WORKSHOP ON PENETRATION TESTING
Pisa 9th OCTOBER 2014

NUMERICAL AND EXPERIMENTAL MODELLING OF PIEZOCONE PENETRATION IN PARTIALLY DRAINED CONDITIONS: PRELIMINARY RESULTS

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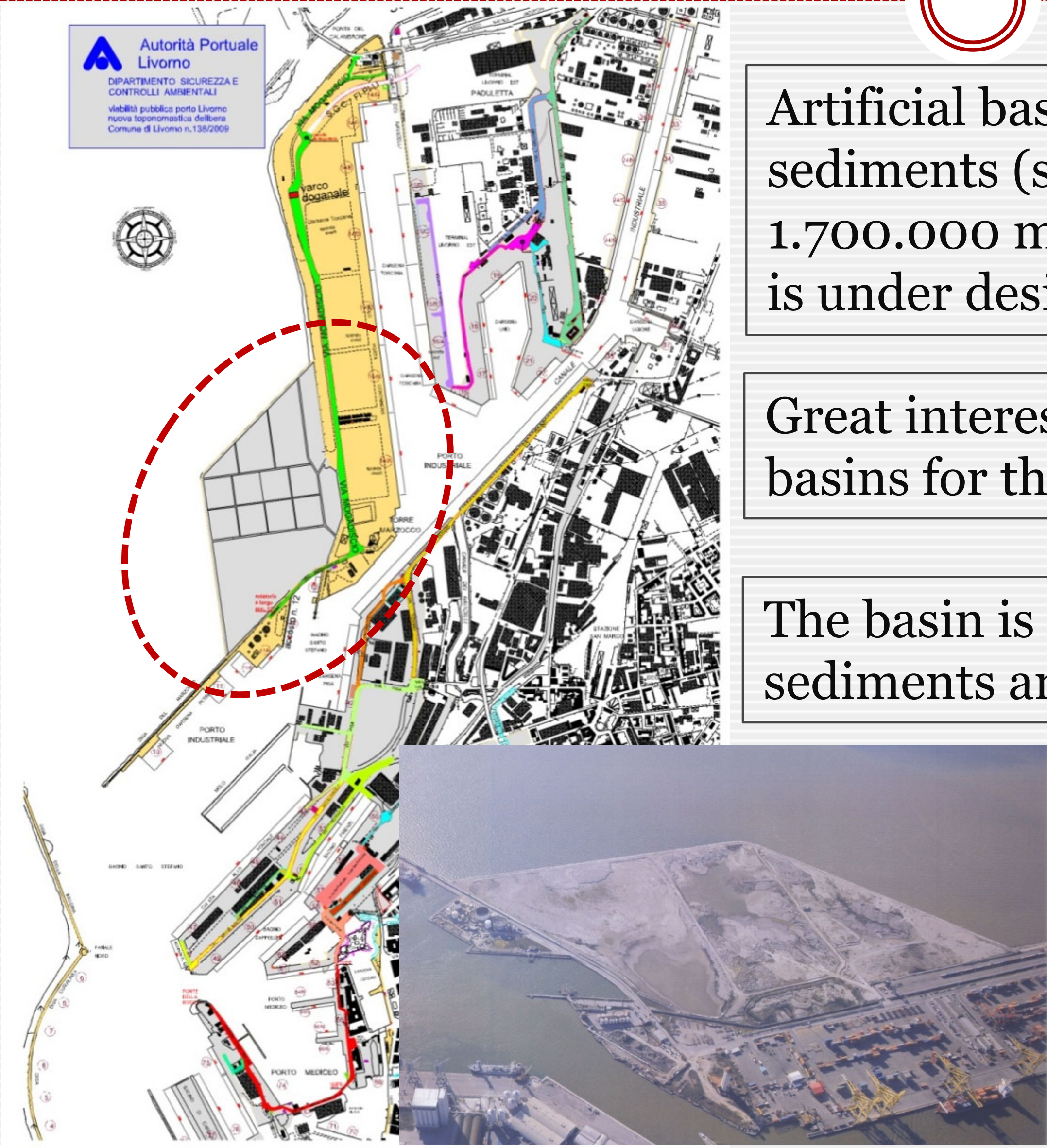
Livorno Port Authority



Artificial basin for the storage of dredged sediments (surface of 40 hectares and capacity of 1.700.000 m^3); New artificial basin (35 hectares) is under design

Great interest in re-using the top surfaces of these basins for the development of Port Infrastructures

The basin is impermeable therefore dredged sediments are “underconsolidated”

Huge investigation area - it is necessary to use economic, expeditious and reliable methods to identify the soil types and their spatial variability.

Studies of partially drained penetration

CLAY SOILS — Fully undrained conditions

SANDS — Fully drained conditions

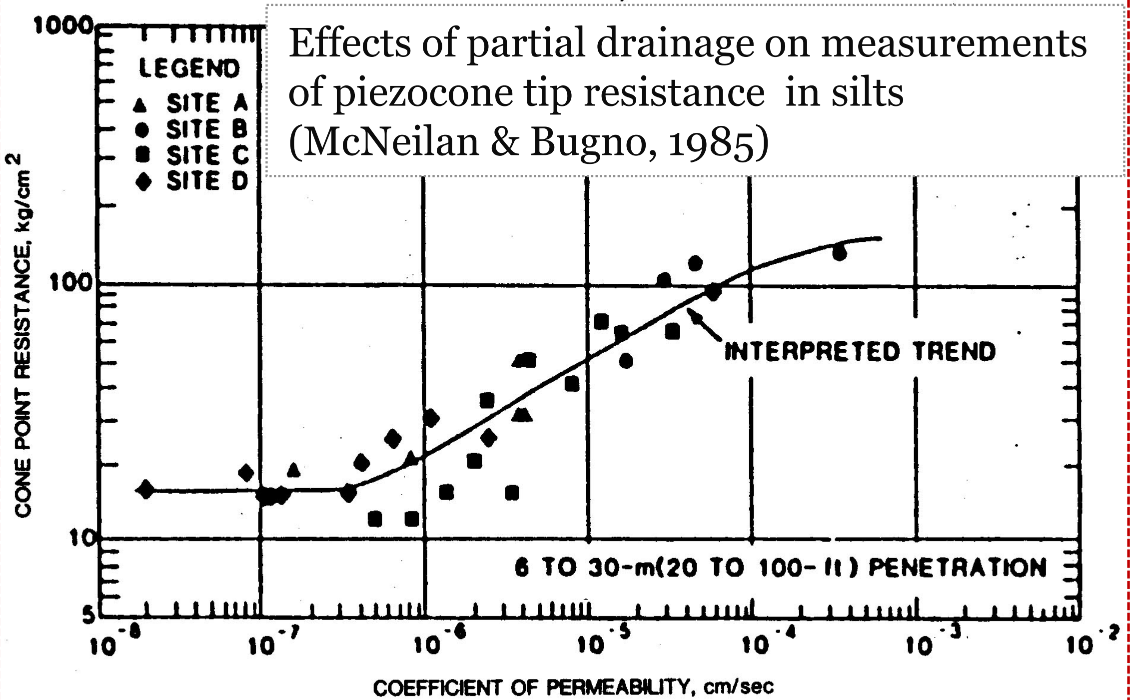
Semi-empirical correlations → Shear strength, consolidation and permeability properties (Wroth, 1984; Baligh, 1986a, b; Teh & Houlsby, 1991)

INTERMEDIATE SOILS — Partially drained conditions

↓

More difficult to interpret tests results (Ramsey, 2010; Lo Presti et al., 2010)

Effects of partial drainage on measurements of piezocone tip resistance in silts (McNeilan & Bugno, 1985)



Studies of partially drained penetration

THE INFLUENCE OF PENETRATION RATE ON CONE RESISTANCE IS WELL RECOGNIZED:

Link between penetration resistance and the coefficient of consolidation of the soil (Randolph&Hope,2004)

Validation

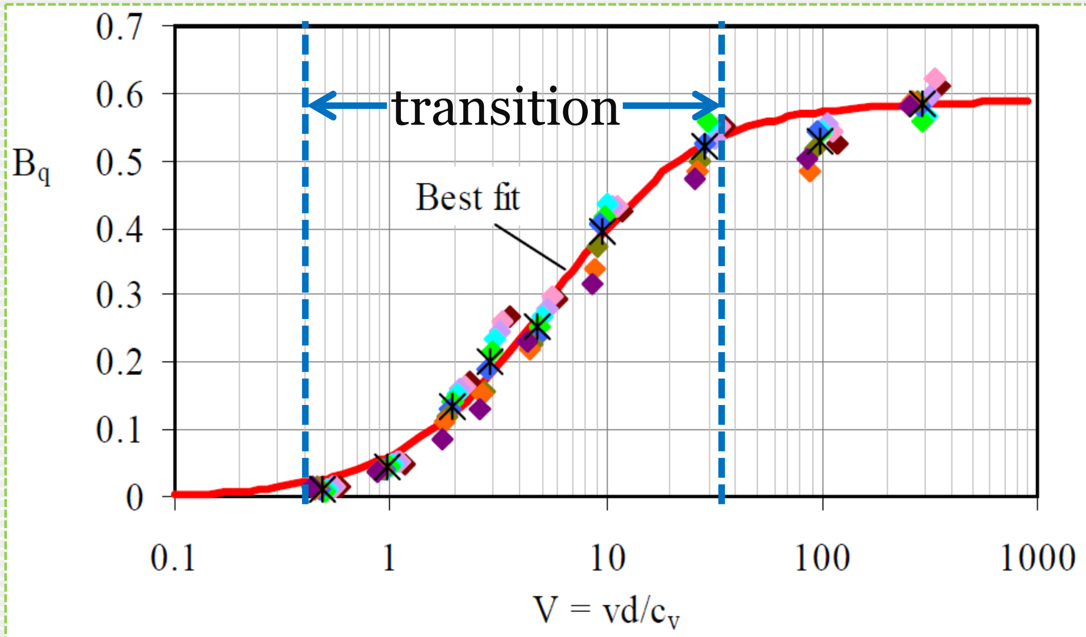
Controlled laboratory physical model tests on kaolin clay

Limited number of in situ tests

(Chung et al., 2006; Lo Presti et al., 2010; Tonni et al. 2010)

T-bar penetrometer

Cylinder:
d: 5mm
L: 20 mm



Variation of excess pore pressure ratio with cone velocity (Randolph&Hope 2004)

Studies of partially drained penetration

Randolph&Hope,2004

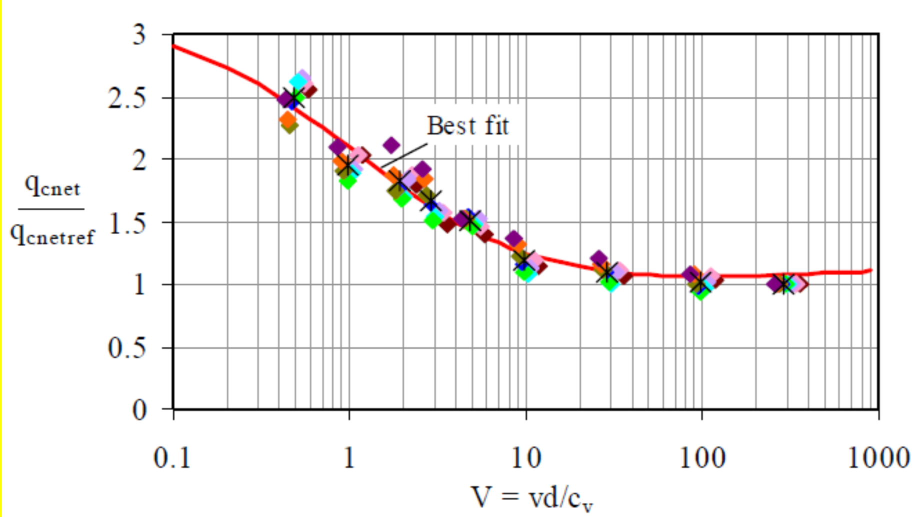
$$\frac{q}{\sigma'_v} = \left[a + \frac{b}{1 + cV}\right]$$

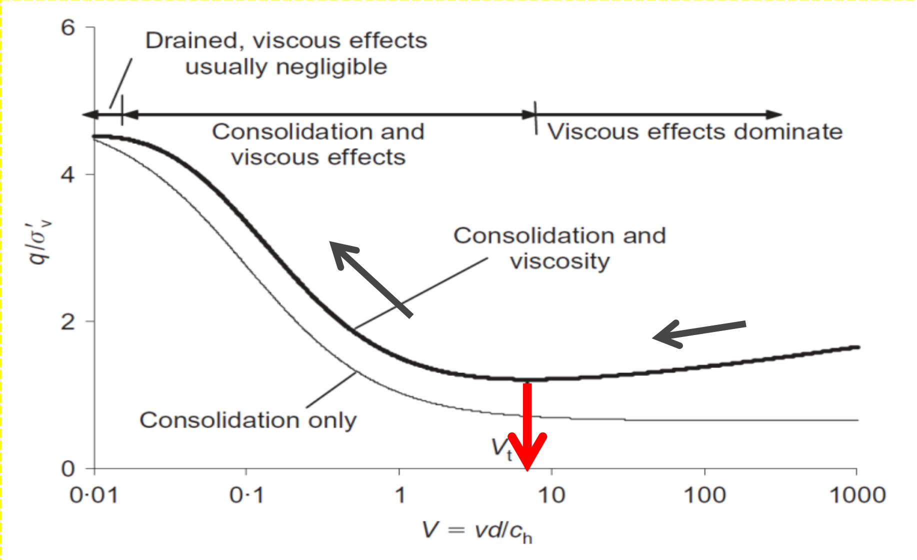
Lehane et al., 2009

$$\frac{q}{\sigma'_v} = \left[a + \frac{b}{1 + cV}\right]\left[\frac{v/d}{(v/d)_{ref}}\right]^m$$

$$V_t \approx \left[\frac{b}{acm}\right], m < 0.1$$

$$\left[\frac{q}{\sigma'_v}\right]_{max,drained} = [a + b]$$





Numerical analysis of the cone penetration process

Numerical analysis of the cone penetration process has been conducted using:

the strain path method

- (Levadoux and Baligh, 1980; Teh and Houlsby, 1991)

cavity expansion analysis

- (Vesic, 1972; Salgado et al. 1997; Yu, 2004)

finite element analysis

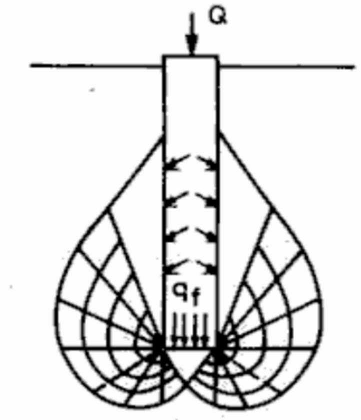
finite difference analysis

However most of these analyses assumed either **fully drained** or **undrained** conditions.

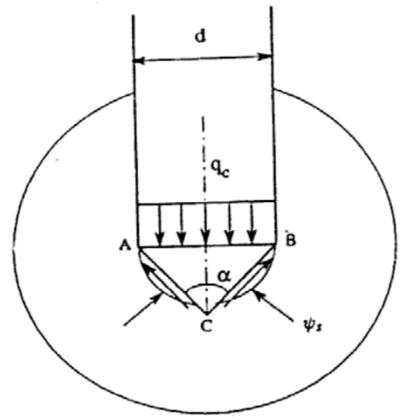
The effect of consolidation is still not well studied.

