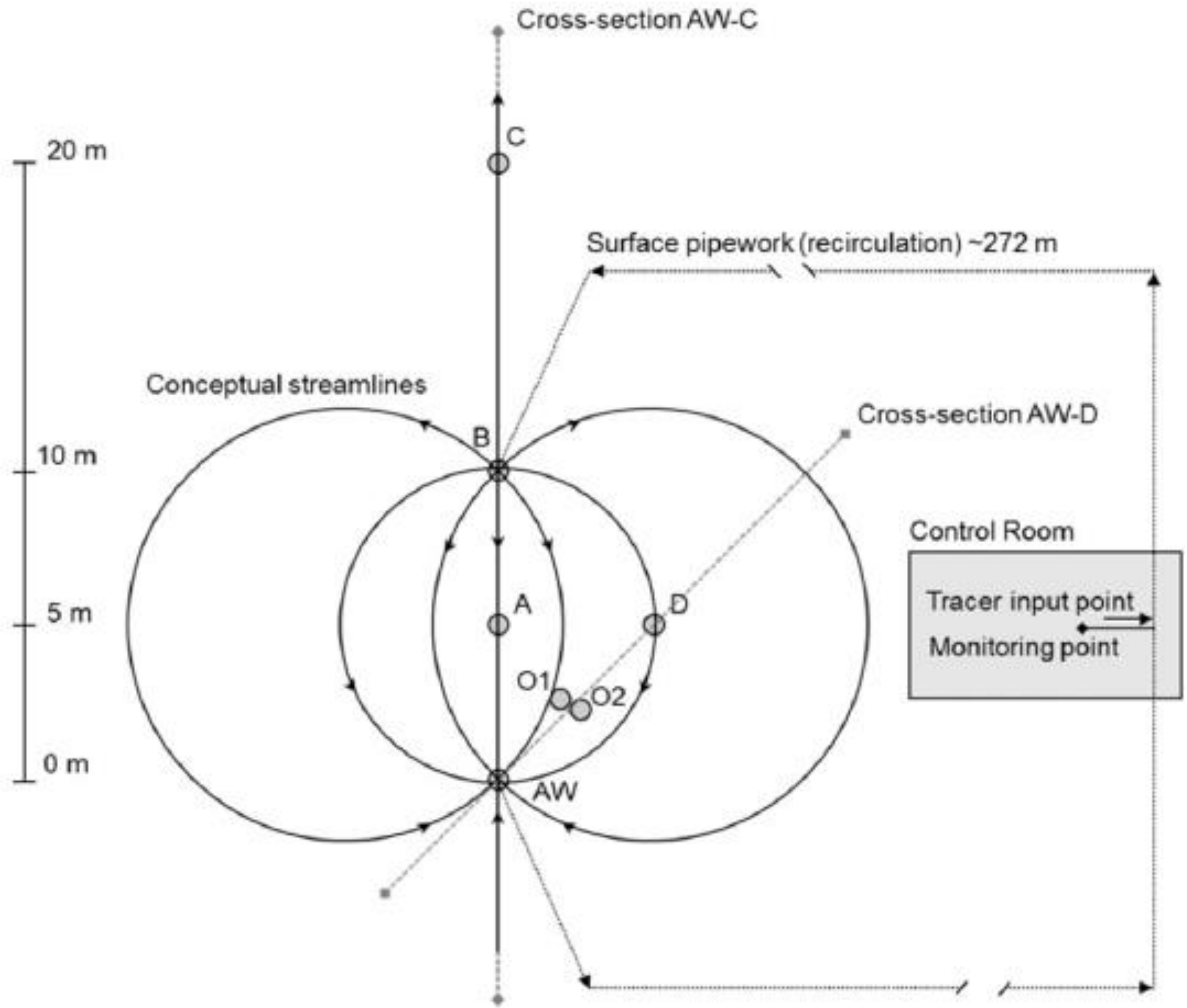
Doublet tracer tests to determine the contaminant flushing properties of a municipal solid waste landfill

CrossMark

N.D. Woodman*, T.C. Rees-White, R.P. Beaven, A.M. Stringfellow, J.A. Barker

Faculty of Engineering and the Environment, University of Southampton, Southampton SO17 1B, UK.


