Three-node zero-thickness hydro-mechanical interface finite element for geotechnical applications

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Outline

1. Context
2. Modelling interfaces
3. Application
4. Conclusions
1. Context
2. Modelling interfaces
3. Application
4. Conclusions
Suction caisson

- Foundation for offshore structures
- Hollow cylinder open towards the bottom
- Made of steel

- Installed by suction
- Increased transient resistance to pull and push loads
- Crucial role of interfaces
Interface in geomechanics

Interface

Surface between two media (=discontinuity)

Soil

Caisson

Interface

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Interface in geomechanics

- Interface: Surface between two media (=discontinuity)
- Contact: Shearing, Sliding, Unsticking, Flow

Push load
Contact pressure
Soil
Interface in geomechanics

- Interface
- Contact
- Shearing

Surface between two media (=discontinuity)

Pull load
Shear stresses
Soil
Interface in geomechanics

- **Interface**
- **Contact**
- **Shearing**
- **Sliding**

**Surface between two media (=discontinuity)**

Diagram:
- Pull load
- Sliding in soil
Interface in geomechanics

- **Interface**
- **Contact**
- **Shearing**
- **Sliding**
- **Unsticking**

**Surface between two media (=discontinuity)**

- **Unsticking**
- **Pull load**
- **Soil**
- **Sliding**
Interface in geomechanics

- Interface
- Contact
- Shearing
- Sliding
- Unsticking
- Flow

Surface between two media (=discontinuity)

- Pull load
- Fluid flow
- Soil
- Unsticking
- Sliding
1. Context

2. Modelling interfaces
   - Mechanical problem
   - Hydraulic problem
   - Coupled problem

3. Application

4. Conclusions
Normal behaviour

Contact

\[ p_N \geq 0 \quad g_N \geq 0 \quad p_N g_N = 0 \]
Normal behaviour

Contact

\[ p_N \geq 0 \quad g_N \geq 0 \quad p_N g_N = 0 \]

Approaches

- Regularisation
  \[ p_N = f(g_N) \]
- Discretisation

1. Thin layer
2. Zero-thickness

- No contact
- Contact

Thin layer elements

Medium 1

Medium 2

Medium 3

Boundary elements

Medium 1

Medium 2
Normal behaviour

Contact

\[ p_N \geq 0 \quad g_N \geq 0 \quad p_N g_N = 0 \]

Approaches

- Regularisation
- Discretisation
  - Lagrange multiplier method
  - Penalty method

Regularisation

- Pressure distribution
  - No penetration
- Penetration

Zoom
Normal behaviour

- Contact
  - $p_N \geq 0$
  - $g_N \geq 0$
  - $p_N g_N = 0$

- Approaches
  - Regularisation
    - $p_N = f(g_N)$
  - Discretisation

- Intricate asperities
  - First contact point

- Compression
  - Asperities deformation

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Normal behaviour

Contact

\[ p_N \geq 0 \quad g_N \geq 0 \quad p_N g_N = 0 \]

Approaches

Regularisation

\[ p_N = f(g_N) \]

Discretisation

Node to node

Node to segment

Segment to segment

Contact domain

Gap

Penetration

Gap interpolation
Tangential behaviour

Shearing

\[ \tau \geq 0 \quad \dot{\gamma}_T \geq 0 \quad \tau \dot{\gamma}_T = 0 \]

Sticking

\[ \tau = \tau_{\text{max}} \]

Sliding

\[ E_1 \quad E_2 \]

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Tangential behaviour

Shearing

\[ \tau \geq 0 \quad \dot{g}_T \geq 0 \quad \tau \dot{g}_T = 0 \]

Criterion

\[ f = \|\tau\| - \mu p_N \]

Sticking state

Sliding state

No contact

\( \mu \)

\( p_N \)
Fluid flows

Interface

Longitudinal and transversal flows

Discontinuity = porous medium
Modelling interfaces

Hydraulic problem

Fluid flows

Interface

Discretisation

Longitudinal and transversal flows

Single node

Double node

gN

Porous medium

Discontinuity

Finite element mesh

Triple node

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Couplings

Hydro-mechanical couplings

Effective pressure

Terzaghi’s principle

\[ p_N = p'_N + p_w \]