Strain Path Method (Baligh, 1985)

BEARING CAPACITY
AND
CAVITY EXPANSION THEORY TREAT CONE RESISTANCE AS A COLLAPSE LOAD PROBLEM



De Beer (1948)
Meyerhof (1951)



(a). Ladanyi & Johnston (1974)

Strain Path Method is the first example of **steady state approach**: Penetration process is treated as a **steady flow of soil** passing the **fixed cone penetrometer**

Due to the severe kinematic constraints that exist in deep penetration problems

Soil deformation are indipendent of shearing resistance of the soil

Deep penetration problem is considered strain-controlled

Strain Path Method (Baligh, 1985)

Deep undrained penetration:

Velocity fields are estimated ← «Source & sinks» Method

Differentiated with respect to spatial coordiantes

Strain rates

Integrated along streamlines

Strain path for individual soil elements around the cone

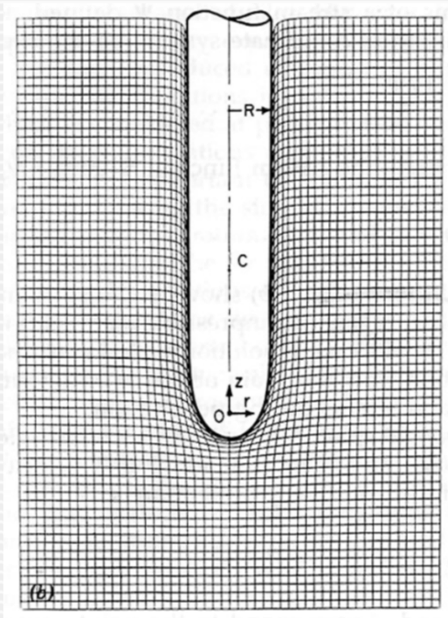
Costitutive model for soil

Effective stress field

Equilibrium considerations

Evaluation of pore water pressures

«Simple Pile» geometry: generated by a single spherical source inserted in a uniform flow



Strain Path Method (Baligh, 1985)

DISTINCT MODES OF SHEARING CAN BE DEFINED

R = 1.78 cm, U = 2 cm/s

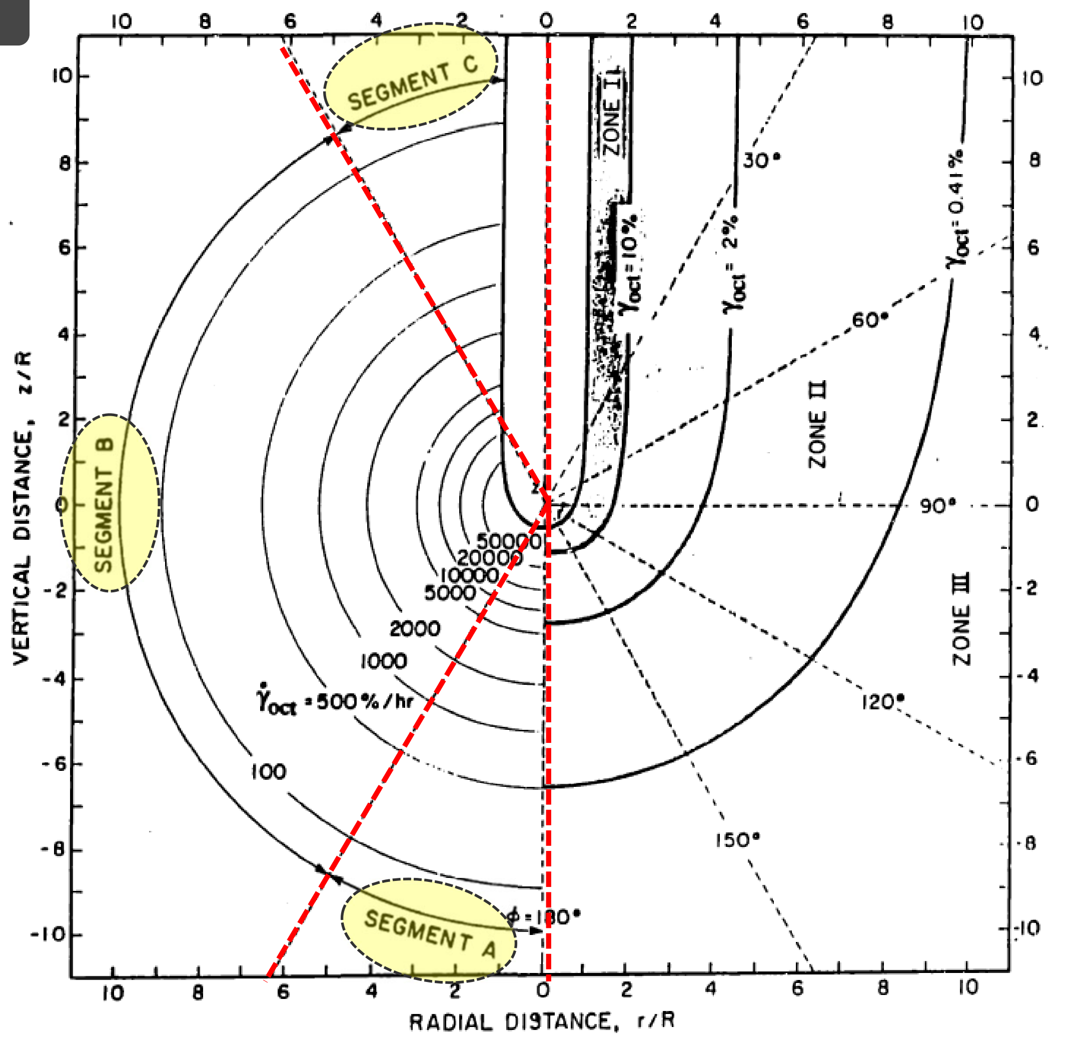
Segment A:
Principal mode of shearing is triaxial compression

Segment B:
Rotation of principal strain directions & reversal of individual strain components

Segment C: conditions similar to the expansion of a cylindrical cavity

The complete analysis of the simple pile geometry using the SPM is highly complex

Octahedral strain rates contour



Octahedral strain contour

Strain Path Method (Baligh, 1985)

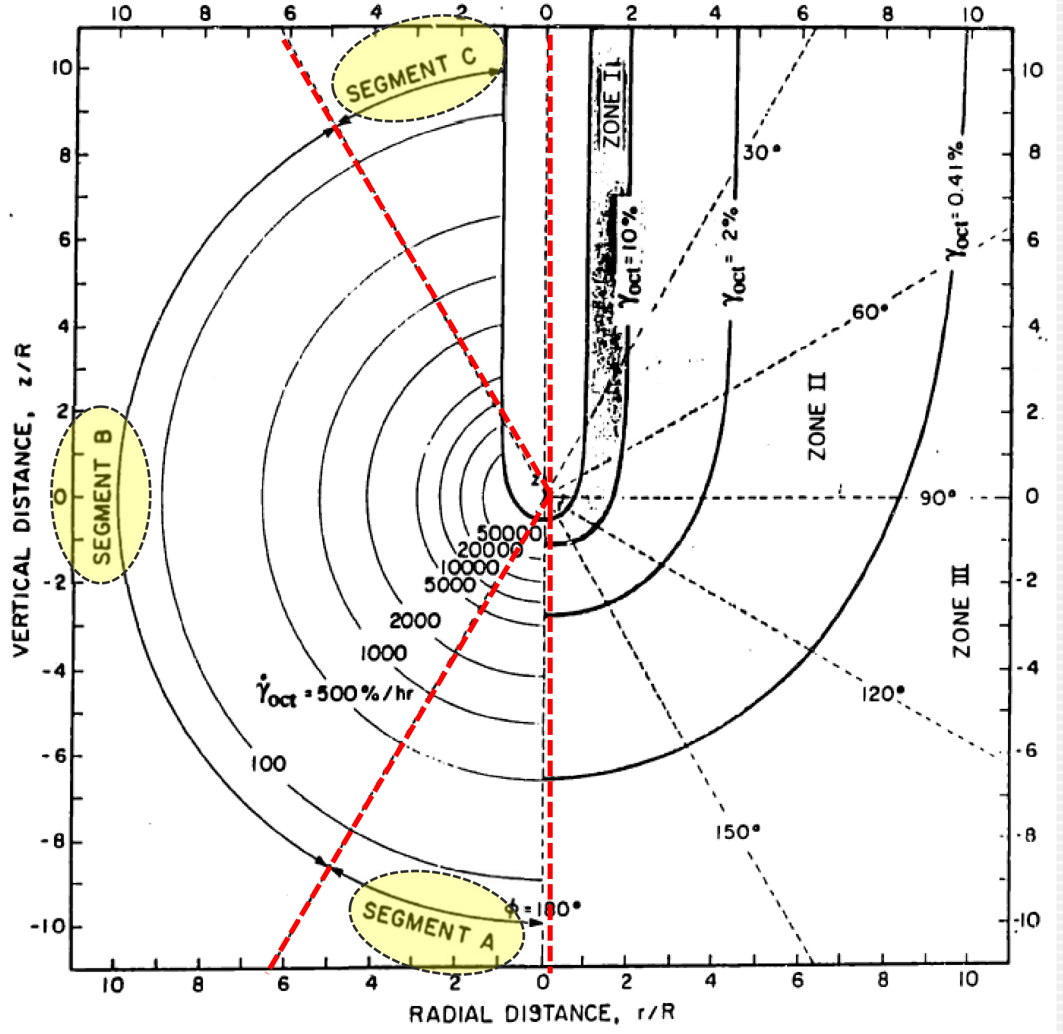
Elghaib (1989) developed a simplified predictive framework based on the SPM for conditions along the centerline of the simple pile penetrometer

- The mode of shearing of soil elements is restricted to triaxial compression
- Monotonically increasing strain rates and strain components magnitudes
- Small gradients of the field variables in the radial direction - conditions of vertical equilibrium

Closed form solutions along the centerline for the simple pile geometry

Permits partial drainage to be incorporated in the analysis

R = 1.78 cm, U = 2 cm/s

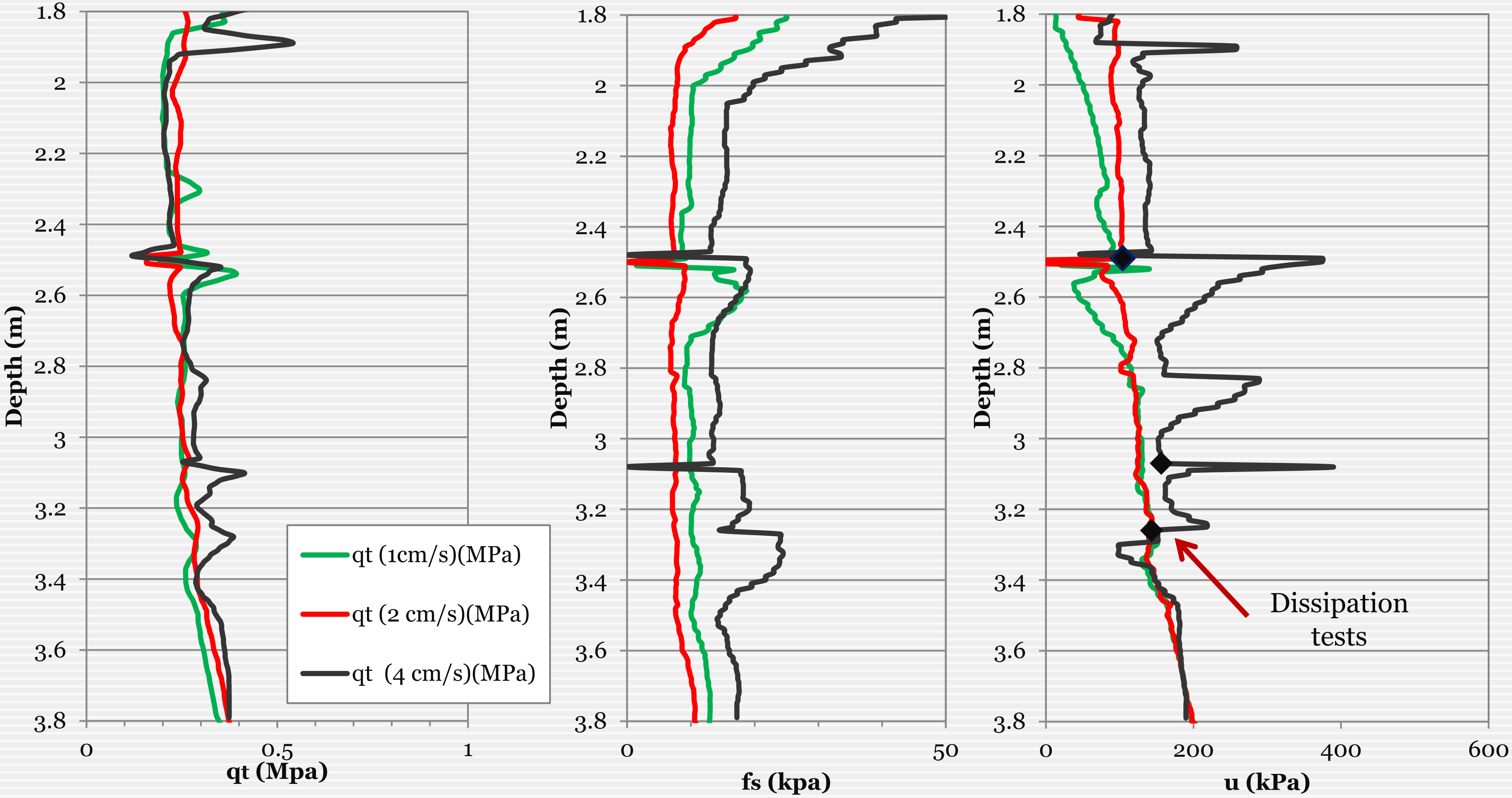


Main goal & activities

INVESTIGATE POTENTIAL IMPROVEMENTS IN THE USE AND INTERPRETATION OF PIEZOCONE TESTS FOR SOILS OF INTERMEDIATE PERMEABILITY

- **EXPERIMENTAL ACTIVITIES**
  Dredged sediments
  Livorno Port Area
  - In situ tests
    - Piezocone tests with different penetration rates
    - Seismic piezocone tests
    - Dissipation test for each CPTu test
    - Extraction of block samples and Osterberg samples
  - Laboratory tests
    - Oedometer test (Incremental loading and constant rate of strain)
    - Triaxial test TxCIU
    - Resonant column test
- **NUMERICAL ANALYSES**
  - Simulation of large strain penetration processes using finite element methods
    - ALE method
    - UL method

Experimental activities at the Livorno port area: preliminary results



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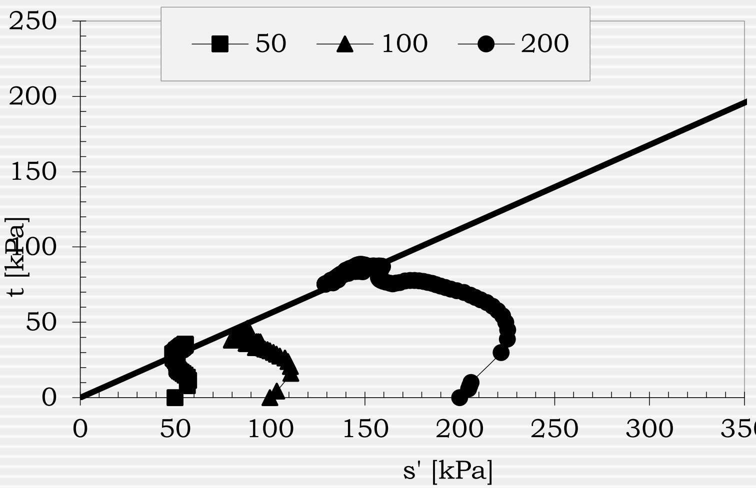
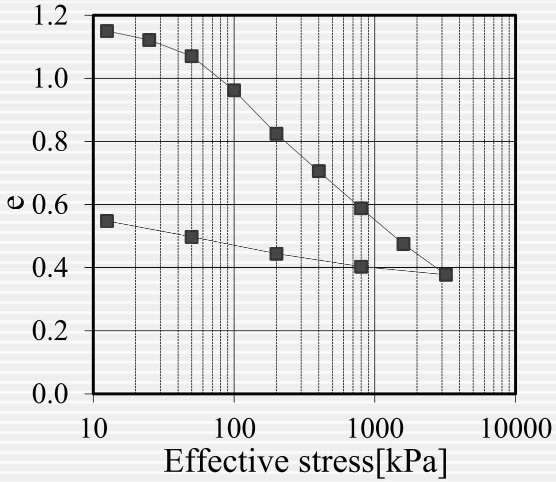
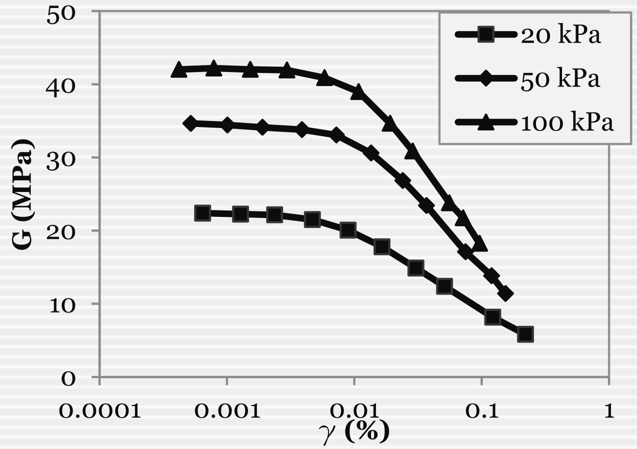
Experimental activities at the Livorno port area: preliminary results

- Incremental loading oedometer test
- Oedometer test with costant rate of strain
- Triaxial test TxCIU (50, 100, 200 kPa)
- Resonant column test (20, 50, 100 kPa)

