AD FALCON API Manual

Introduction

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March 26, 2026

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1 Introduction

This chapter summarizes the theoretical framework implemented in FALCON. It connects the continuum balance laws and effective-stress concepts to the finite element discretization and time-integration schemes used in the code.

In particular, it:

- Classifies analysis scopes into Uncoupled, Coupled (saturated), and Fully Coupled (unsaturated) formulations.
- Highlights the associated primary degrees of freedom and governing matrix equations.
- Provides a compact view of time-integration schemes and sign conventions adopted in FALCON.
- Links each formulation to representative verification and benchmark problems documented elsewhere in this manual.

1.1 Key Features

Table 1: FALCON Feature Overview

Feature Area	Highlights
Analysis Types	**Uncoupled** (single-phase), **Coupled** (bi-phase), and **Fully Coupled** (multi-phase) simulations for planar, axisymmetric, and 3-D problems.
Rigid Body Motion	Apply prescribed or computed rigid motions.
Contact Mechanics	Surface interaction with frictional contact elements.
Dynamic Analysis	Implicit time-integration schemes.
Material Models	Built-in elastic and plastic models plus user-defined **UMAT** support.
Stress & Loads	Complex loading, including time-varying loads.

Feature Area	Highlights
Multiphase Interactions	Liquid–solid–gas interactions for coupled analyses.
Automatic Step Control	Adaptive time-stepping for efficient convergence.
Mesh Operations	Large deformations, mesh updating, and element remapping.
User Extensions	Hooks for custom user materials (UMATs).

1.2 Types of Analysis in FALCON

1.3 Uncoupled Analysis — *Single-Phase (Solid-Only)*

In an **uncoupled analysis**, *only the mechanical response of the solid skeleton is solved*. There are **no pore-pressure or fluid-flow degrees of freedom**, making it highly efficient but blind to hydro-mechanical feedback. Ideal when:

- The soil is essentially dry **or**
- Fluid effects are demonstrably secondary.

Table 2: Uncoupled Analysis Modes

Mode	Typical Use-Cases	Governing Assumptions
Static	Long-term equilibrium of soils.	No inertia or fluid terms.
Dynamic	Vibrations, impacts, seismic loading where solid inertia dominates.	Time-dependent inertia for the solid; **no pore flow**.

1.4 Coupled Analysis — *Bi-Phase (Solid + Water)*

Coupled analysis solves deformation **and** pore-water pressures, capturing hydro-mechanical feedback in saturated soils.

Table 3: Coupled Analysis Modes (Saturated)

Mode	Typical Use-Cases	Governing Assumptions
Static (steady)	Long-term equilibrium without seepage; constant pore-water field.	No inertia; no rate terms active: $\dot{\mathbf{U}} = \mathbf{0}$, $\dot{\mathbf{P}}_w = \mathbf{0}$; no Darcy flux.
Consolidation (transient)	Terzaghi-type dissipation under load; settlement over time.	No acceleration terms (quasi-static); rate terms active: $\dot{\mathbf{U}} \neq 0$, $\dot{\mathbf{P}}_w \neq 0$; Darcy flow present.
Dynamic	Saturated soil dynamics; seismic and impact problems.	Solid inertia present; coupled pore-pressure response; time-dependent flow.

1.5 Fully Coupled Analysis — *Multi-Phase (Solid + Water + Air)*

Fully coupled analysis adds the air phase (and optionally energy balance), essential for unsaturated or variably saturated soils.

Table 4: Fully Coupled Analysis Modes (Unsaturated)

Mode	Typical Use-Cases	Governing Assumptions
Static (steady)	Hydro-mechanical equilibrium without flow; fixed saturation/-pressures.	No inertia; no rate terms active: $\dot{\mathbf{U}} = \mathbf{0}$, $\dot{\mathbf{P}}_w = \mathbf{0}$, $\dot{\mathbf{P}}_g = \mathbf{0}$; no Darcy fluxes.
Consolidation (transient)	Unsaturated consolidation; infiltration/drainage with settlement.	No acceleration terms (quasi-static); rate terms active for $\mathbf{U}, p_w, p_g$; Darcy flows present.
Dynamic	Unsaturated soil dynamics with air–water–solid coupling.	Solid inertia present; transient pore-water/air pressures and saturation evolution.

1.6 Governing Equations at a Glance

Below is a compact view of the formulations used in FALCON. Use the tabs to switch between analysis types.

Uncoupled (Solid)

Primary DOFs: $\mathbf{U}$

Implementation note (FALCON): in `*NonCoupled` / `*UnCoupled` analyses, the density ρ used in Eqs. (2)–(3) is taken directly from `@PhaseChar: Solid rhos ...` (i.e., `rho = rhos`).

$$\mathbf{M}\ddot{\mathbf{U}} + \mathbf{C}\dot{\mathbf{U}} + \mathbf{K}\mathbf{U} = \mathbf{F} \tag{1}$$

with

$$\mathbf{M} = \int_{\Omega} \mathbf{N}^{\mathsf{T}} \rho \, \mathbf{N} \, d\Omega, \quad \mathbf{K} = \int_{\Omega} \mathbf{B}^{\mathsf{T}} \mathbf{D} \, \mathbf{B} \, d\Omega \tag{2}$$

and the external load vector

$$\mathbf{F} = \int_{\Omega} \mathbf{N}_u^{\mathsf{T}} \rho \, \mathbf{b} \, d\Omega + \int_{Gamma_t} \mathbf{N}_u^{\mathsf{T}} \bar{\mathbf{t}} \, d\Gamma \tag{3}$$

See details: Uncoupled Analysis.