Cross-section AW-C
C
20 m
Surface pipework (recirculation) ~272 m
Conceptual streamlines
B
10 m
Cross-section AW-D
Control Room
Tracer input point
Monitoring point
A
D
5 m
O1
O2
0 m
AW

NUMERICAL MODEL 'EXPLICIT GEOMETRY MODEL (EGM)'

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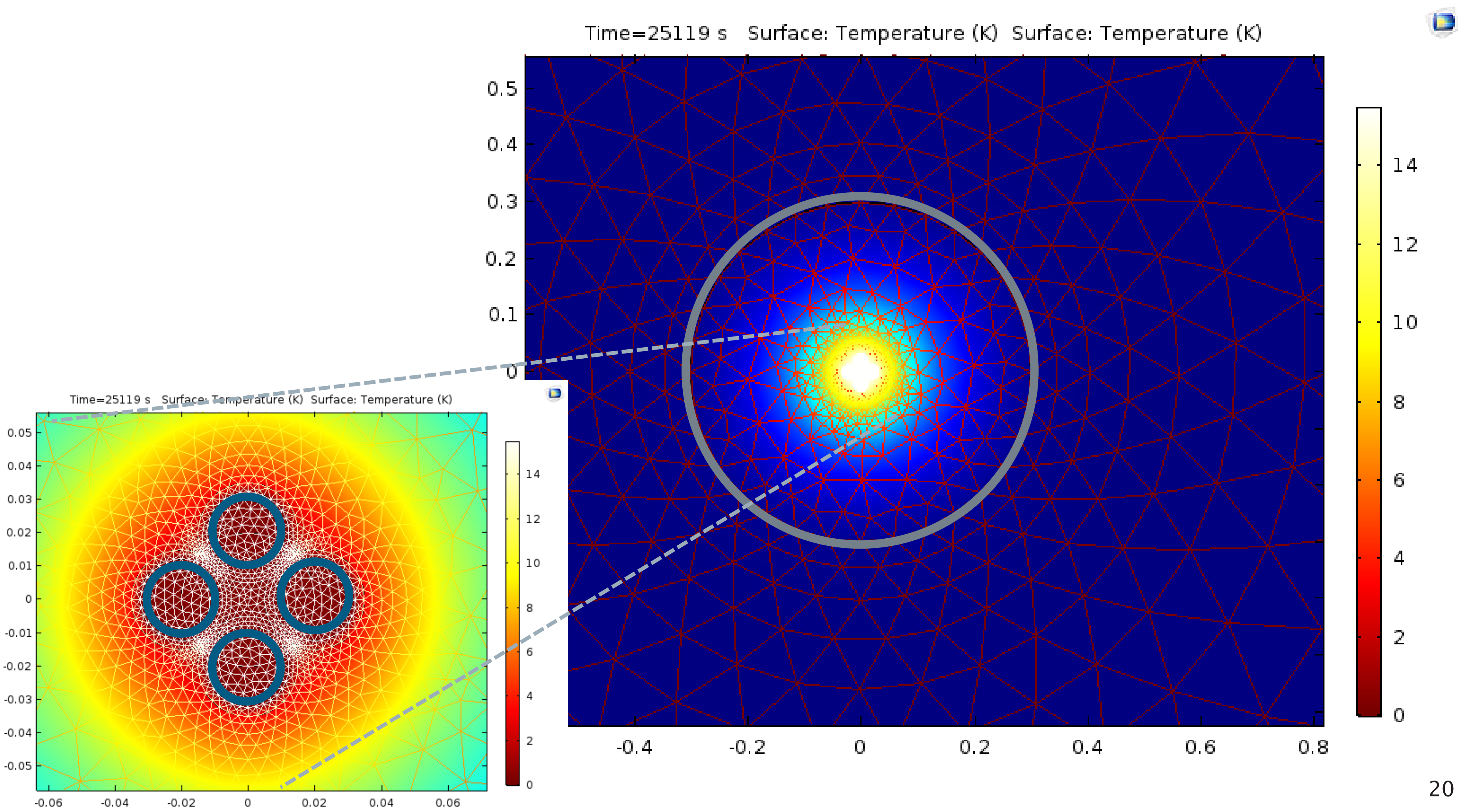