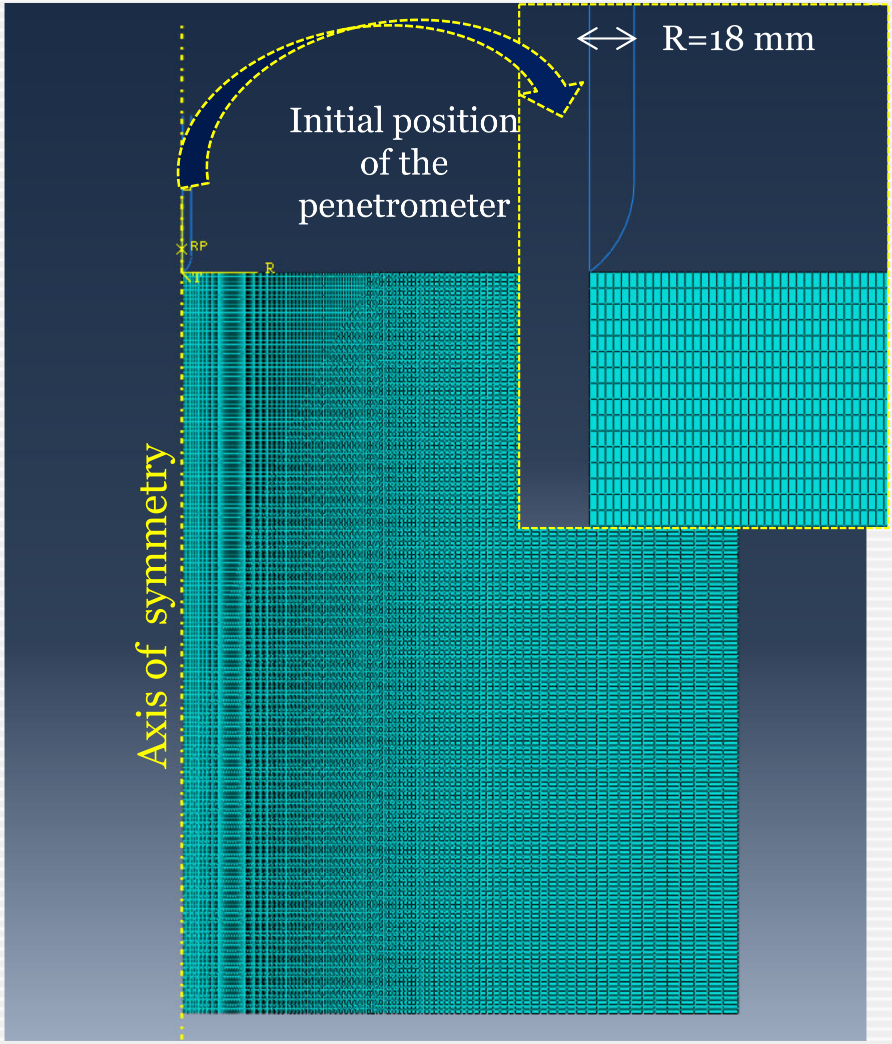
n°reg.	campione	profondità (m) da	profondità (m) a	Wn (%)	γ (kN/m3)	e0	σ'p (kPa)	σ'v0 (kPa)	OCR	K (cm/s)	M (MPa)
729	cubico 1	1	1.3	29.1	18.03	0.906	92	23.44	3.93	3.29E-08	1.9
730	cubico 2	1.2	1.5	47.27	16.99	1.306	65	25.49	2.55	2.26E-08	1.4
754	profondo 1	1.6	2.2	44.68	17.54	1.225	43	32.21	1.33	5.86E-08	1.3
755	profondo 2	2	2.5	42.72	17.7	1.174	40	34.93	1.15	4.24E-08	0.9
756	profondo 3	2.5	3	40.01	18.75	0.972	79	42.03	1.88	6.4E-08	1.4





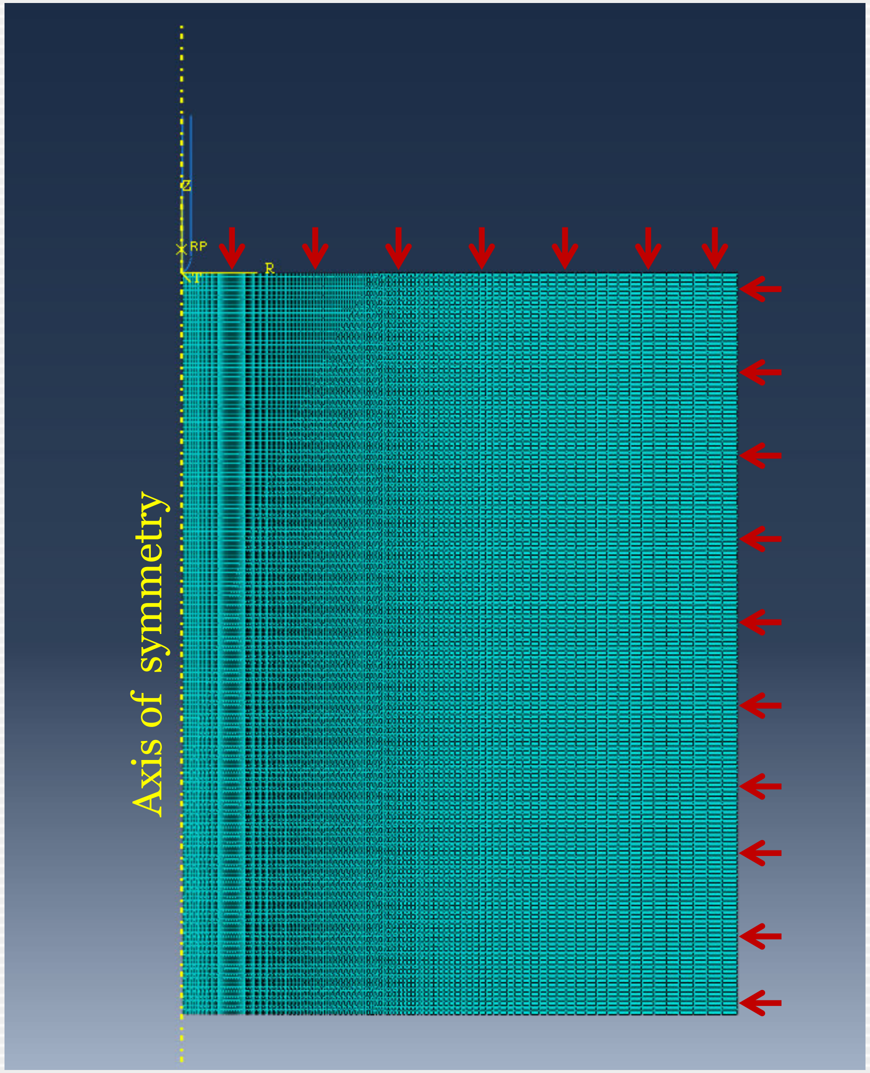


Finite Elements analyses of cone penetration



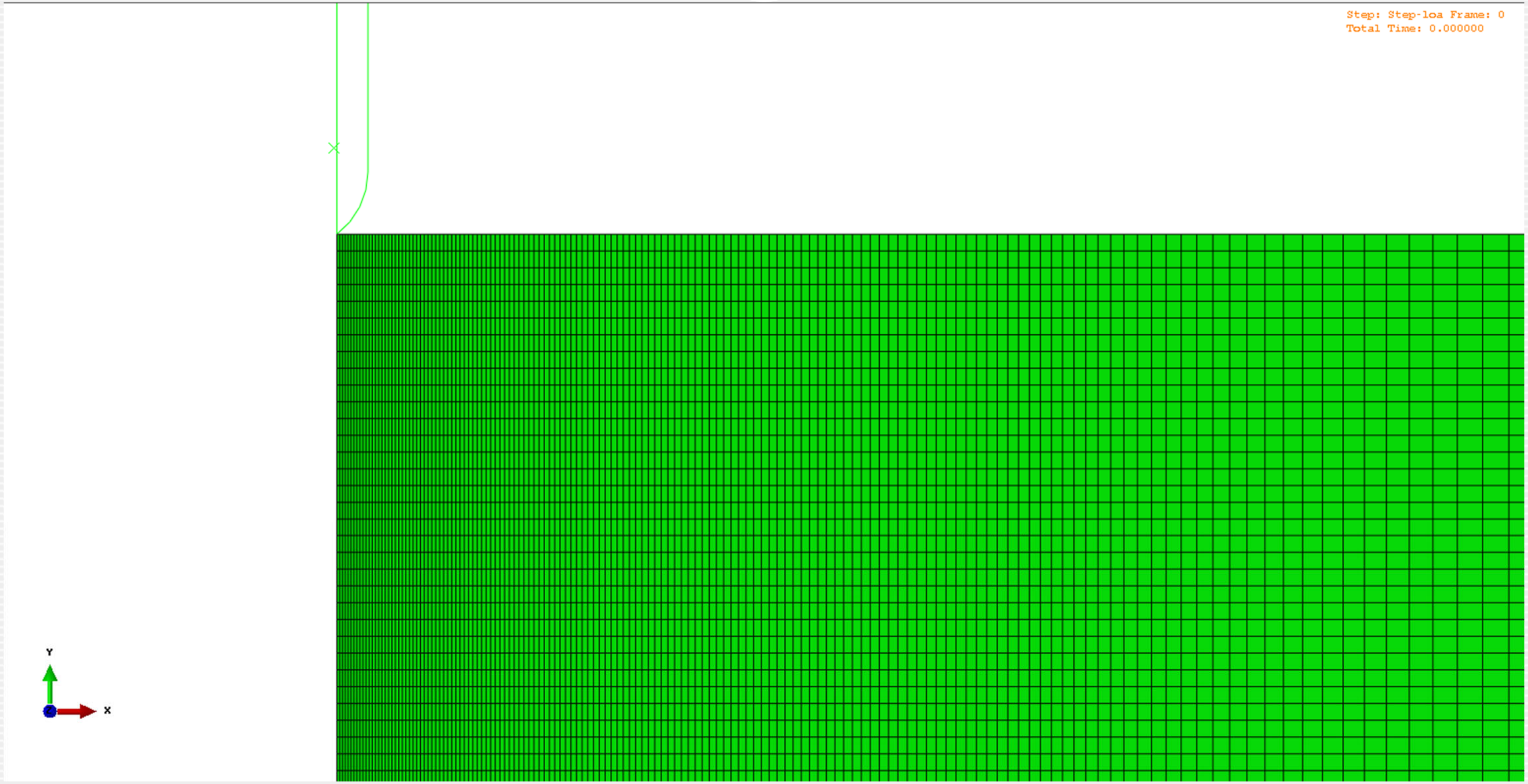
- The software used is Abaqus (v. 6.13-2)
- Model A: Undrained penetration process; total stress analysis; Abaqus/Explicit - explicit direct-integration procedure; Arbitrary Lagrangian-Eulerian (ALE) scheme
- Model B: effective stress analysis; Abaqus/Standard - implicit integration procedure; Updated Lagrangian scheme (UL)
- The cone penetrometer is treated as a rigid body (2D analytical surface); contact interaction is assumed frictionless; rate of 2 cm/s

Finite Elements analyses of cone penetration

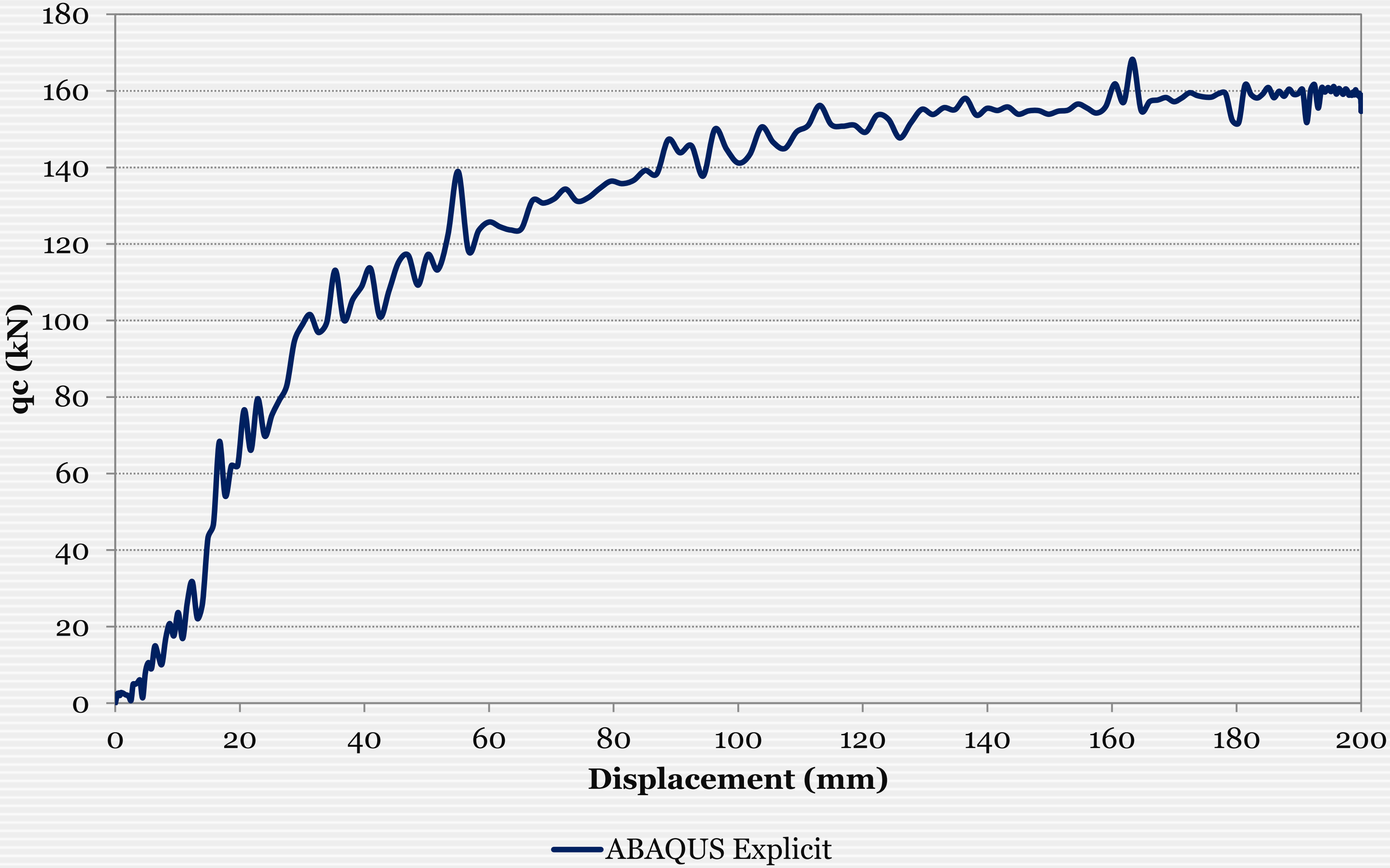


Model A - Tresca	
Model geometry	1.2 m x 1.6 m
Penetrometer	R = 18 mm
Poisson's ratio	0.49
G	960 kPa
s_u	20 kPa
Initial vertical and horizontal load	35 kPa
Adaptive technique	ALE method
Abaqus/Explicit	

ALE method – Abaqus/Explicit



ALE method – Abaqus/Explicit



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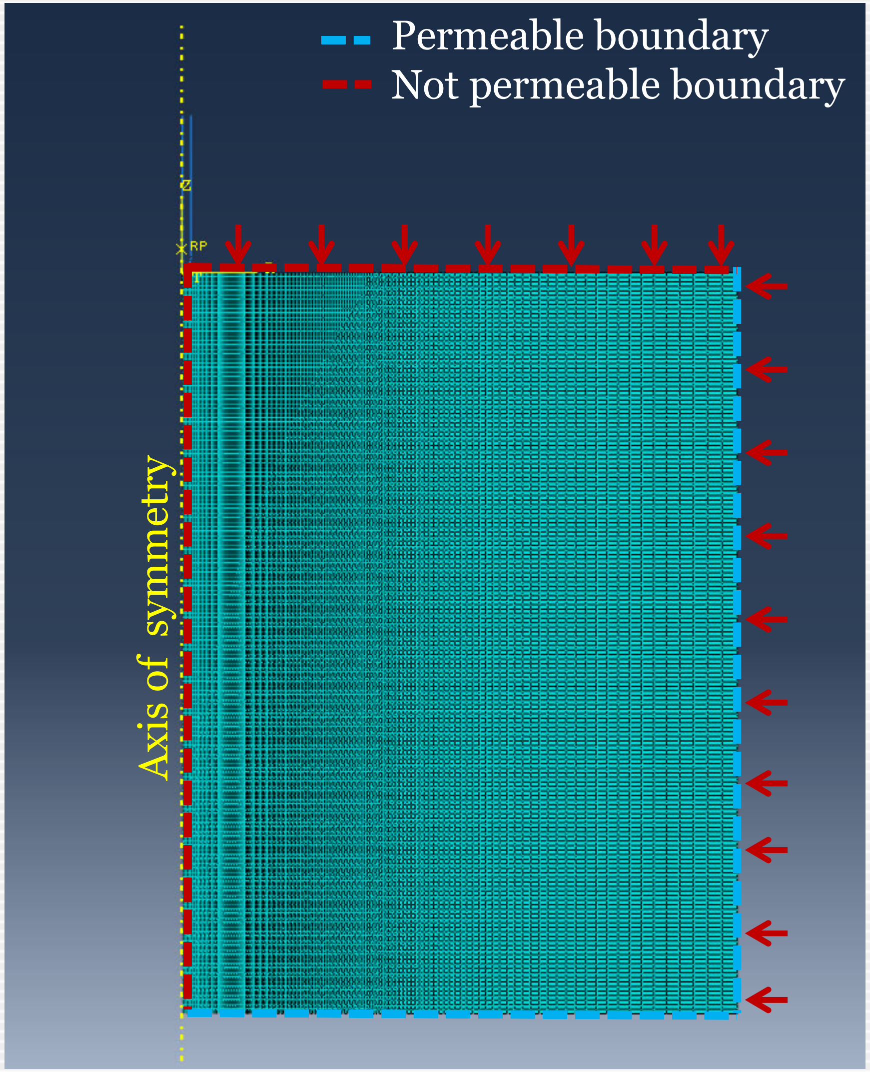
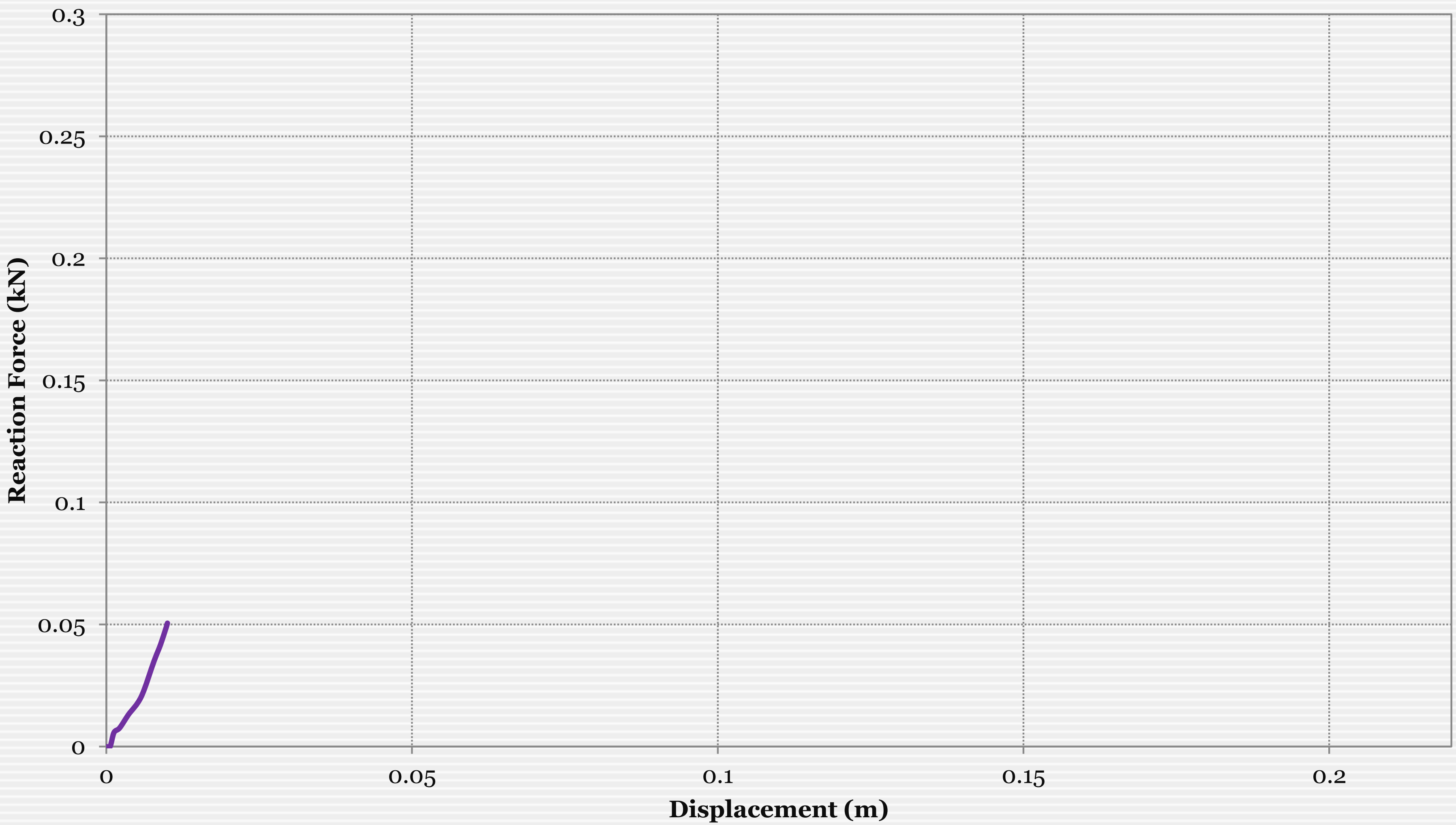


