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Comparative assessment of finite element formulations for dynamic analysis in low-permeability saturated porous media

Key words: Cover function; Linear dependence; Unequal-order element; Stabilized element; Pressure oscillations

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Main Contributions

- Based on the unequal-order interpolation element enriched with cover functions, specialized quadrilateral and triangular elements are developed for 1D and 2D problems, respectively, to circumvent the inherent linear dependence issues in the cover function-enriched formulation.

- The numerical performance of the cover element and the stabilized equal-order interpolation element is systematically compared under both compressible and incompressible material conditions, clarifying the limitations and applicable scopes of stabilization methods across varying material properties.

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Methodology

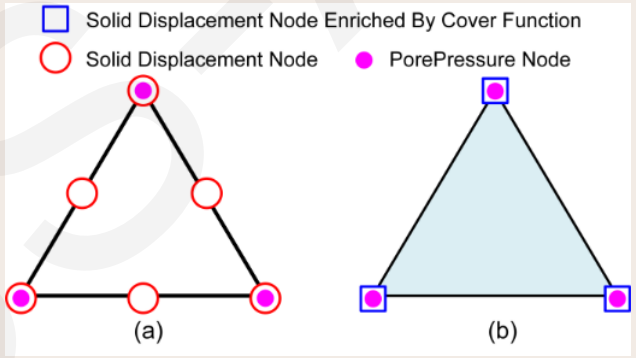
Equal-order Element: U1P1

Low-permeability Saturated Media: spurious pore pressure oscillations

Stabilized Equal-order Element: U1P1M

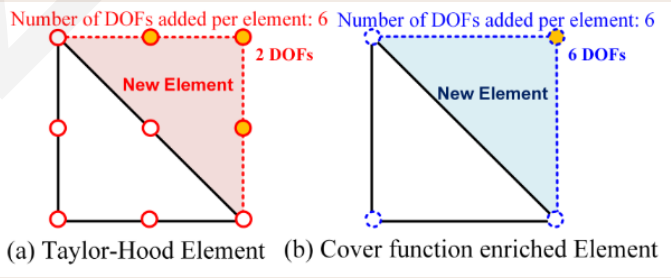
Add an artificial stabilization term to modify the governing equations.

Unequal-order Element: U2P1

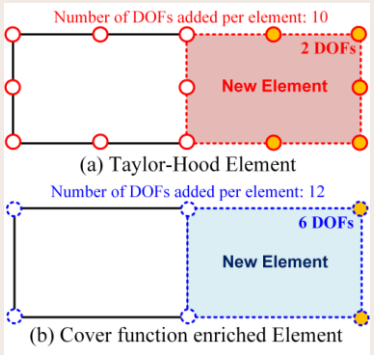


(a) Taylor-Hood Element; (b) cover function-enriched element

Linear Dependence Issue of Cover Elements



Triangular element



Quadrilateral element

Results Analysis and Comparison

- **For incompressible materials, the stabilized element U1P1 is accurate only when the solid skeleton is substantially stiff. The cover element U2P1 accurately captures the pore pressure response of incompressible saturated porous media in all cases, giving it broad applicability.**