Simulated Thermal Response Test

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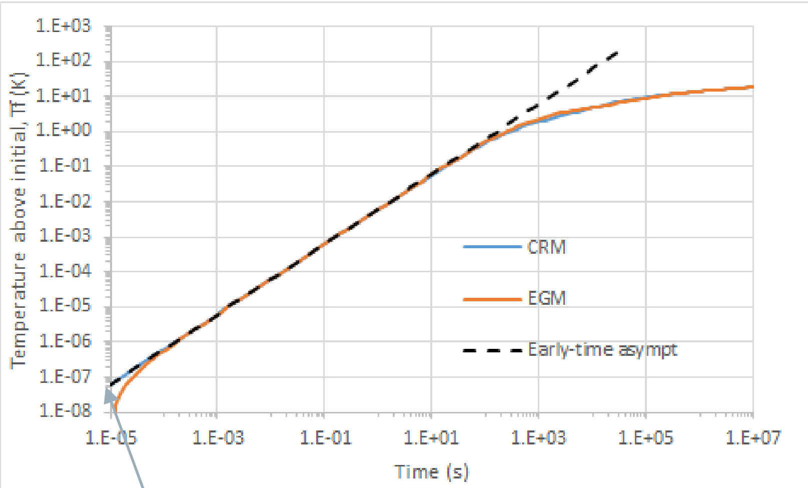
- Inject constant heat into the ground (cooling a building) – 50W/m
- Early-time dominated by the fluid thermal capacity
- Late-time dominated by radial heat flow to the ground
- (with correct steady-state pipe and borehole resistances)
- (ignore axial effects which in reality will come into play at later-time)

Gehlin, 2002

Asymptotes

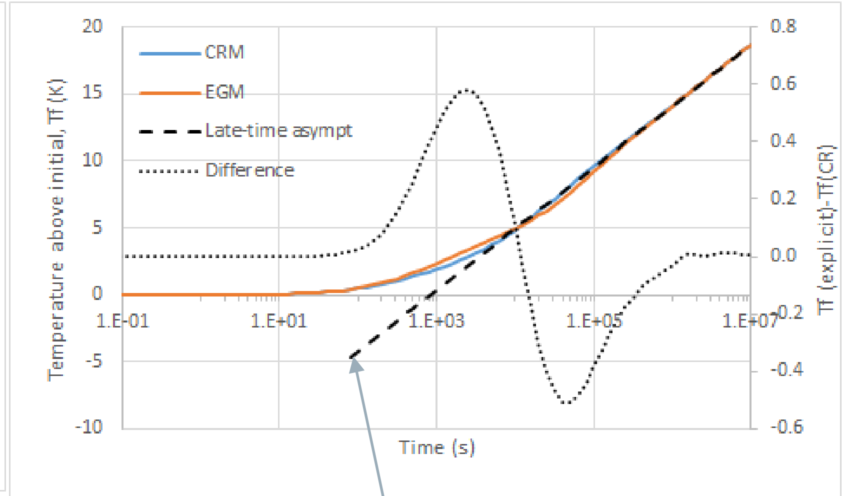
Early-time



$$T_f = qR_p\left(1 - exp\left[-\frac{t}{c_pR_p}\right]\right)$$

$$T_f \sim qt/C_f$$

Late-time ('Jacob approximation')



$$T_f \sim \frac{q}{4\pi\lambda_g}\left[\ln\left(\frac{4\lambda_g t}{c_g\rho_g r_b^2}\right) - 0.5772\right] + qR_p + qR_b$$