Mohr-Coulomb model	
Model geometry	1.2 m x 1.6 m
Penetrometer	R = 18 mm
Young modulus	2400 kPa
Poisson's ratio	0.25
G	960 kPa
φ	30°
c'	0 kPa
Initial vertical and horizontal load	35 kPa
Initial pore water pressure	0 kPa
Initial void ratio	1.25
Hydraulic conductivity	k = 1 exp -9 m/s k = 1 exp -6 m/s
Adaptive technique	Updated Lagrangian
Abaqus/Standard	

Finite Elements analyses of cone penetration



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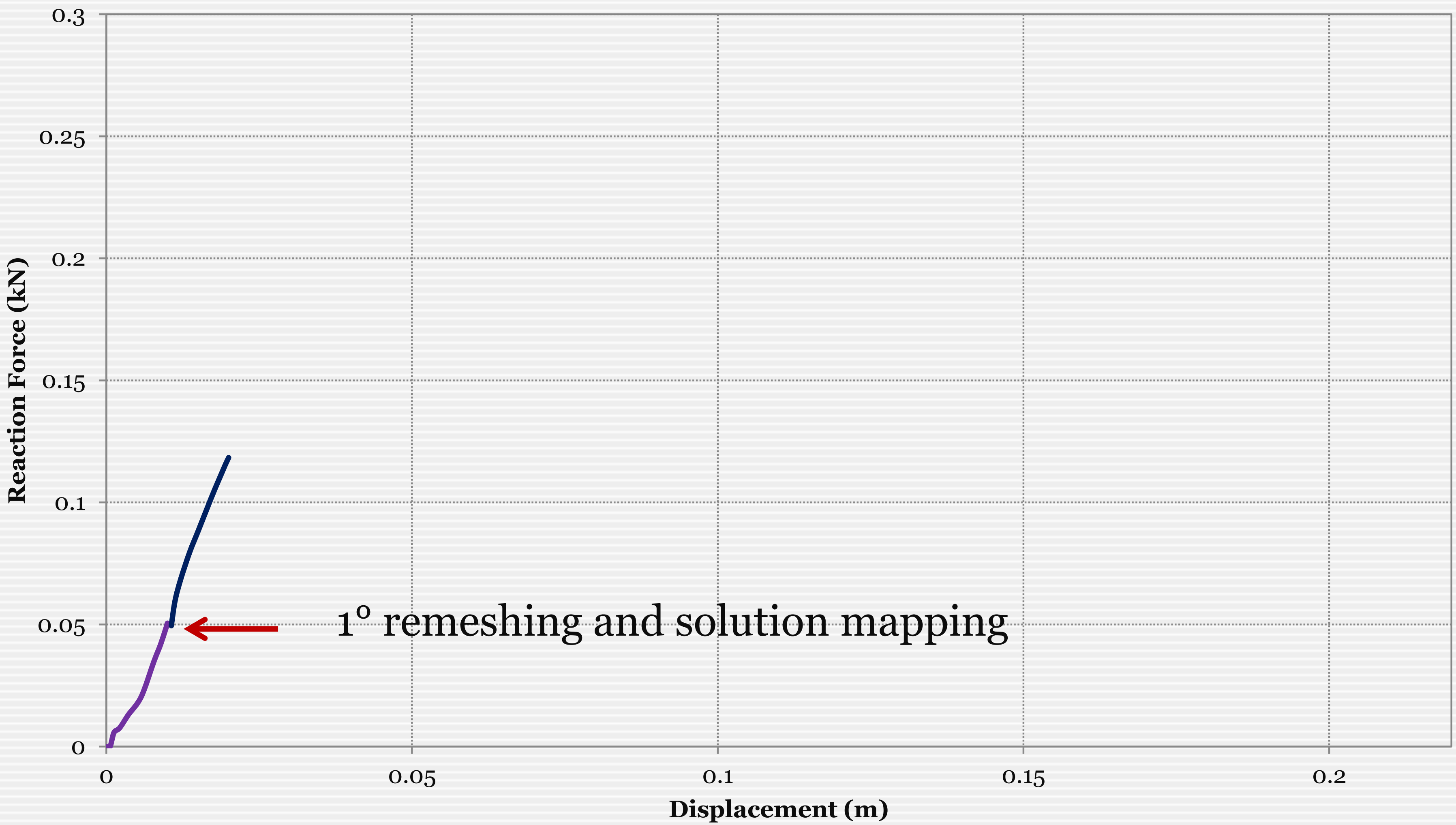

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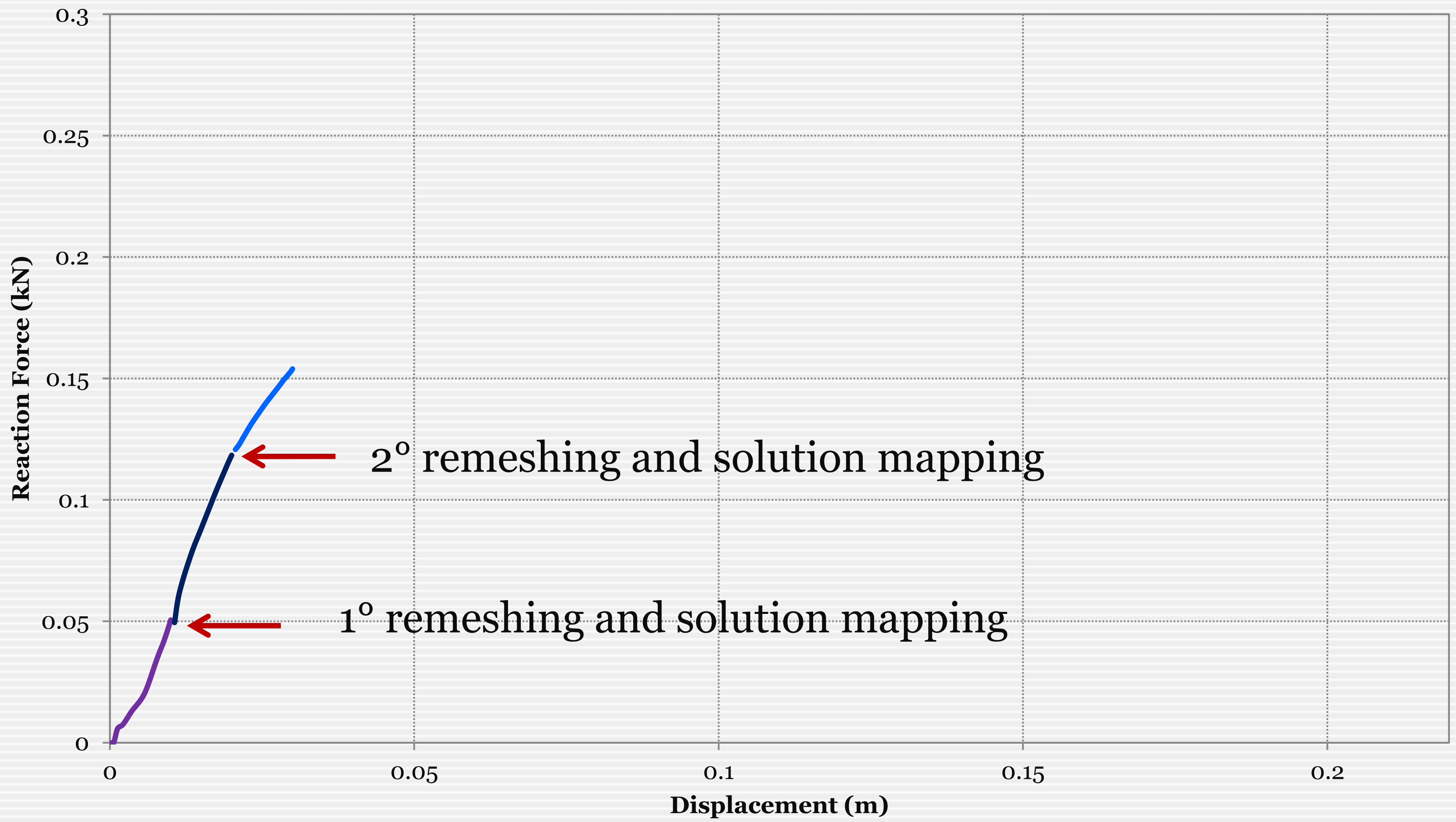

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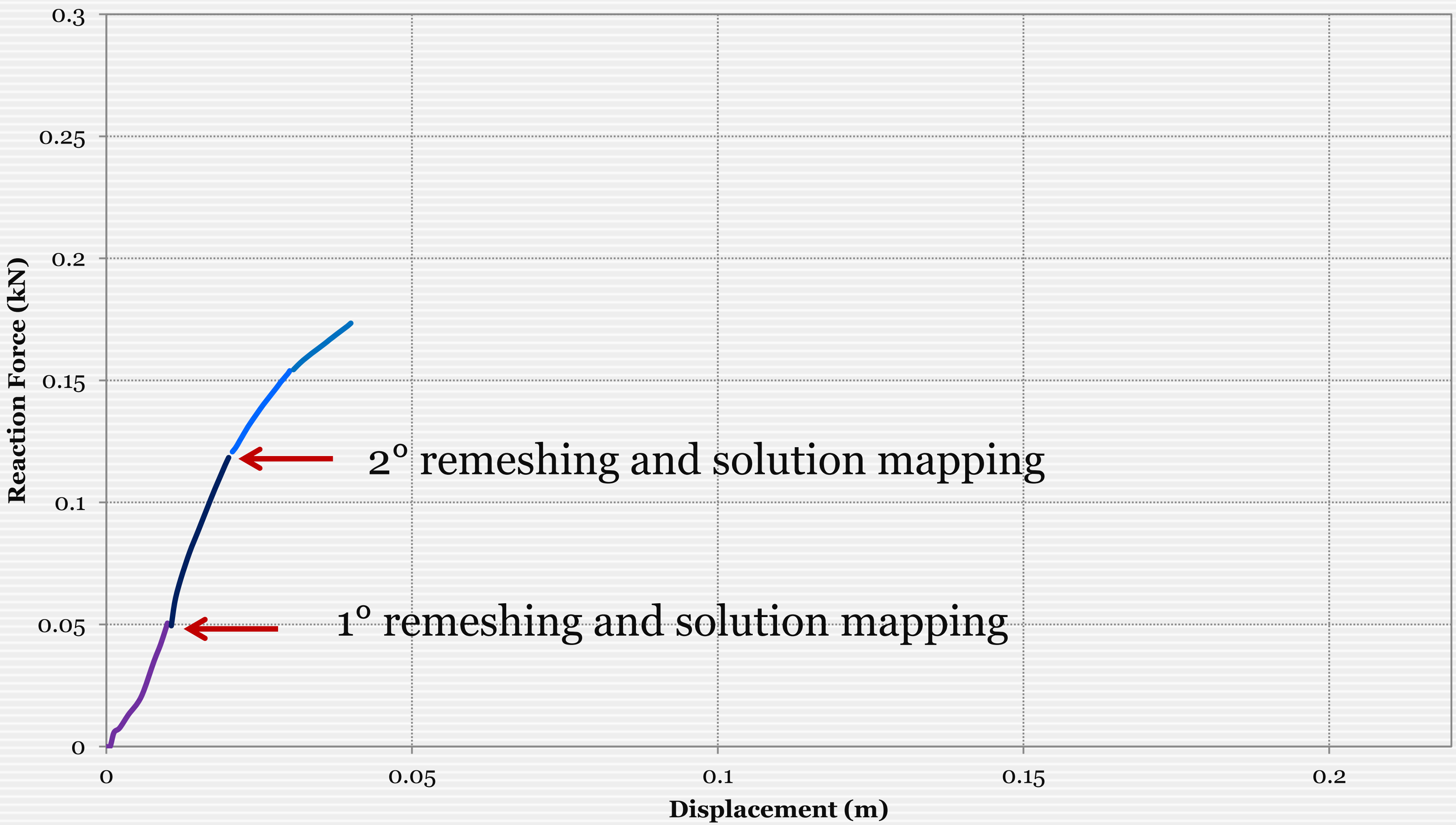

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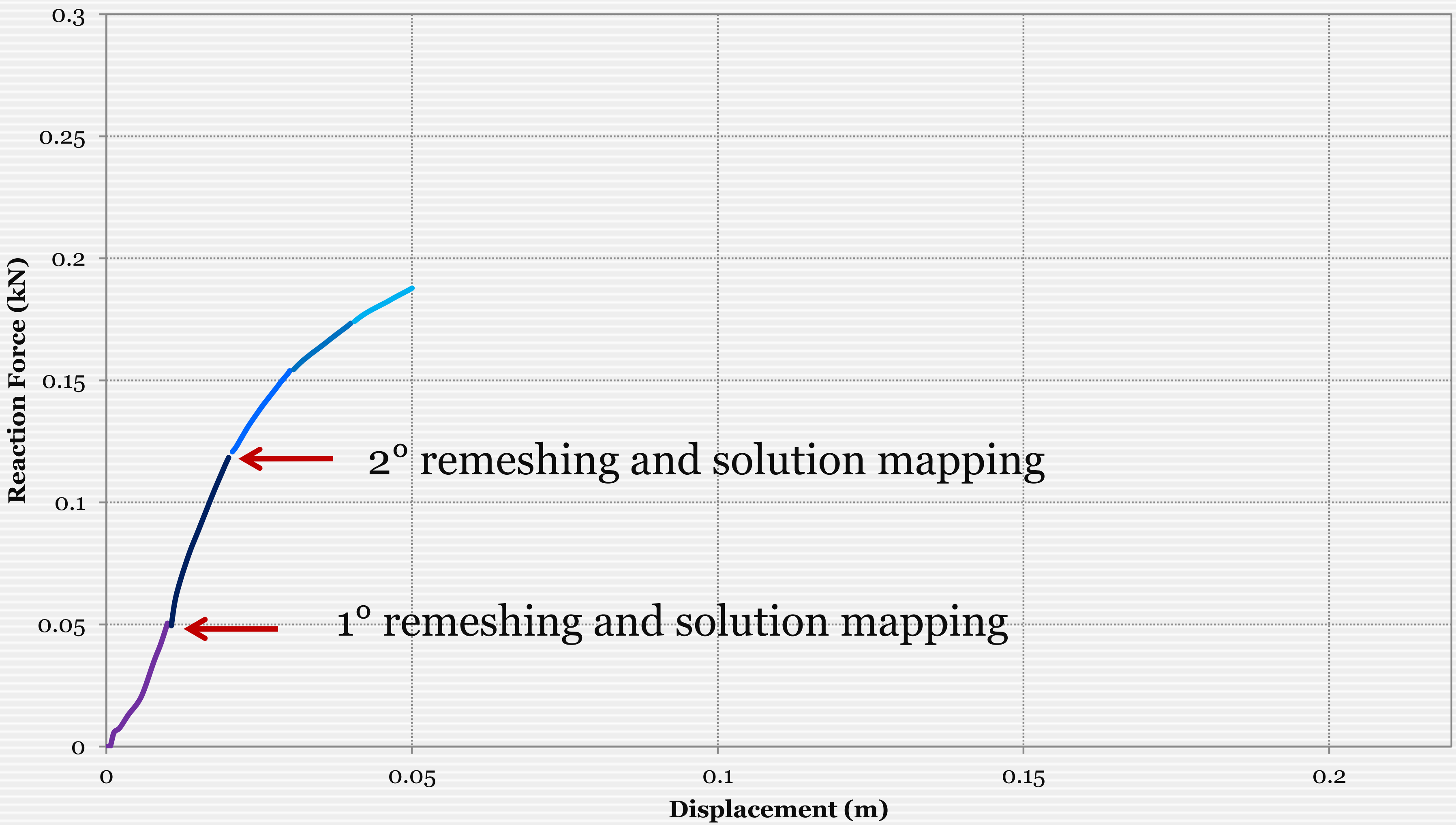