- \( p'_N \), effective pressure (mechanical behaviour)
- \( p_w \), fluid pressure inside the interface
**Couplings**

- Hydro-mechanical couplings
- Effective pressure
- Permeability

### Cubic law

\[ k_l = \begin{cases} 
\frac{(D_0)^2}{12} & \text{if } g_N \leq 0 \\
\frac{(D_0 + g_N)^2}{12} & \text{otherwise.}
\end{cases} \]

- \( k_l \), longitudinal permeability
- \( D_0 \), residual hydraulic opening
**Couplings**

- Hydro-mechanical couplings
- Effective pressure
- Permeability
- Storage

**Stored water within discontinuity**

\[
\dot{M}_f = \left( \rho_w g_N + \rho_w \dot{g}_N + \rho_w g_N \frac{\dot{L}}{L} \right) L
\]

- \(L\), length of the discontinuity
- \(\rho_w\), density of water
Summary

Mechanical problem
- Zero-thickness
- Segment to segment discretisation
- Penalty method to enforce normal and tangential constraints
- Coulomb criterion

Hydraulic problem
- Three-node discretisation
- Longitudinal flow
- Transversal flows

Coupled problem
- Effective pressure
- Permeability
- Storage (transient component)
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1. Context
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Statement of the problem

- Elastic soil and caisson
- Diameter 7.8m
- Water depth 10m
- Soil permeability 1.E-11m²
- $K_0 = 1$

- Friction coefficient 0.57
- Residual hydraulic aperture 1.E-5m
- Penalty coefficient 1.E10 N/m³
- Conductivity 1.E-8m/Pa/s
Drained simulation (mechanical behaviour)

Shearing of the interface

\[ \Delta F_{\text{tot}} \]
\[ \Delta F_{\text{int}} \]
\[ \Delta F_{\text{ext}} \]

\[ \Delta y > 0 \]

Displ. [mm]
\[ \Delta F \] [kN]

\[ \Delta F_{\text{tot}} \]
\[ \Delta F_{\text{ext}} \]
\[ \Delta F_{\text{int}} \]

A

B

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**Drained simulation (mechanical behaviour)**

![Drained simulation graph]

- **Outer friction**
- **Gap opening**

**Shearing of the interface**

- **Depth (m)**
- **Displacement (mm)**
- **Gap opening**

**Outer friction**

- **Gap opening**

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Drained simulation (mechanical behaviour)

Shearing of the interface

- Outer friction
- Gap opening
- Inner friction
- Failure
Partially drained simulation (hydraulic behaviour)

Suction effect

Higher $\Delta F_{tot}$
Partially drained simulation (hydraulic behaviour)

- \( \Delta F_{tot} \)
- Coupling
  \[ p_N = p'_N + p_w \]
- Transient \( \Delta p_w \)

Suction effect
Partially drained simulation (hydraulic behaviour)

- Opening of a gap
- Transversal flow
- Transversal storage
- Stationary phase

\[ \Delta F_{\text{tot}} \]
\[ \Delta F_{\text{uw}} \]
\[ \Delta y_S \]
\[ \Delta y_C \]

\[ v_p = 1 \text{ mm/min} \]
Partially drained simulation (hydraulic behaviour)

- Opening of a gap
- Coupling gap-permeability

Longitudinal flow $f_1$ along the skirt
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1. Context
2. Modelling interfaces
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Conclusions

1. Development of a coupled hydro-mechanical interface element
   - Zero-thickness
   - Three-node flow discretisation

2. Main features of mechanical behaviour
   - Shearing
   - Sliding

3. Main features of hydraulic behaviour
   - Transversal flows
   - Longitudinal flows

4. Hydro-mechanical couplings
   - Suction effect (Terzaghi)
   - Permeability (longitudinal flow)
   - Storage (Unsticking)
Related papers