$$Fo = \alpha_g t/r_b^2 > 5$$

Rotary geometry (r_b=300 mm) for (λ_c,λ_g) =(1,2)W/mK

$\Phi = 2\pi\lambda_g \Delta T_f / q$

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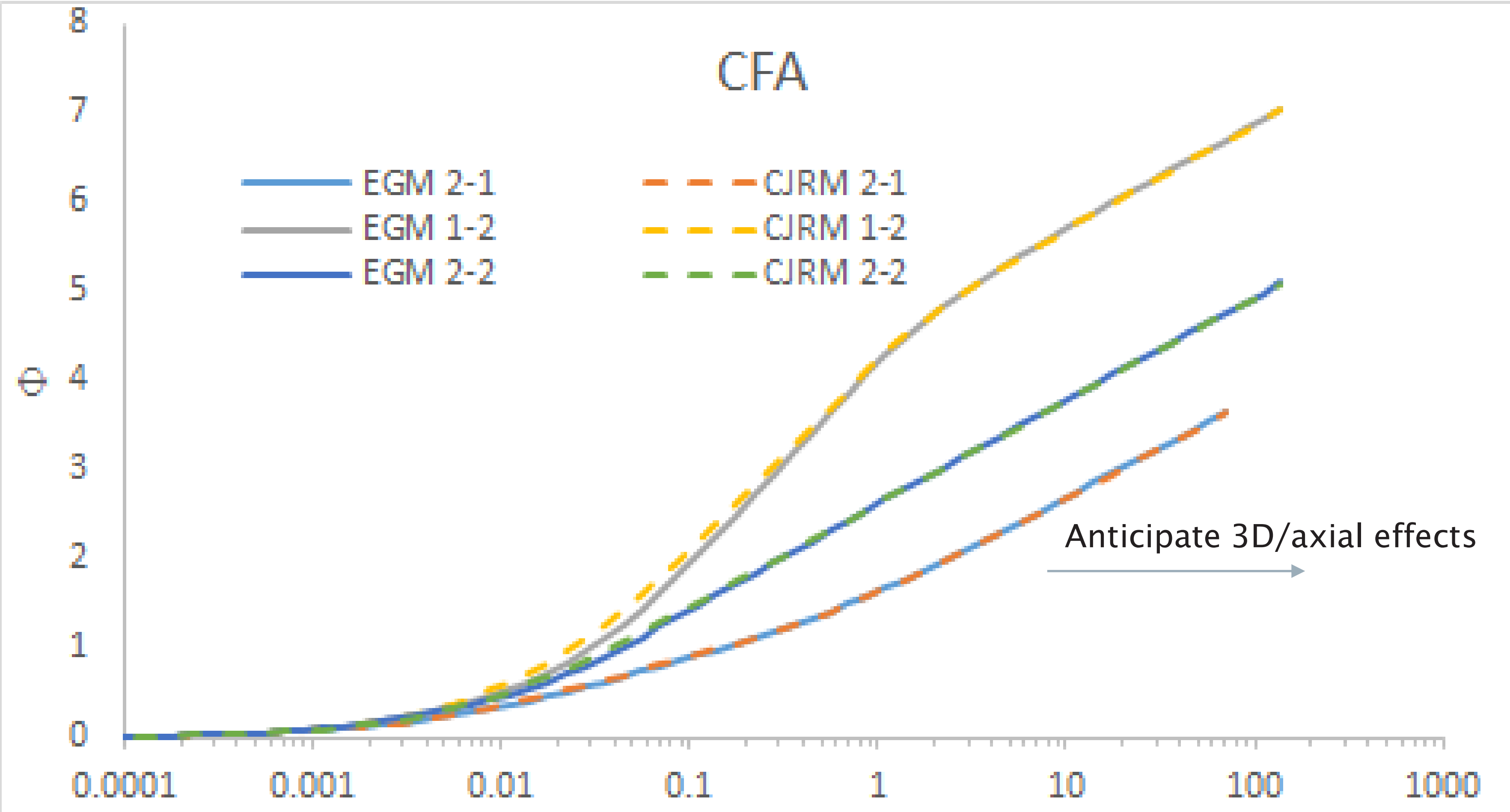
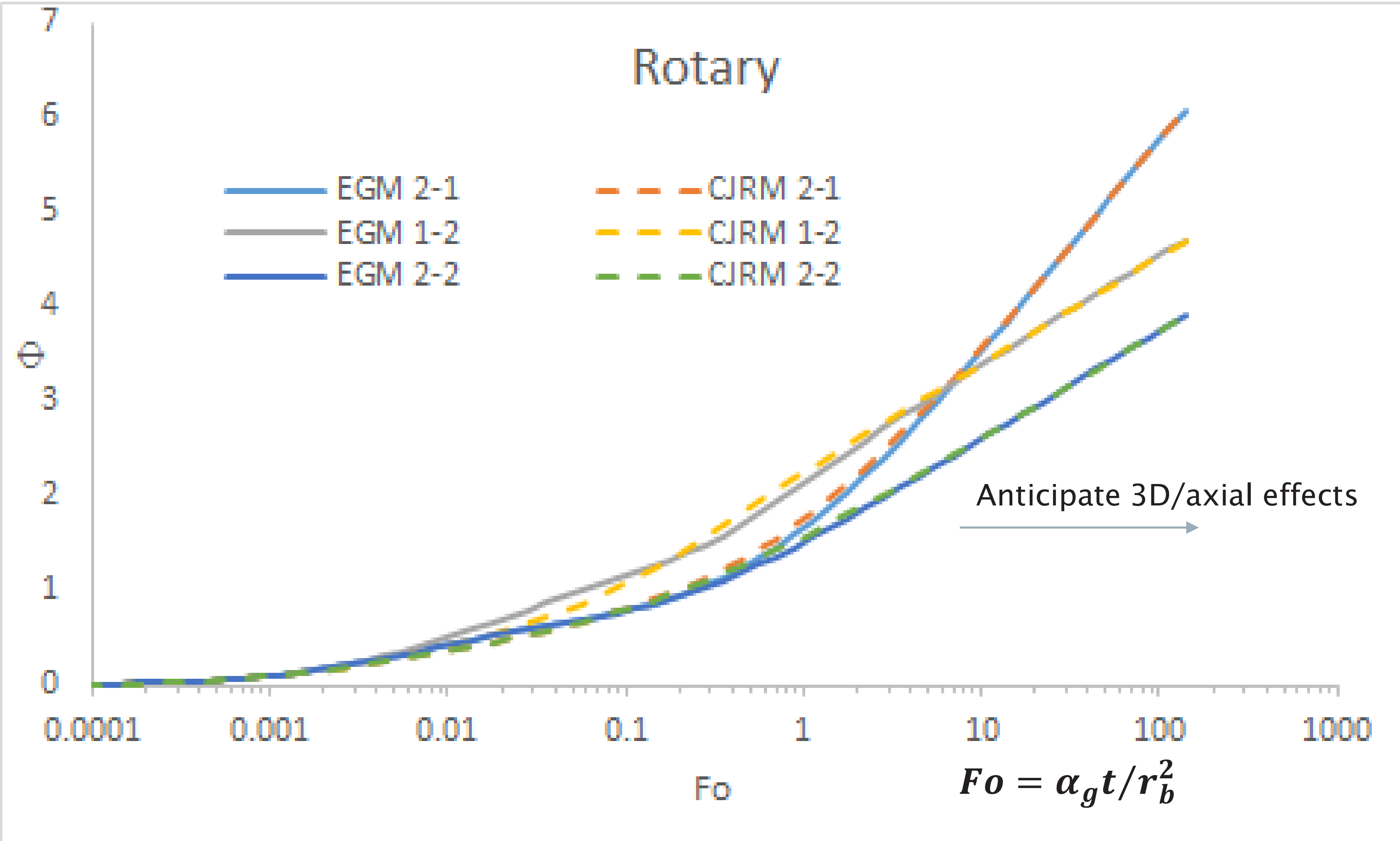