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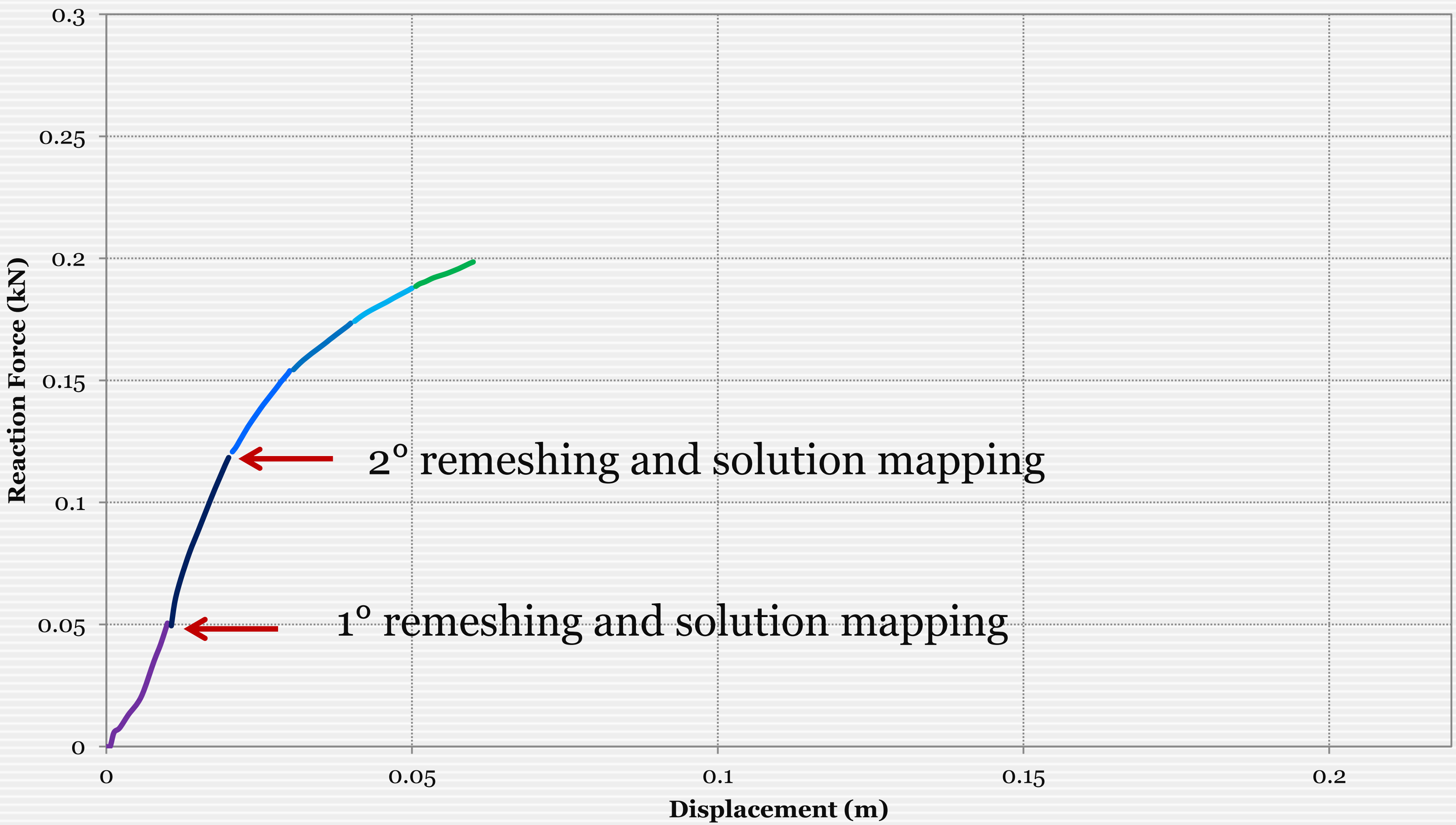

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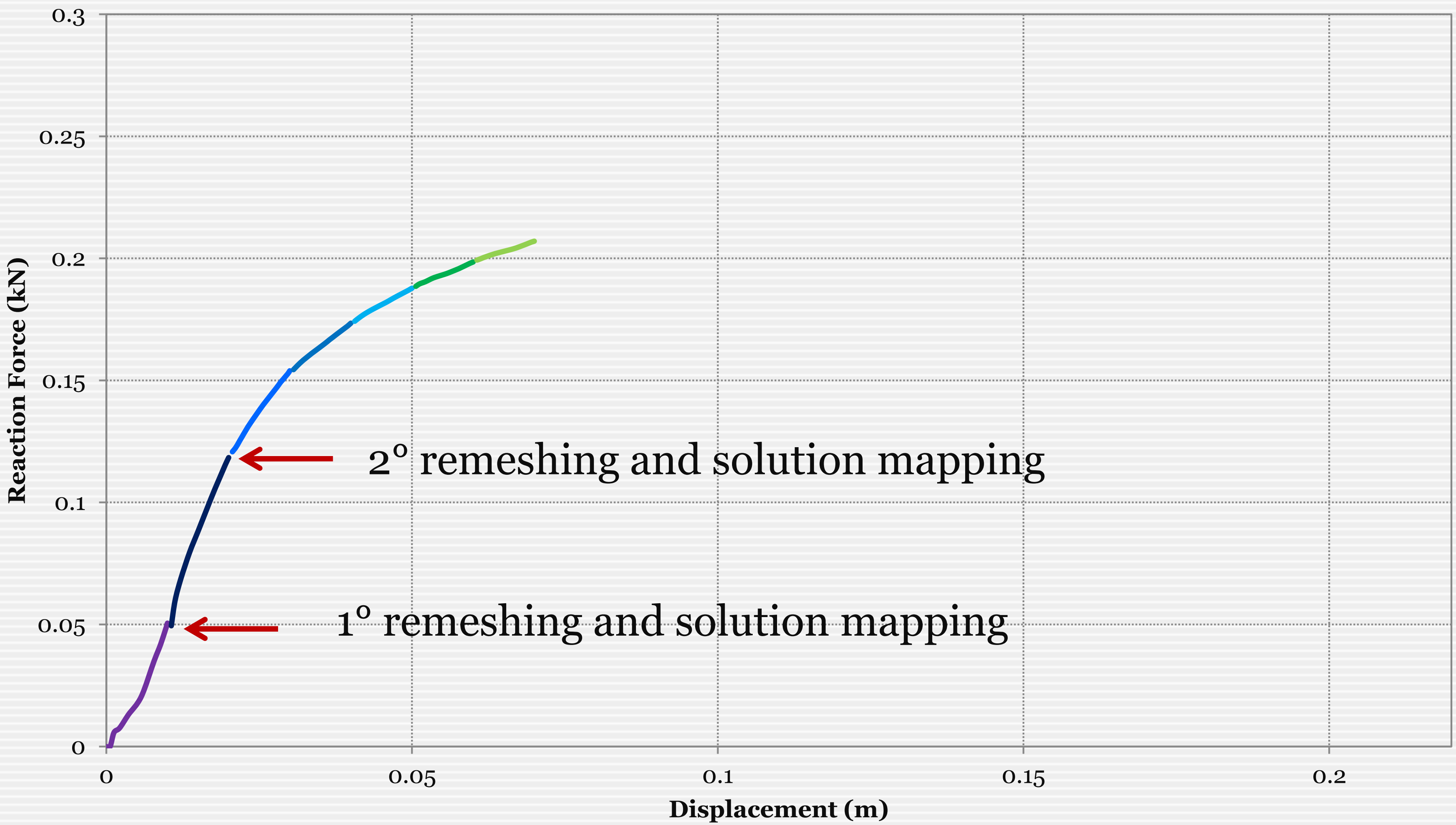

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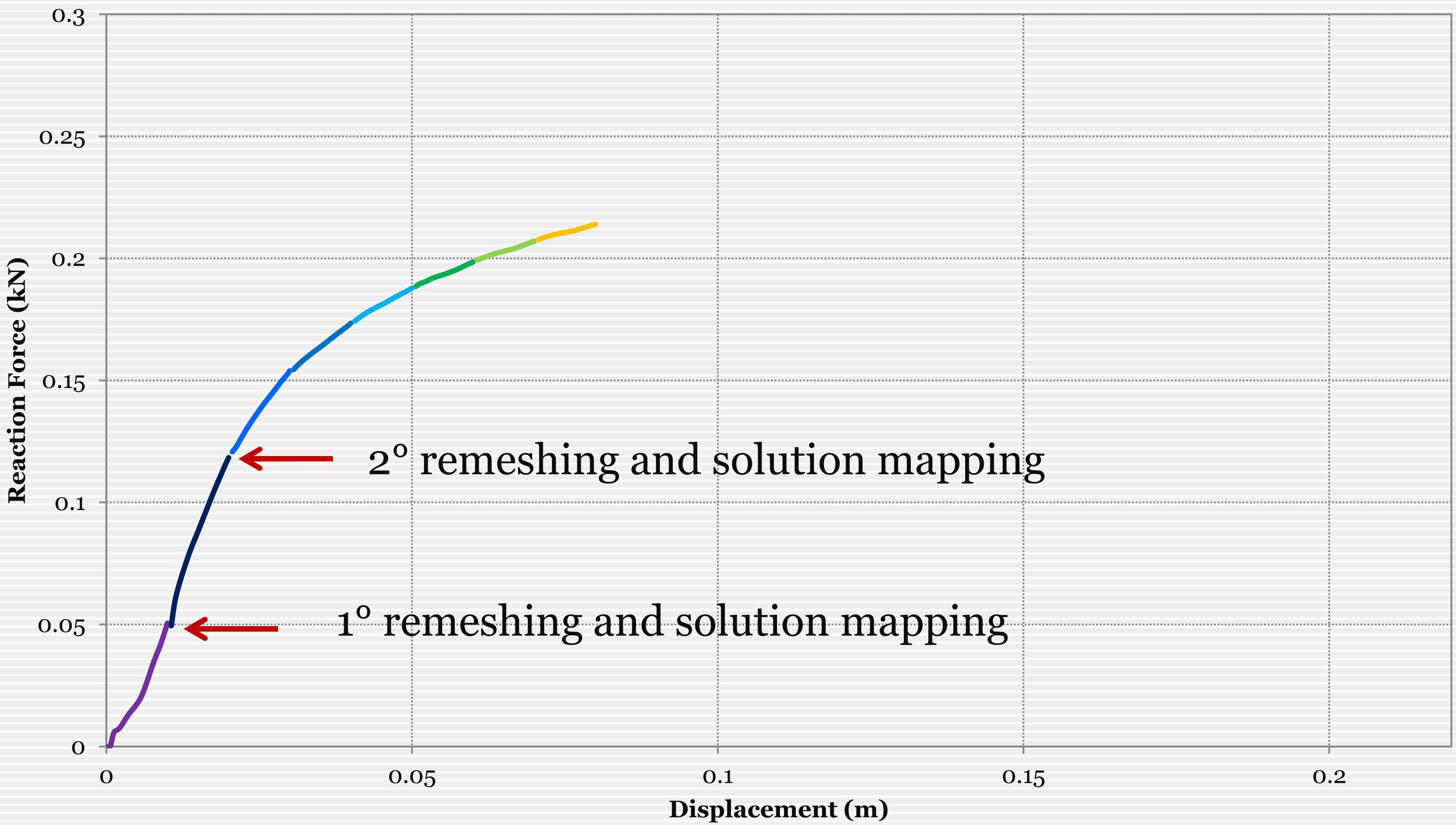

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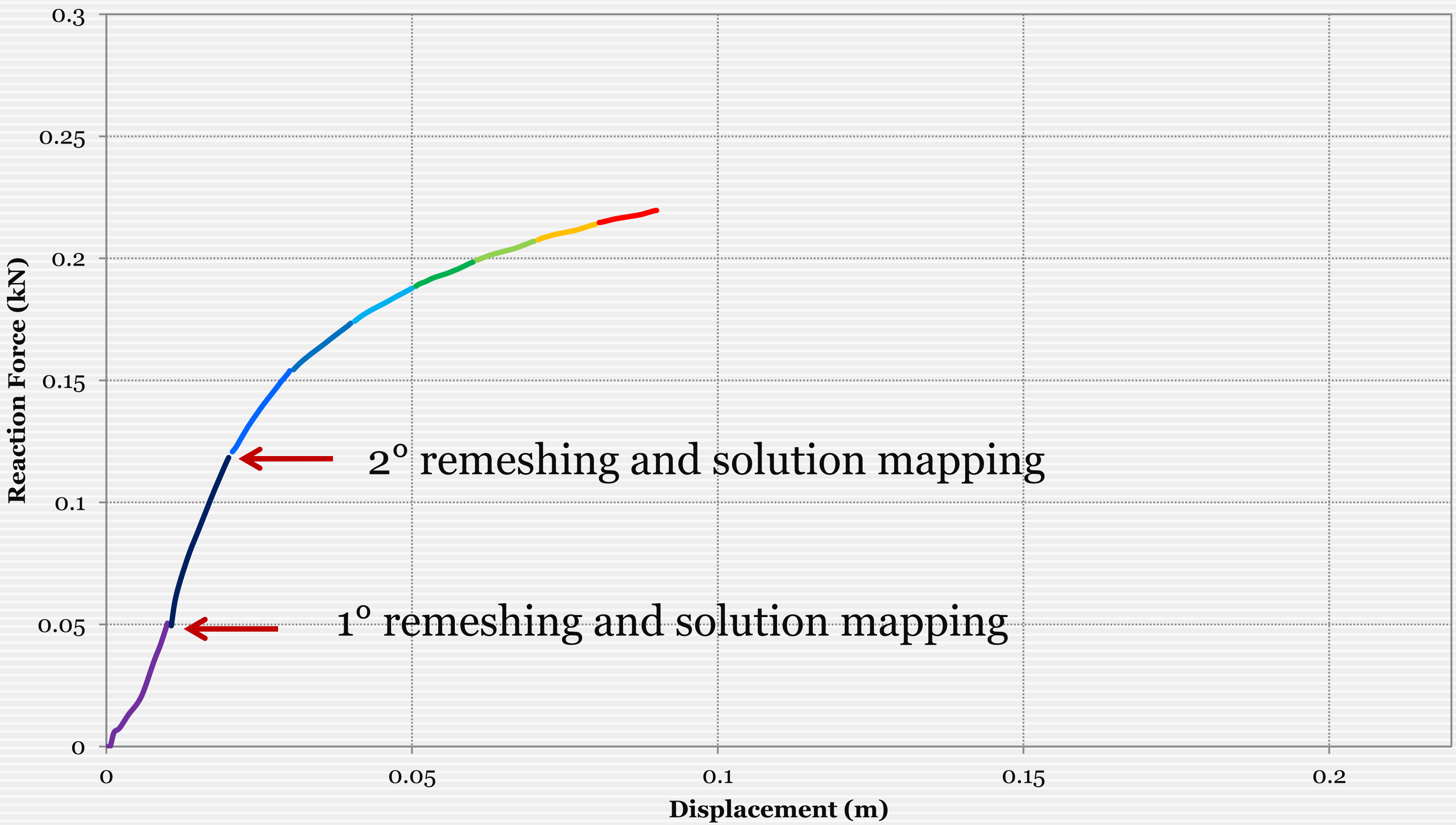