Coupled (Solid + Water)

Primary DOFs: $\mathbf{U}, \mathbf{P}_w$

$$\mathbf{M} \, \ddot{\mathbf{U}} + \mathbf{C} \, \dot{\mathbf{U}} + \mathbf{K} \, \mathbf{U} - \mathbf{Q}_w \, \mathbf{P}_w = \mathbf{F} \tag{4}$$

$$\mathbf{Q}_w^{\mathsf{T}} \, \dot{\mathbf{U}} + \mathbf{C}_{ww} \, \dot{\mathbf{P}}_w + \mathbf{H}_{ww} \, \mathbf{P}_w = \mathbf{F}_w \tag{5}$$

The flux boundary on Γ_{q_w} obeys Darcy's law

$$\mathbf{k}_w \left[-\nabla p_w + \rho_w (\mathbf{b} - \ddot{\mathbf{u}}) \right] \cdot \mathbf{n}^* = \bar{\dot{\mathbf{w}}}_w \tag{6}$$

See details: Coupled Analysis.

Fully Coupled (Solid + Water + Air)

Primary DOFs: $\mathbf{U}, \mathbf{P}_w, \mathbf{P}_g$

Conservation and momentum balances (with negligible fluid-phase inertia) reduce to

$$\mathbf{M}_u \, \ddot{\mathbf{U}} + \mathbf{C} \, \dot{\mathbf{U}} + \mathbf{K} \, \mathbf{U} - \mathbf{Q}_w^* \, \mathbf{P}_w - \mathbf{Q}_g^* \, \mathbf{P}_g = \mathbf{F}_u \tag{7}$$

$$\mathbf{Q}_w^{\mathsf{T}} \, \dot{\mathbf{U}} + \mathbf{C}_{ww} \, \dot{\mathbf{P}}_w + \mathbf{H}_{ww} \, \mathbf{P}_w = \mathbf{F}_w \tag{8}$$

$$\mathbf{R}_g^{\mathsf{T}} \, \dot{\mathbf{U}} + \mathbf{C}_{gg} \, \dot{\mathbf{P}}_g + \mathbf{H}_{gg} \, \mathbf{P}_g = \mathbf{F}_g \tag{9}$$

Effective stress follows an α-enriched Bishop form (see Ghorbani–Kodikara)

$$\boldsymbol{\sigma}' = \boldsymbol{\sigma} + \chi \, p_w \, \mathbf{I} + (1 - \chi) \, p_g \, \mathbf{I}, \quad \chi = \alpha_{\text{eff}} S_w \tag{10}$$

See details: Fully Coupled Analysis.

1.7 Time Integration (Summary)

FALCON supports multiple time-integration options. The selection is made in the analysis input (per simulation step), but this introduction keeps the discussion at the formulation level.

Time integration option	Supported analysis modes	Solid DOFs (displacements)	Pressure DOFs (pore pressures)
Implicit (default)	Static, consolidation, dynamic	Generalized-α / Newmark family (solved with Newton iterations)	One-step θ-method (inside Newton; default θ = 0.6)
Explicit	Dynamic only	Lumped-mass predictor–corrector (modified Euler / Heun)	Not supported
IMEX (implicit–explicit)	Dynamic only	Explicit predictor–corrector (modified Euler / Heun)	Implicit θ-method (two pressure solves per substep to form a coupling-aware error estimate)

Implicit (default). For coupled problems, the implicit formulation advances **displacements** and **pore pressures** together (monolithic Newton solve), but it uses different time-discretization "building blocks" for each field:

- **Solid (displacements): generalized-α / Newmark family.** In the current implementation this is expressed in generalized-α form via algorithmic parameters α_m and α_f, with the associated Newmark-like parameters

$$\gamma = 0.5 + \alpha_f - \alpha_m, \qquad \beta = 0.25\,(1 + \alpha_f - \alpha_m)^2 \tag{11}$$

  Default settings are chosen so the scheme reduces to standard Newmark average-acceleration ($\gamma = 0.5,\ \beta = 0.25$). In generalized-$\alpha$ form, α_f also appears as a weighting on stiffness/load terms.
- **Flow (pore pressures): one-step θ-method.** Pore-pressure DOFs are advanced with a one-step θ-method with $\theta \in [0.5, 1.0]$; in FALCON the default is θ **= 0.6** (θ = 1: backward Euler; θ = 0.5: Crank–Nicolson).

For linear elastodynamics, the classical unconditional-stability conditions for the Newmark family are

$$\gamma \geq 0.5, \qquad \beta \geq 0.25\,(0.5 + \gamma)^2 \tag{12}$$

Explicit. Dynamic-only and mechanical-only (no pore-pressure DOFs). Uses a lumped-mass update and is typically paired with adaptive substepping using an embedded local time-integration error estimate.

IMEX. Dynamic-only. Advances the solid explicitly (as in Explicit), but advances pore pressures with an implicit θ-method to avoid severe diffusion-type stability limitsg.

See also: Explicit and IMEX Time Integration.

1.8 Sign Conventions

> **Note**
>
> Stresses are negative in compression, while pore pressures p_w, p_g are positive in compression.

1.9 Where to Next

- Theory details: Uncoupled, Coupled, Fully Coupled
- Implementation properties: see the entries under “Analysis Properties” in the navigation.