$Fo = \alpha_g t / r_b^2$

Maximum fluid temperature discrepancy 0.7°C

$$\Phi = 2\pi\lambda_g \Delta T_f / q$$



Maximum fluid temperature discrepancy 0.6˚C

Fitting – change λ_c

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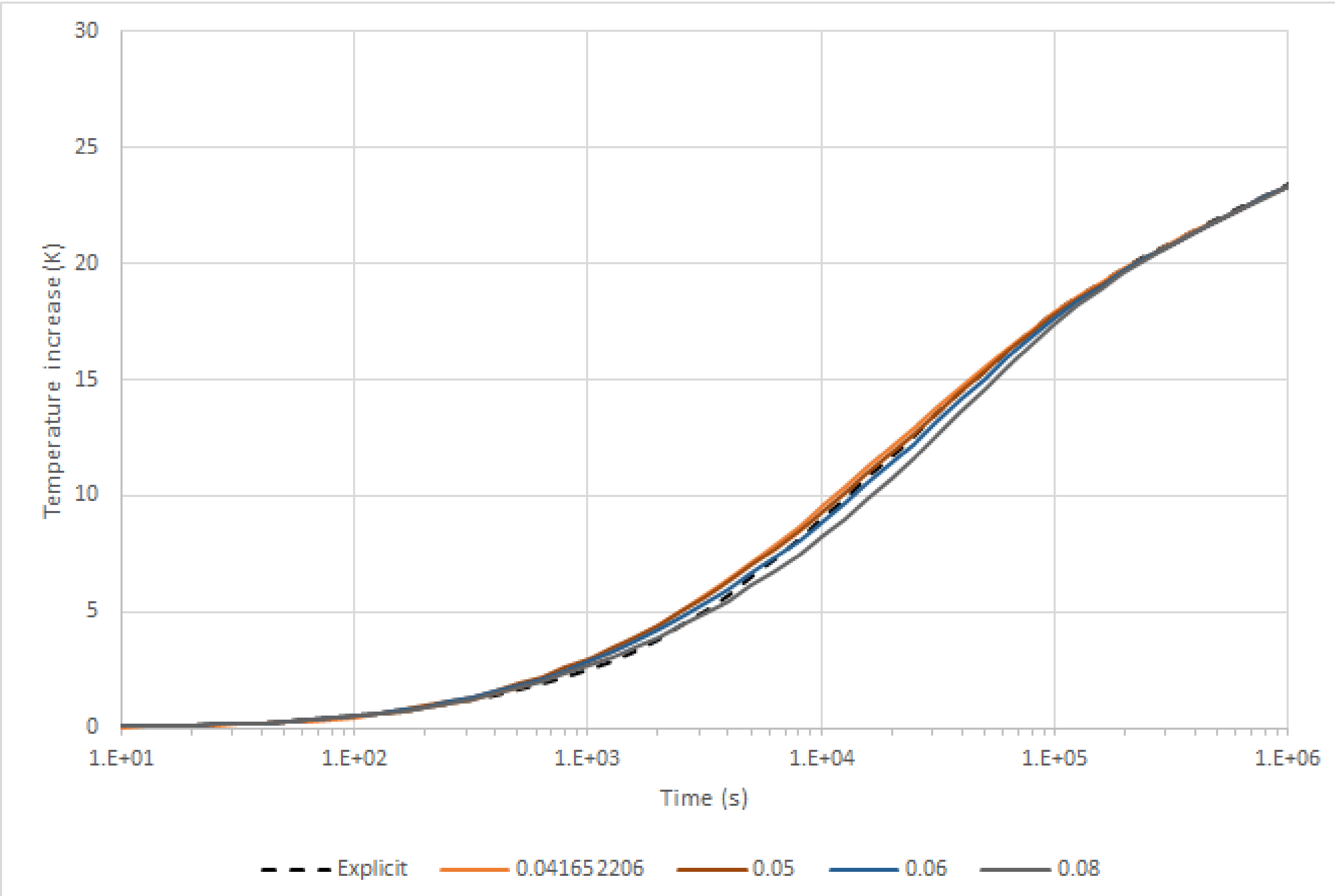
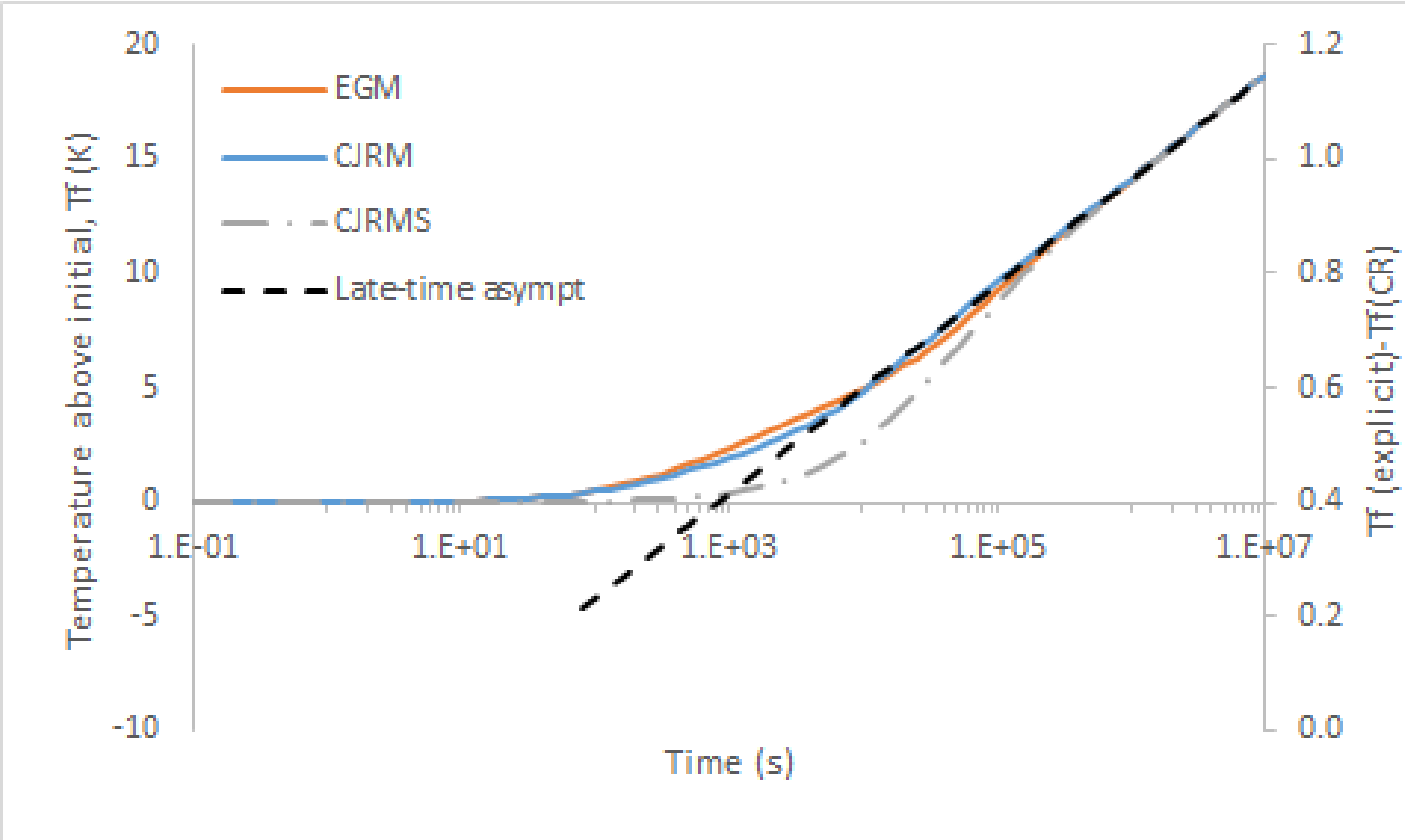