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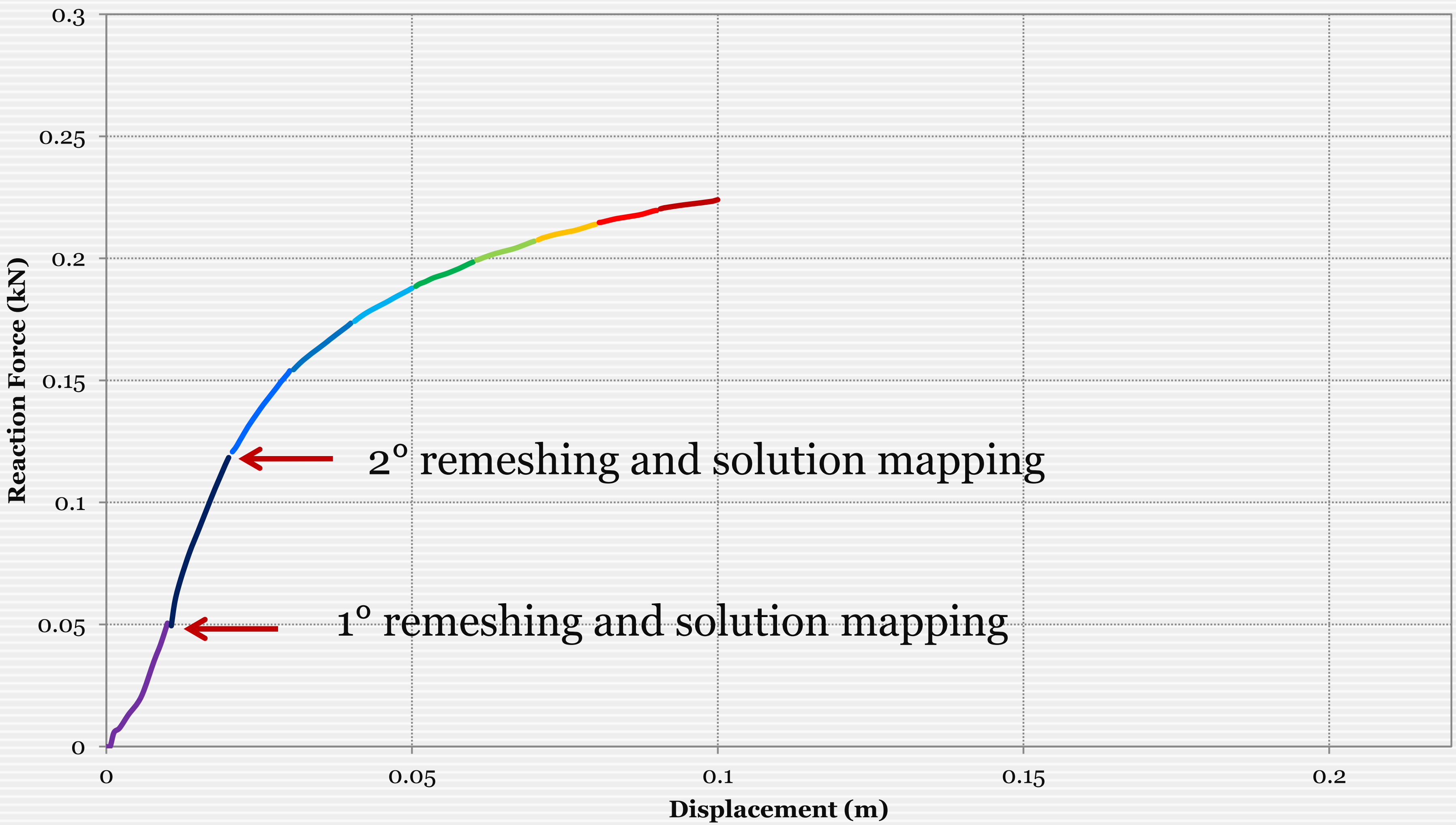

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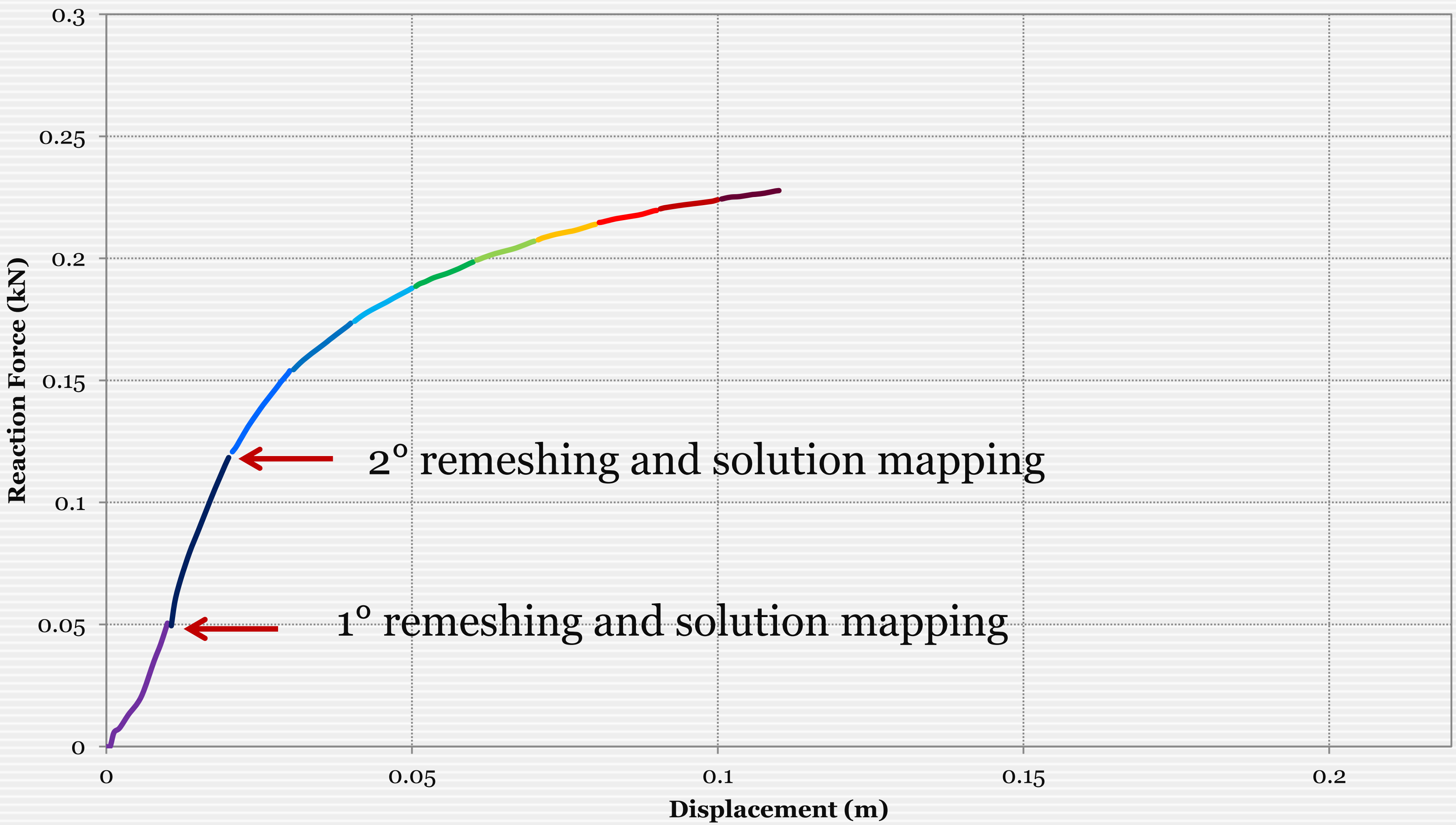

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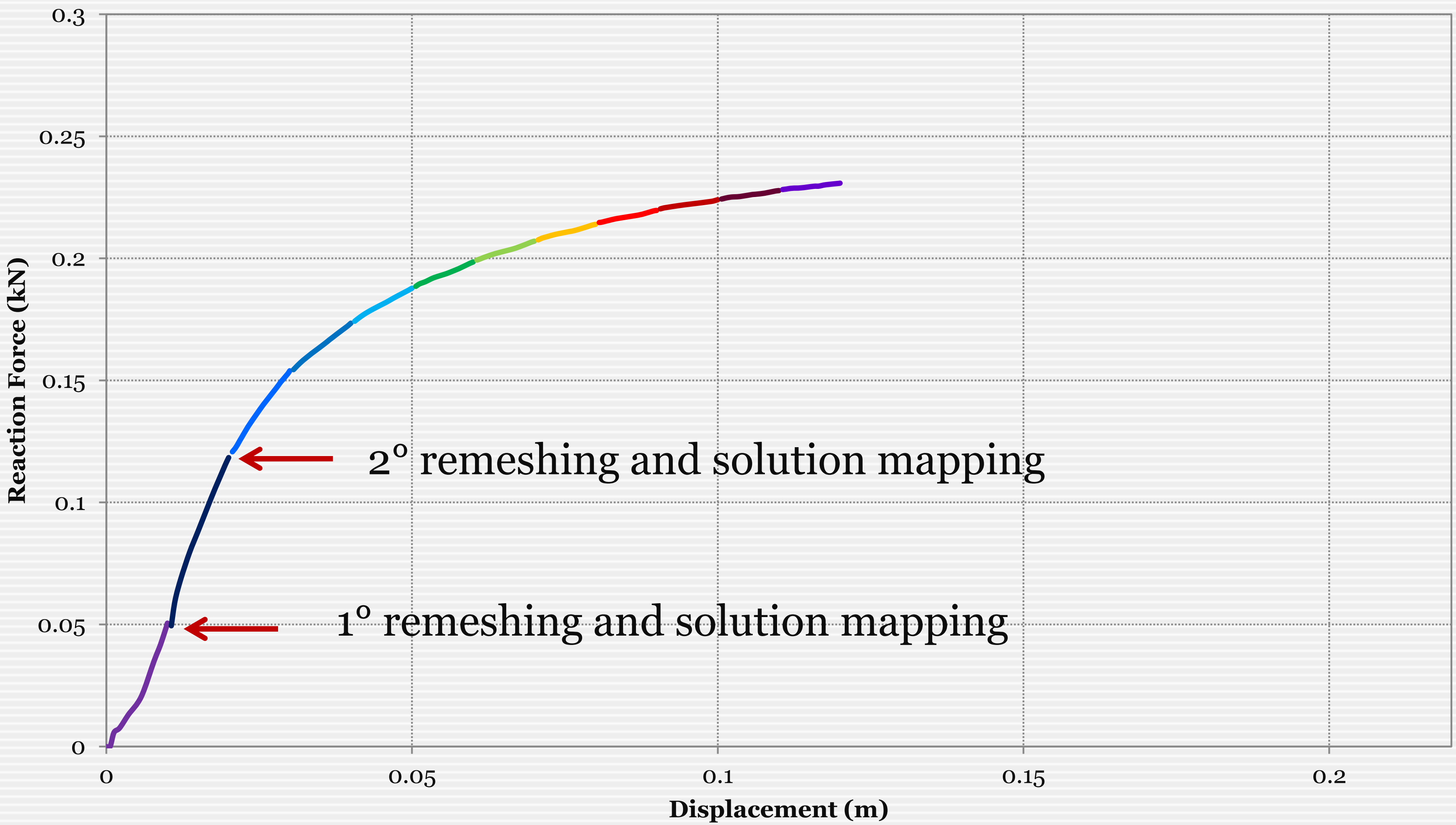

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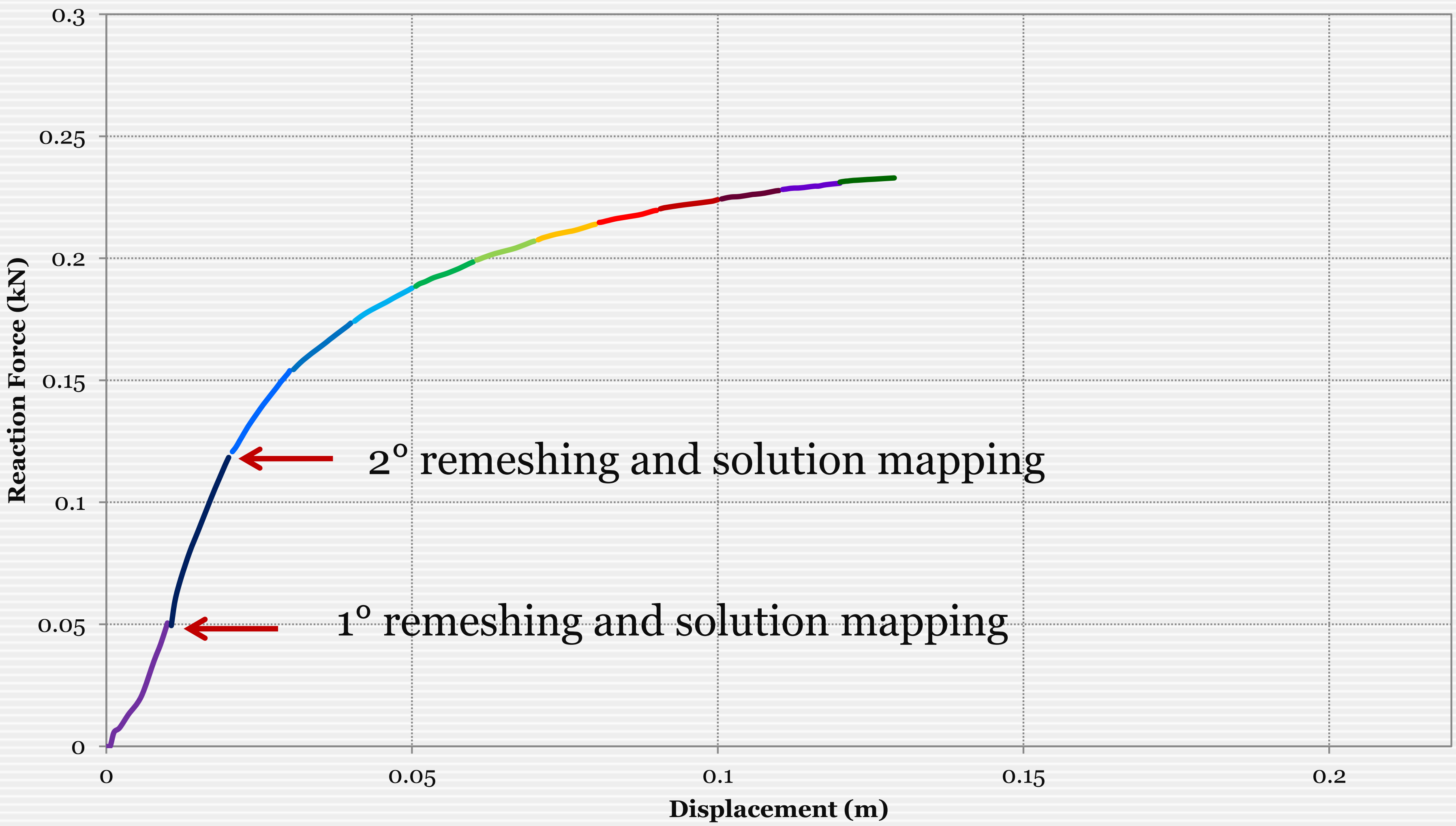

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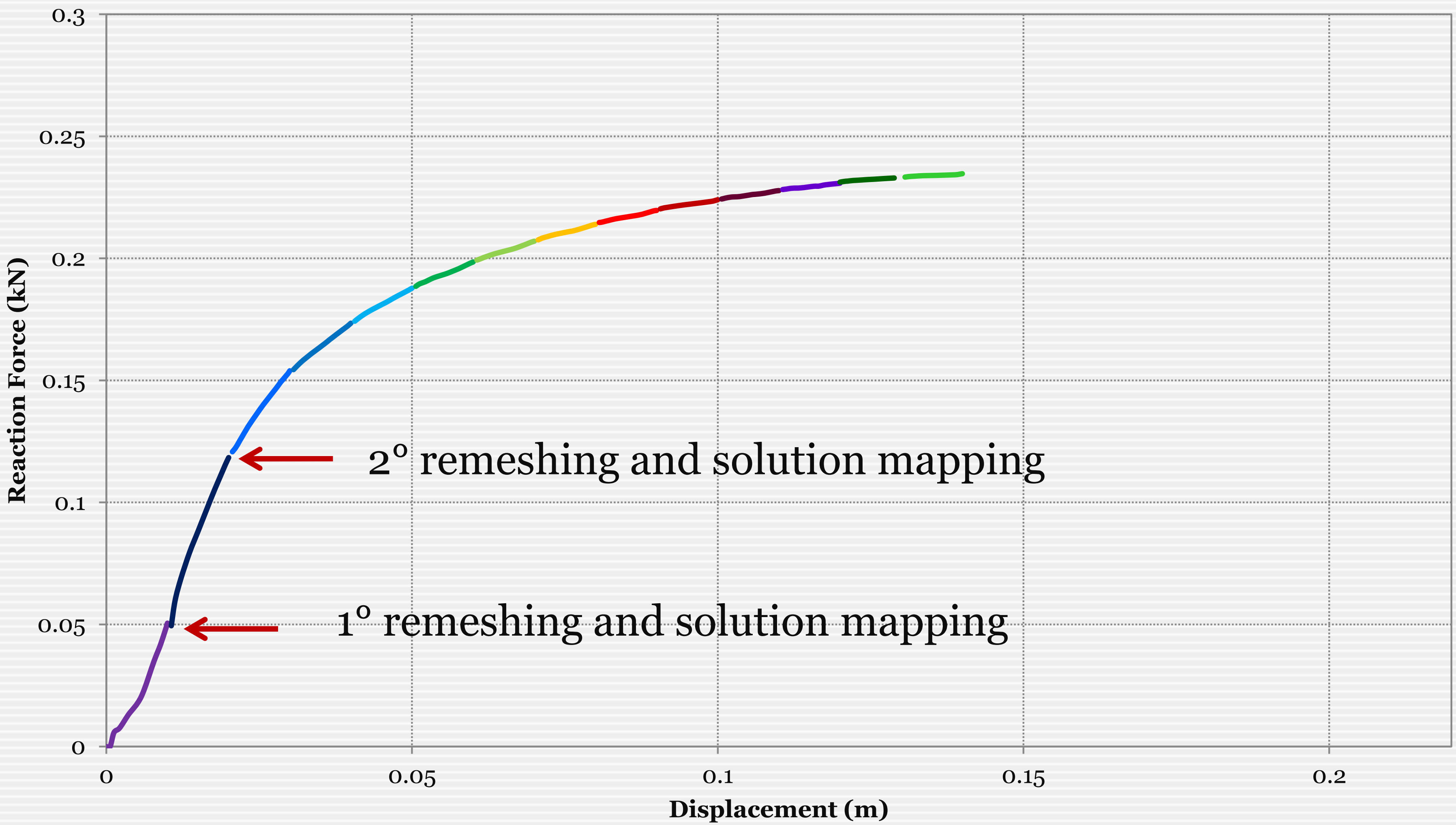