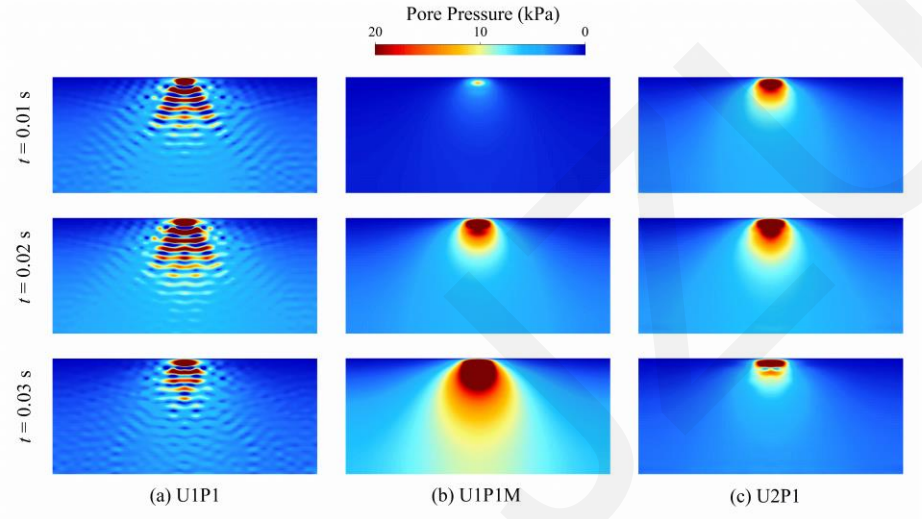


Fig. 10 Contours of pore pressure when E = 0.3 MPa

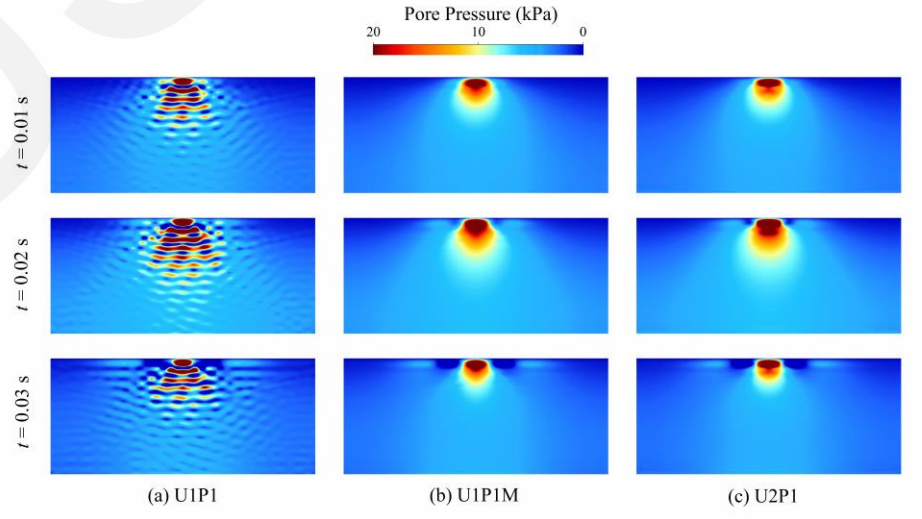


Fig. 11 Contours of pore pressure when E = 30 MPa

Results Analysis and Comparison

- For compressible materials, U2P1 offers robust, accurate simulations of compressional wave propagation, whereas U1P1M alters the mechanical properties of saturated porous media, thereby distorting wave characteristics and yielding only limited improvement through parameter tuning.

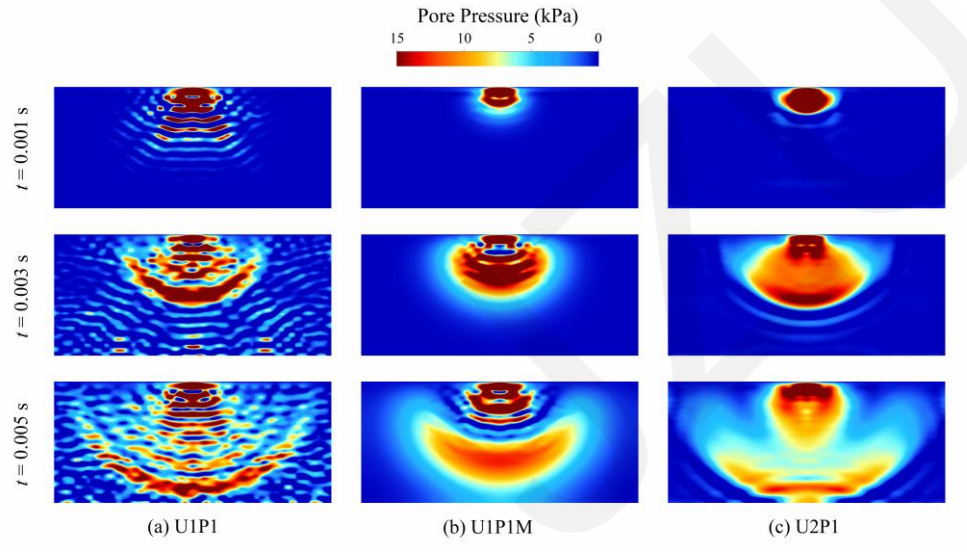


Fig. 16 Contours of pore pressure when E = 30 MPa

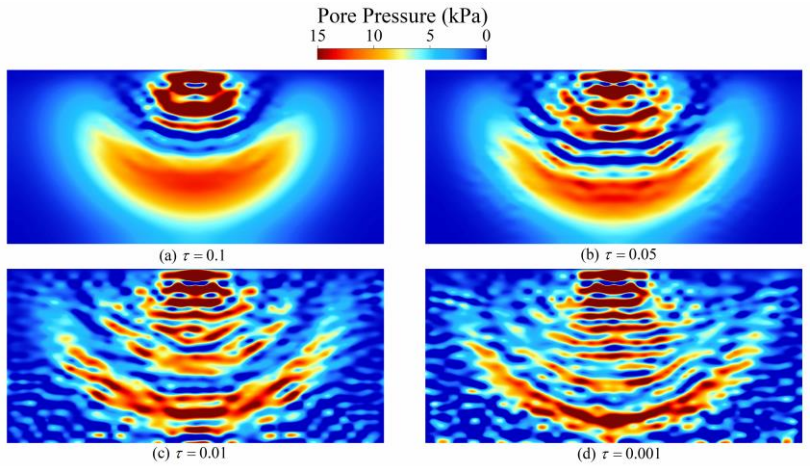


Fig. 17 Contours of pore pressure at t = 0.005 s versus the stabilization parameter when E = 30 MPa for the stabilized element U1P1M: (a) $\tau = 0.1$; (b) $\tau = 0.05$; (c) $\tau = 0.01$; (d) $\tau = 0.001$

Conclusions

- **While the standard equal-order element can capture the general trend of pore pressure evolution in nearly undrained saturated porous media, it fails to suppress unphysical oscillations.**

- **The stabilized equal-order element is sensitive to the artificial stabilization terms, leading to an overestimation of compressional wave dissipation and an underestimation of wave velocity. Achieving a balance between accuracy and numerical stability remains challenging, even when the stabilization parameter is calibrated based on Young's modulus, mesh size, and other relevant factors. Notably, the adverse effects of the stabilization term are more pronounced in compressible media than in incompressible media. As a result, an acceptable accuracy level is only achieved for incompressible porous media with sufficiently rigid solid skeletons.**

- **The cover function-enriched unequal-order element consistently and accurately captures the evolution of pore pressure for both compressible and incompressible media. When employed for dynamic analysis, this type of element maintains computational robustness, demonstrating insensitivity to variations in solid skeleton rigidity, compressibility of the solid and fluid phases, and permeability.**