Rotary 1-2. 300mm

CJRMS

Rotary1-2, 300mm
Makes it worse!
Poor conjecture: not physically realistic



Step back – recall the simple models

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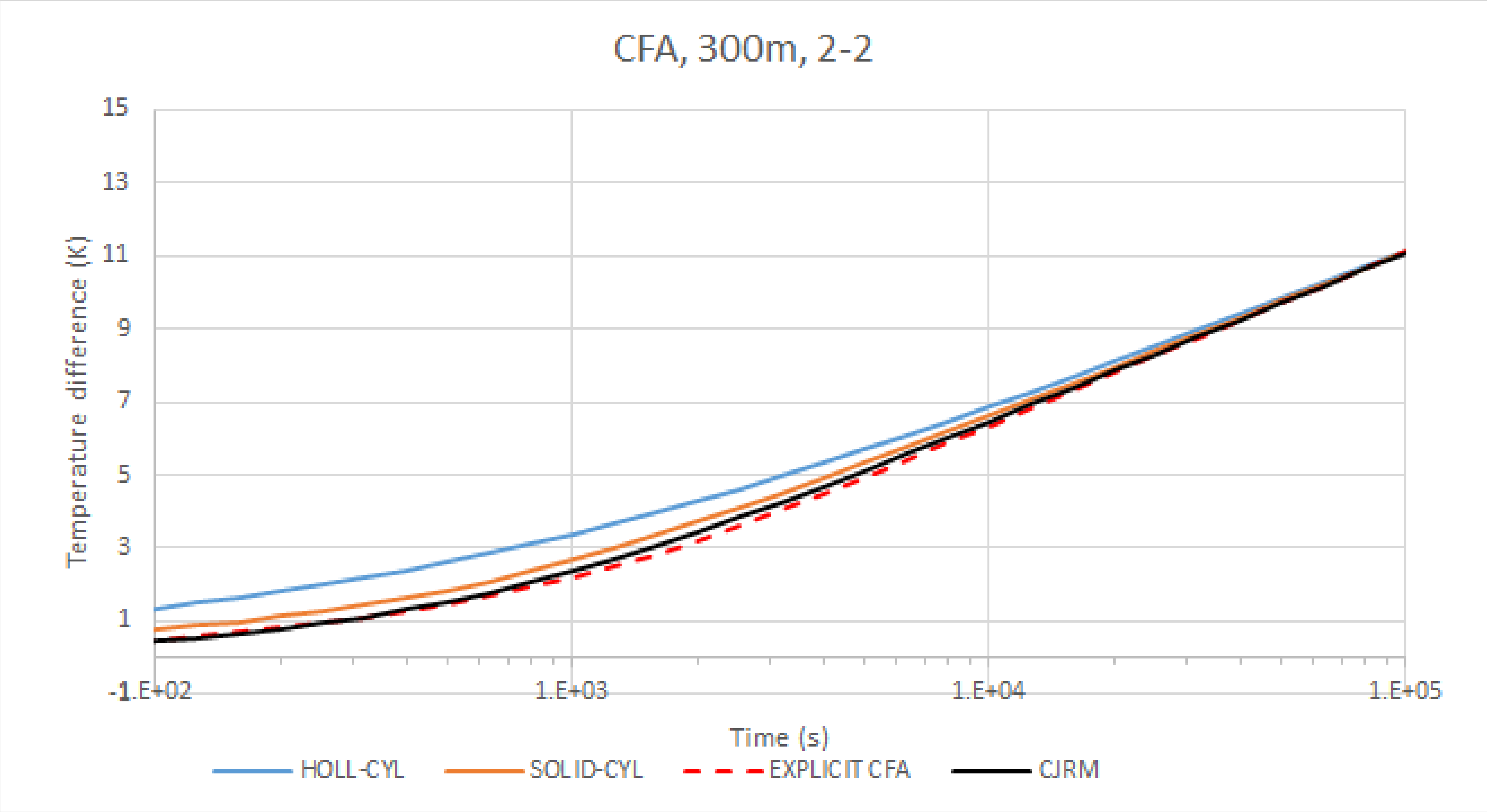

Conclusions

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Plus points...

- Simple radial model (CJRM) performs well
- Handy addition to the quiver of semi-analytical tools
- CFA and Rotary arrangements matched
- Essentially this because the basic diffusion physics are reproduced, albeit embedding geometrical ‘mistakes’
- (Reinforcing steel makes little difference; not shown here)

Minus points...

- ‘Mid-time’ error for CJRM
- (although could reduce a little by adjusting rpe / lamba)
- Central store (CJRMS) makes worse fit: reject!
- We are in 2D...need to include axial effects for longer term simulation
- EGMs: smooth numerical error can hide
- So, care with simulating cyclic loads in numerical models...

We will now simulate a broader range of conditions

Acknowledgements

EPSRC
Engineering and Physical Sciences Research Council

‘Non Steady Analytical Models for Energy Pile Testing and Design‘
(EPSRC EP/P001351/1)