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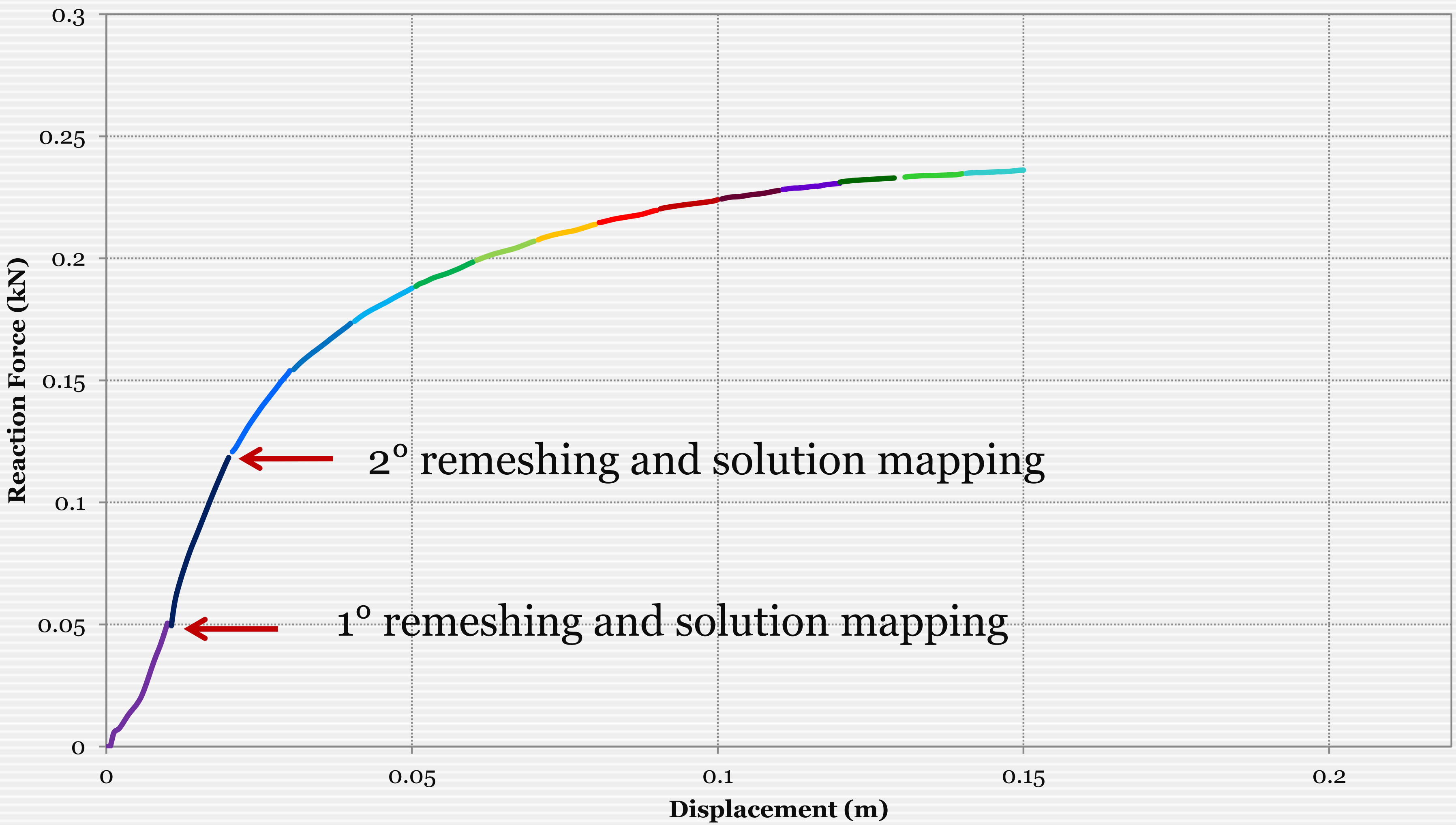

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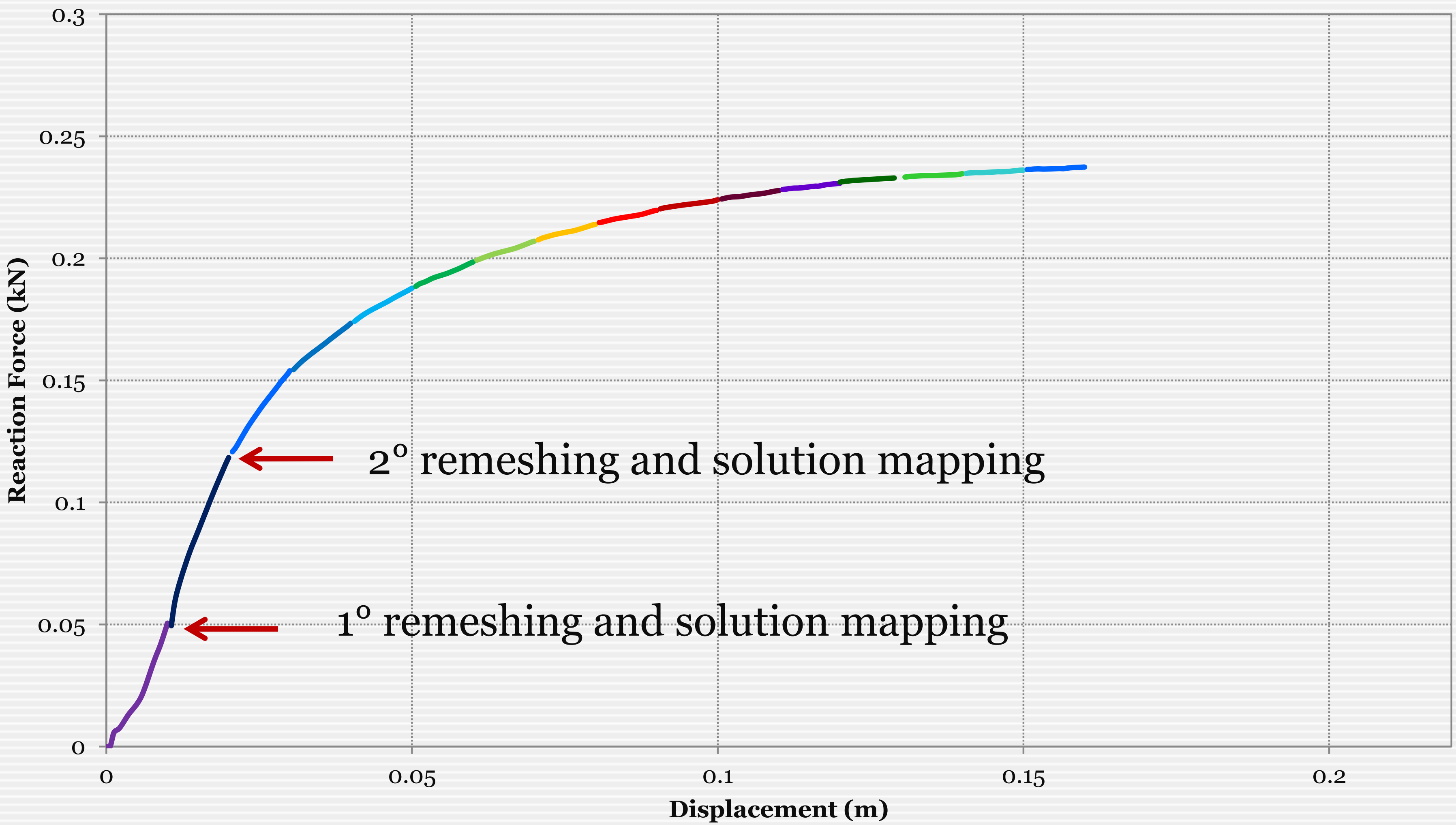

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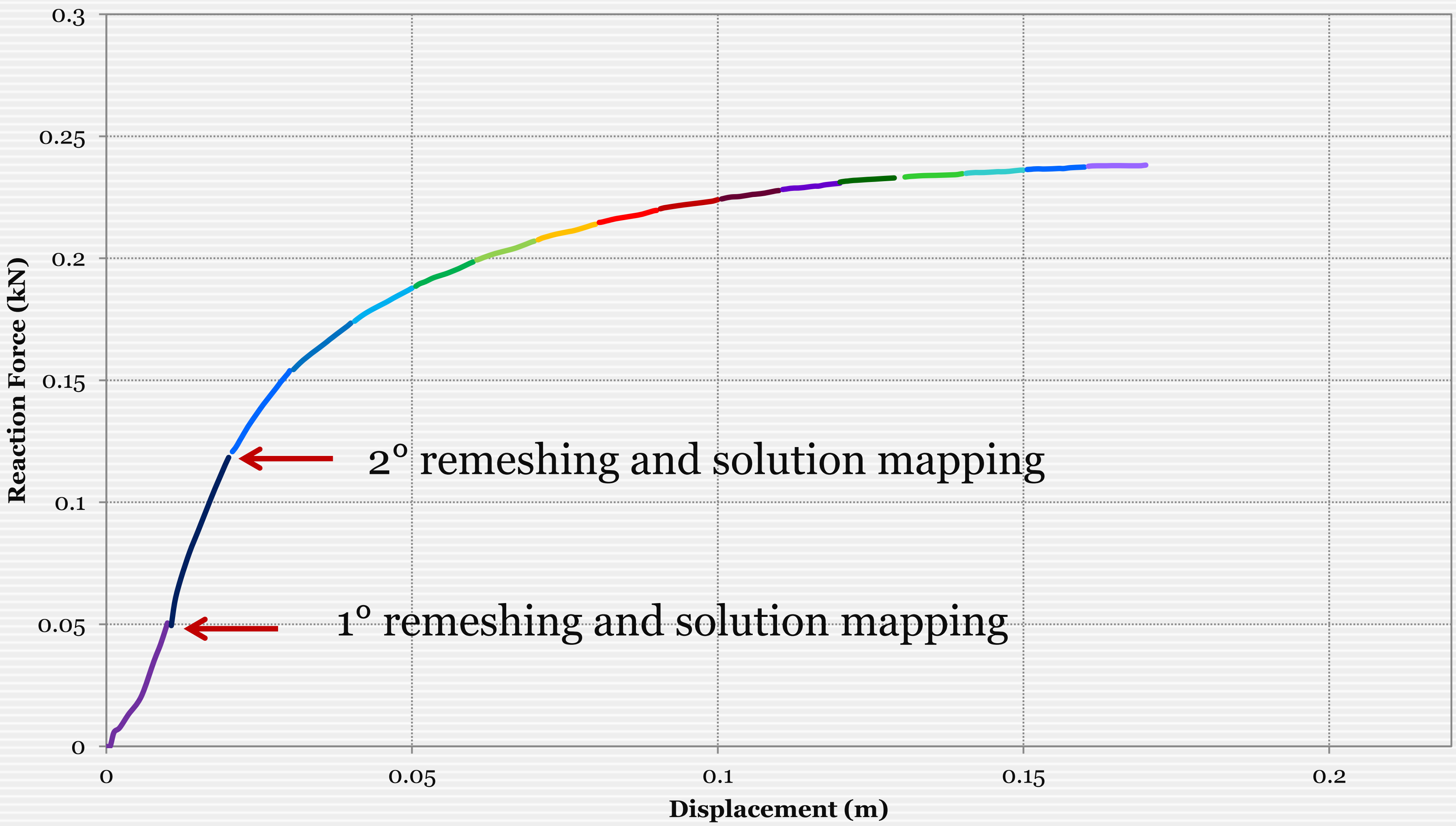

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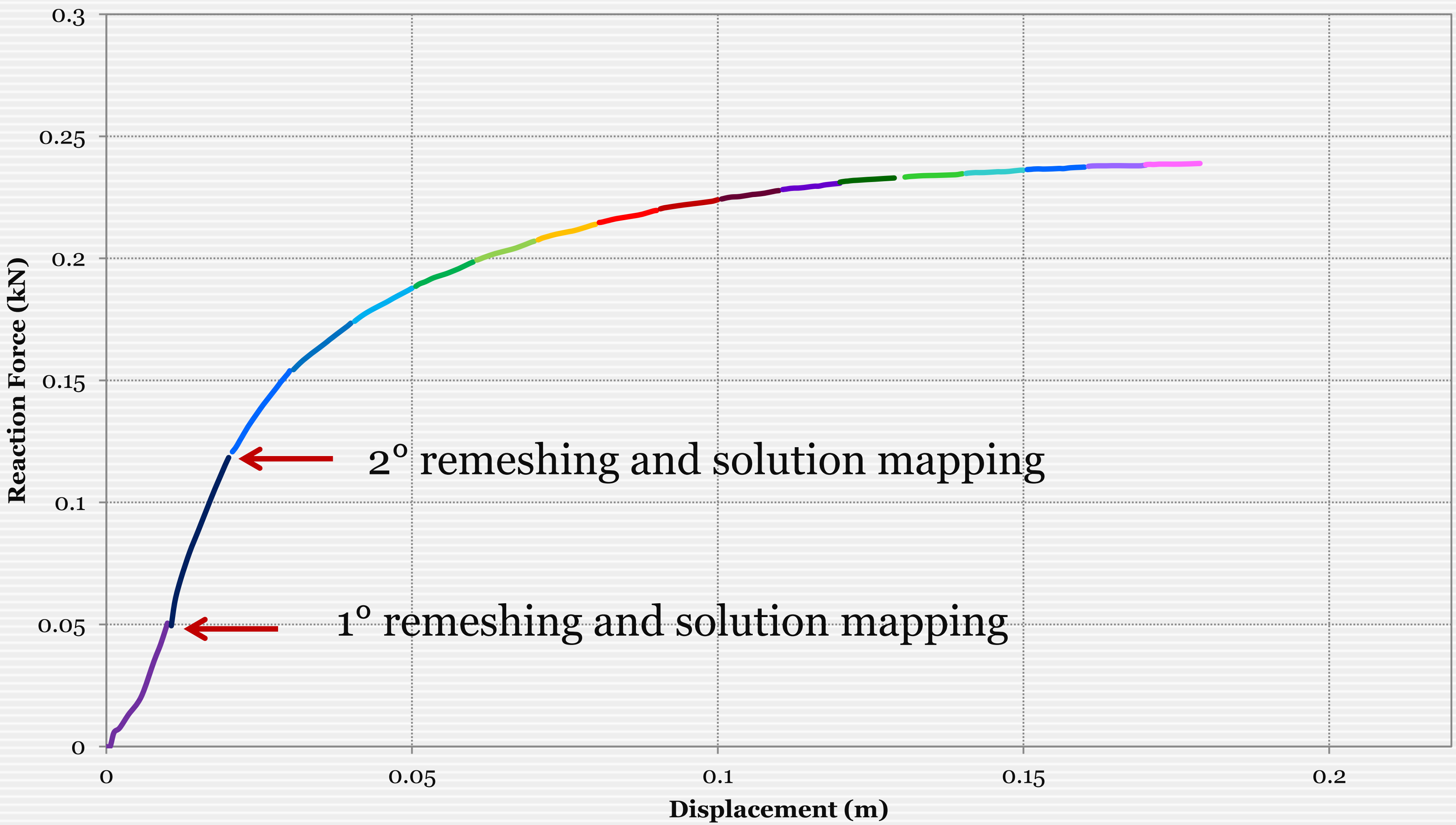

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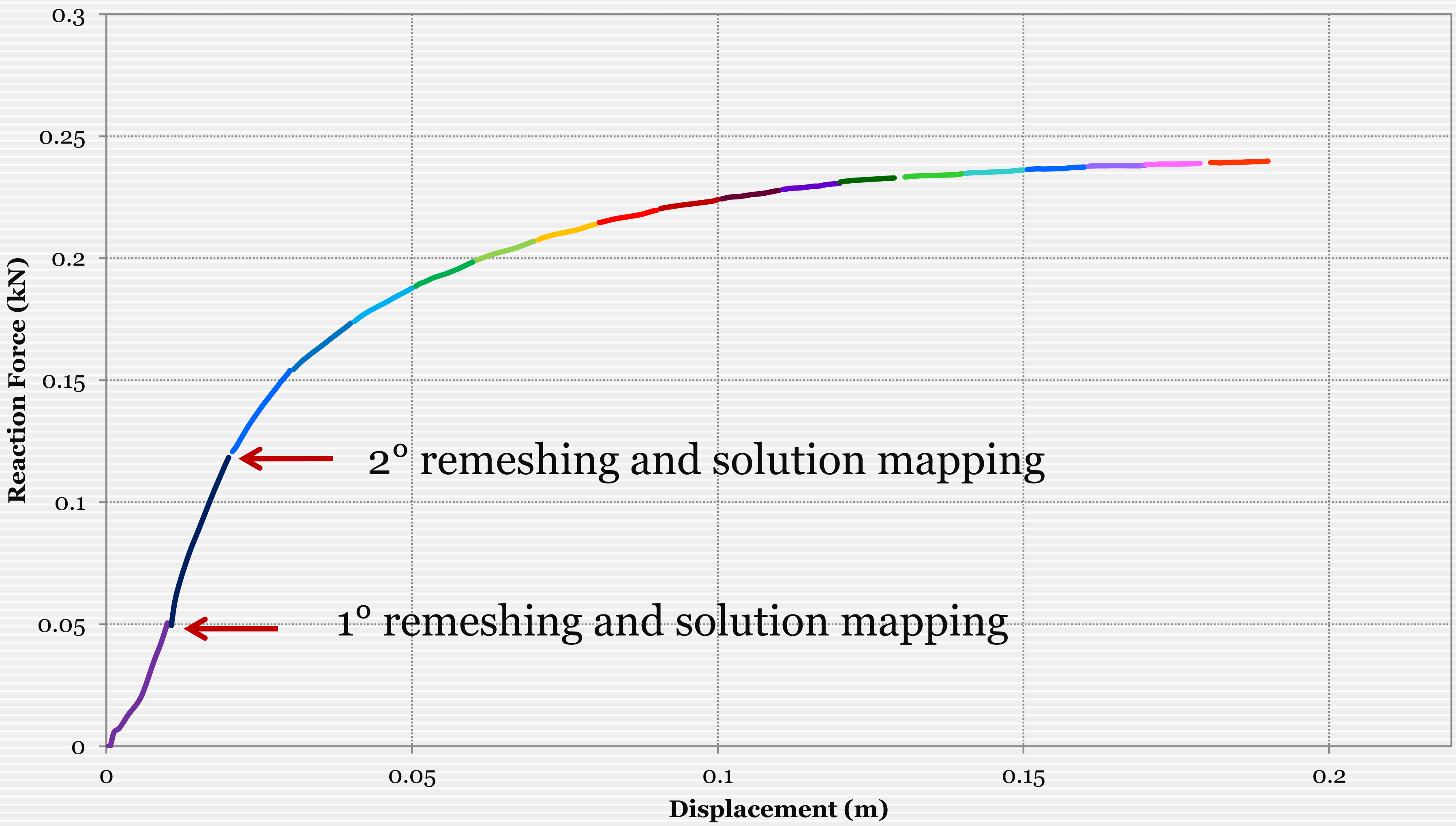

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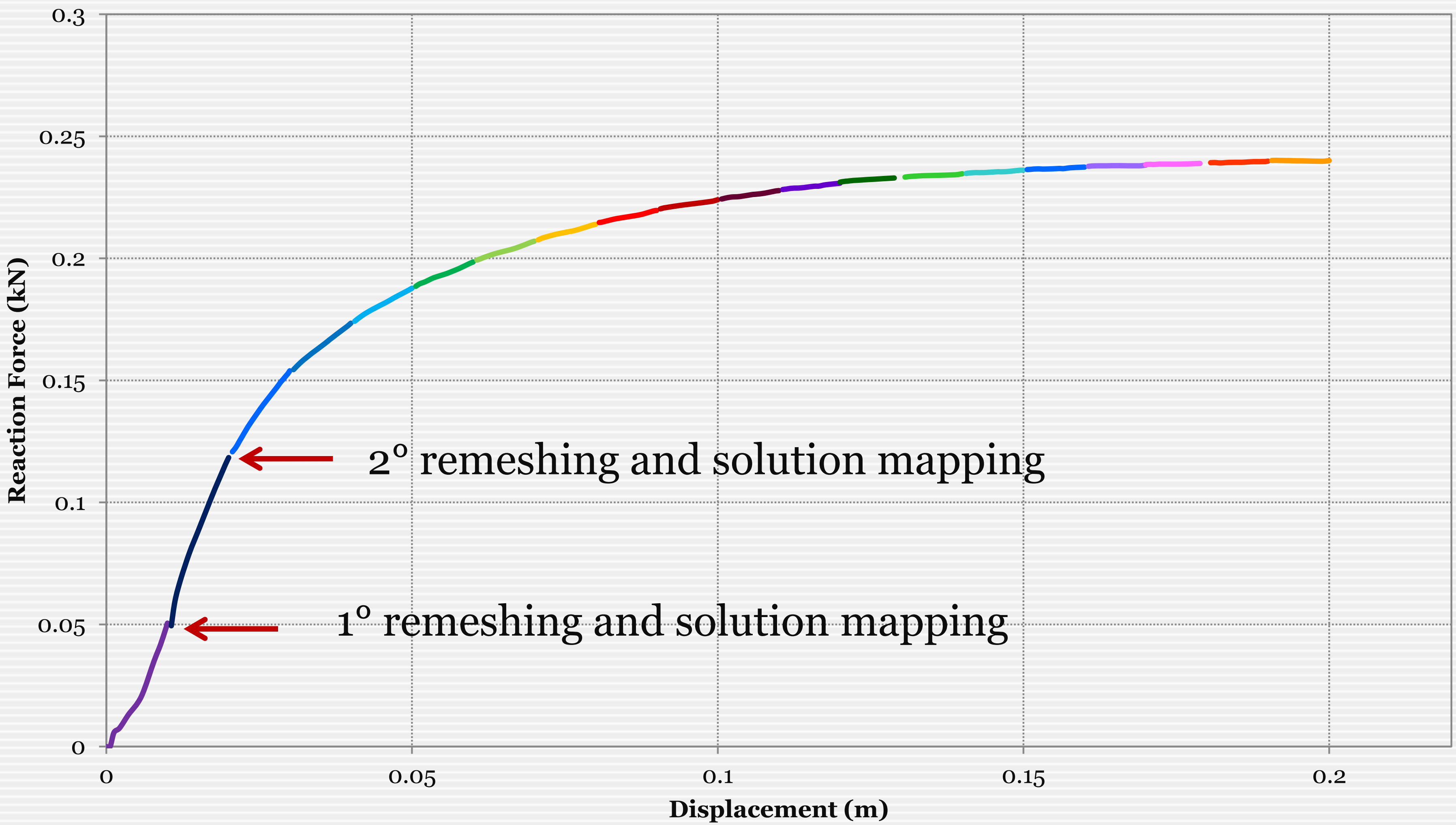

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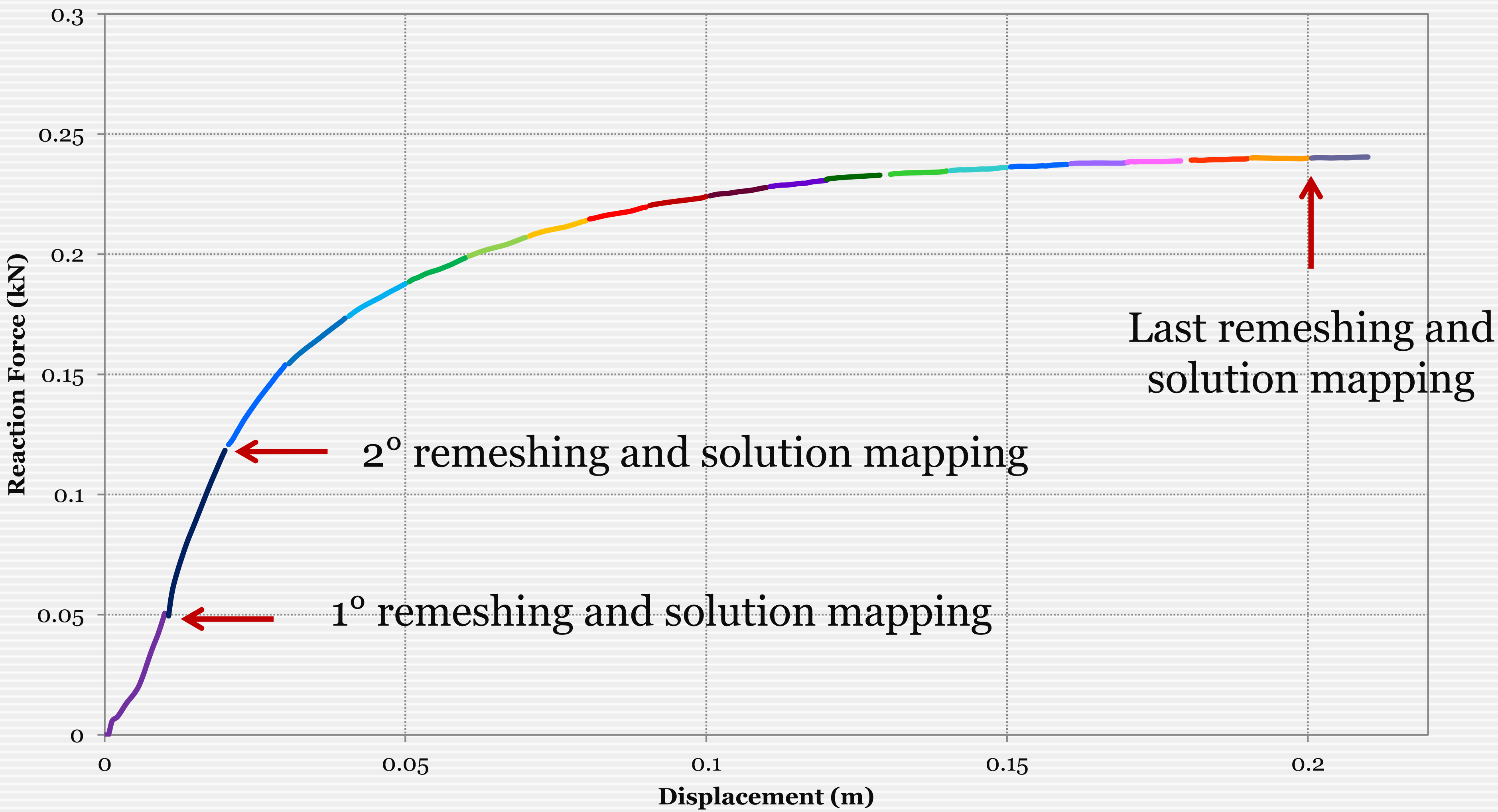

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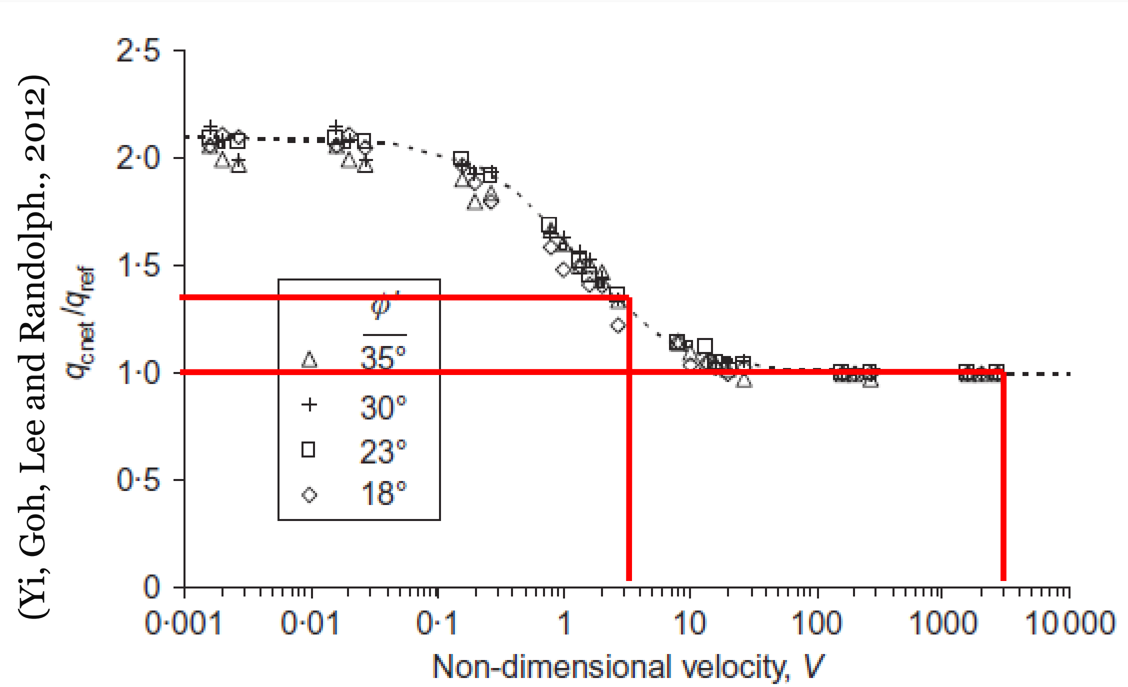
Finite Elements analyses of cone penetration

$$D' = \frac{2G(1-\nu')}{(1-2\nu')}$$

$$c_v = \frac{k}{m_v \gamma_w} = \frac{k\,D'}{\gamma_w}$$

Hydraulic conductivity k (m/s)	D' (kPa)	Penetration rate v (m/s)	c_v (m^2/s)	V	q_{cnet}/q_{ref}
1.E-06	2880	0.02	2.9E-04	2.5E+00	1.3
1.E-09			2.9E-07	2.5E+03	1.0



"Following Randolph & Hope (2004), the normalized cone resistance qcnet/qref is defined as the net cone resistance normalized by the reference (or undrained) net cone resistance."

$$V = \frac{v\,d}{c_v}$$

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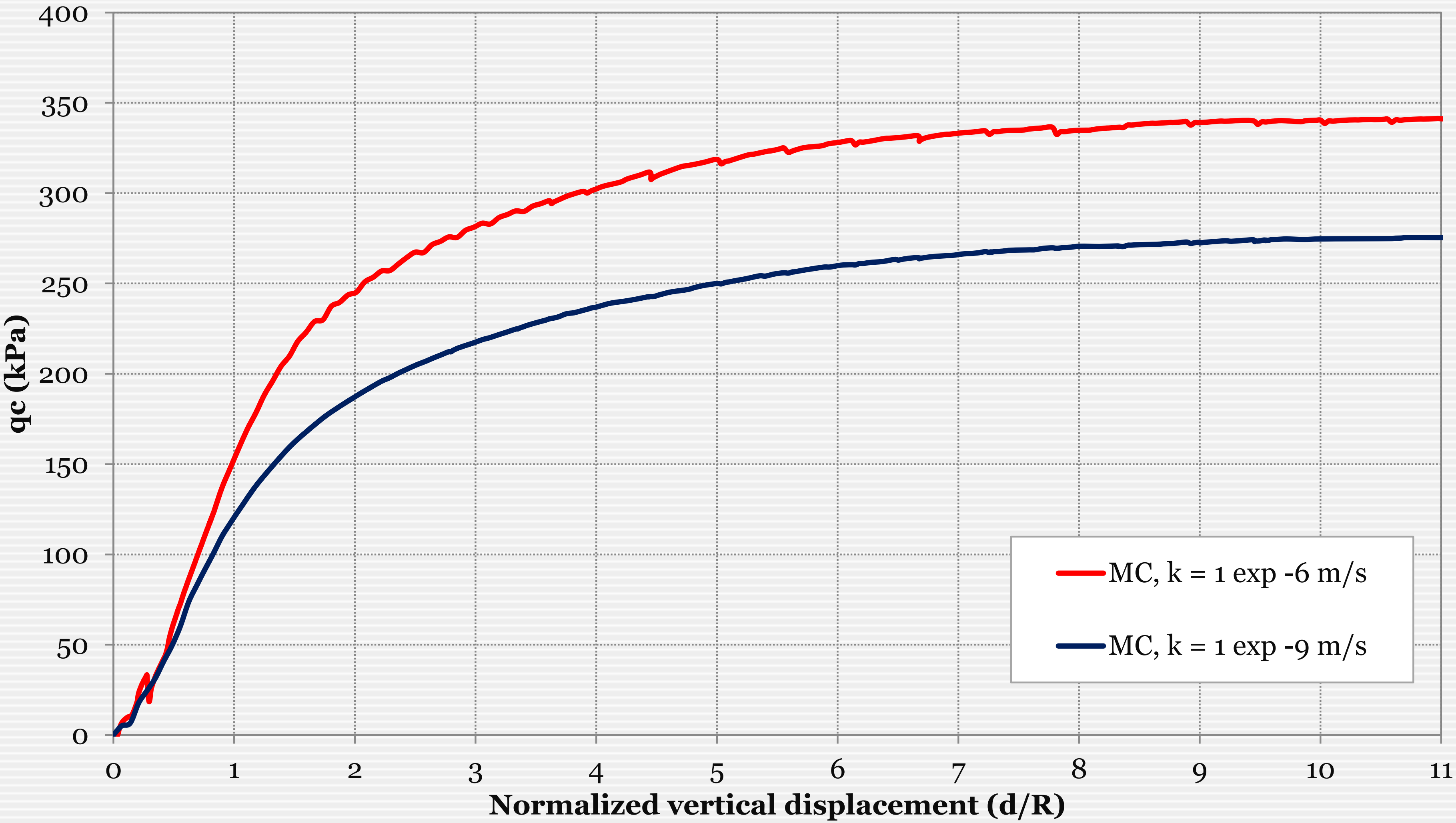

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Finite Elements analyses of cone penetration

- This study represents the first step to develop a methodology aimed at simulating the large strain penetration process under different drainage conditions. For this purpose the Updated Lagrangian technique will be used for coupled-consolidation analysis, adopting more complex constitutive models for the soil

- Laboratory characterization and in situ testing of dredged sediments from the port of Livorno is currently underway. These data will be used to investigate the robustness of proposed classification schemes and will provide data for evaluating predictive capabilities of the numerical analyses.