AD FALCON API Manual

Rigid Strip Footing on Unsaturated Soils: Fully Coupled Analysis with MCC Model

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1 Rigid Strip Footing on Unsaturated Soils: Fully Coupled Analysis with MCC Model

1.1 Problem Description

This study investigates the fully coupled hydro-mechanical response of unsaturated soil beneath a rigid strip footing using the MCC model. Three simulations are compared to demonstrate the effect of matric suction on bearing capacity:

- **Saturated soil - coupled** ($p_c = 0$ kPa): Fully coupled analysis under saturated conditions
- **Saturated soil - uncoupled** ($p_c = 0$ kPa): Uncoupled drained analysis (from rigidfooting-gcc.md)
- **Unsaturated soil** ($p_c = 5$ kPa): Fully coupled analysis with constant matric suction of 5 kPa

All analyses use the MCC model with $\alpha = 0.77$ (Lode-angle dependent yield surface) and employ the same geometry and boundary conditions. The comparison of saturated coupled and uncoupled results validates the coupled formulation, while the unsaturated case demonstrates the strength enhancement due to matric suction.

Reference

Sheng, D., Sloan, S. W., & Yu, H. S. (2000). *Aspects of finite element implementation of critical state models.* Computational Mechanics, 26, 185–196.

1.2 Input Files

Three input files are used for the comparison:

- **Saturated (coupled):** `fem_data_GCC_Sat_slow.txt` — Fully coupled saturated analysis ($p_c = 0$ kPa)
- **Saturated (uncoupled):** `fem_data_GCC.txt` — Uncoupled drained analysis ($p_c = 0$ kPa)
- **Unsaturated:** `fem_data_MCC_suc_5.txt` — Fully coupled with constant suction ($p_c = 5$ kPa)

1.3 Material Parameters

1.3.1 Modified Cam-Clay (MCC) Model

- **Friction angle** ϕ: 23°
- **Compressibility index** λ: 0.25
- **Poisson's ratio** ν: 0.30

- **Swelling index** κ: 0.05

- α **parameter**: 0.77 (Lode-angle dependent yield surface)
- **Default isotropic hardening**: 50 kPa (minimum isotropic hardening in the domain)

- **Critical-state specific volume** v_{CSL}: 2.60 → **Initial specific volume** v_N: 2.739

- **Overconsolidation pressure at surface**: 50 kPa

1.3.2 Unsaturated Parameters

- **Coupling coefficient** c_1: 0.20
- **Exponential coefficient** c_2: 1.50
- **SWRC void ratio parameter** Ω': 0.2
- **van Genuchten parameter** n: 2.5
- **van Genuchten parameter** m: 0.6
- **Inverse air-entry (drying)** P^d: 0.05 kPa^{-1}
- **Inverse air-entry (wetting)** P^w: 0.10 kPa^{-1}

1.3.3 Hydraulic Parameters

- **Permeability (saturated)**: $k = 2.5 \times 10^{-14}$ m^2
- **Water density**: $\rho_w = 997$ kg/m^3
- **Air density**: $\rho_a = 1.1$ kg/m^3
- **Water bulk modulus**: $K_w = 2.25 \times 10^6$ kPa
- **Air bulk modulus**: $K_a = 1.01 \times 10^2$ kPa
- **Water viscosity**: $\eta_w = 1.0 \times 10^{-3}$ Ns/m^2
- **Air viscosity**: $\eta_a = 1.8 \times 10^{-5}$ Ns/m^2

Tolerance parameters - **Stress tolerance (STOL):** 1.0×10^{-6}
\- **Yield surface tolerance (FTOL):** 1.0×10^{-4}
\- **Loading/unloading detection tolerance (LTOL):** 1.0×10^{-6}

1.4 Initial Assignment

Initial stresses, void ratio, and hydraulic state variables are applied to the entire domain.

1.4.1 Saturated Case

```
% Initial Assignments
@Stress: H 0 values -1e0 -1e0 -1e0 0 0 0 H 10 values -1e0 -1e0 -1e0 0 0 0
@Void: H 0 values 1.74 H 10 values 1.74
@OCR: H 0 values 0.0 H 10 values 0.0
@PoreWaterPressure: H 0 values 0.0 H 10 values 0.0
%%%
```

1.4.2 Unsaturated Case (5 kPa Suction)

```
% Initial Assignments
@Void: H 0 values 1.74 H 10 values 1.74
@Alpha_p_c: H 0 values 0.5 H 10 values 0.5
@PW: H 0 values -5 H 10 values -5
@TotalStress: H 0 values -1.0e0 -1.0e0 -1.0e0 0 0 0 H 10 values -1.0e0
-1.0e0 -1.0e0 0 0 0
%%%
```

Note: For the unsaturated case, `@Alpha_p_c` is the SWRC hysteresis parameter (0 = wetting curve, 1 = drying curve), and `@PW` specifies pore water pressure using the compression-positive convention (negative values indicate suction).

1.5 Step 1: Geostatic Initialization via Body Force

In Step 1, body forces are applied to establish the geostatic stress state. The flag `@@EnforceElasticFlag: All` temporarily deactivates plasticity during initialization.

```
% Step Definitions
@Step 1:
@@StartStep: 0
@@StepTime: 1.0
@@SolverType: Direct
@@NumberSteps: 10
@@OutputInterval: 10
@@OutputTypes: Displacement EffStress VoidRatio PoreWaterPressure
DegreeOfSaturation
@@ErrorTarget: 1.0e-1
@@UL: No
@@SimMode: Static
```

```
@@EnforceElasticFlag: All
%%%
```

The body force is applied with the same parameters:

```
% Body Force
Force 0.0 -9.81 0.0
WaterContribution 0.0 0.0 0.0
AirContribution 0.0 0.0 0.0
ElementIDs All
LoadType Ramp Step 1
StartStep 1
Propagate: FinalStep 2
DisplacementReset: End of Step 1
InitialVoidinBF: Yes
%%%
```

1.6 Yield Surface Correction

After geostatic stresses are established, the yield surface is corrected using `OverconsolidationControl ≠ 1`. We assumed the soil has an overconsolidation pressure of 50 kPa at the surface (`OCR = 0` and `DefIsoH = 50 kPa`), consistent with Sheng et al. (2000). The void ratio across the domain is then updated to enforce consistency conditions.

1.7 Geometry and Boundary Conditions

The geometry is identical to the uncoupled and saturated analyses:

Geometry - **Half-width of footing:** $B_a/2 = 1$ (m)
- **Soil domain:** 10×10 (m)

Mechanical Boundary Conditions - Side boundaries: **laterally restrained** (roller supports)
- Base: **vertically restrained** (fixed in Y direction)

Hydraulic Boundary Conditions - Top surface: **drained** (prescribed pore water and air pressures) - Side boundaries and base: **impermeable** (zero flux for both water and air)

For the unsaturated case, constant suction of 5 kPa is maintained at the top surface by prescribing $p_w = 0$ kPa and $p_a = 5$ kPa.

1.8 Step 2: Loading (Prescribed Settlement Under the Footing)

1.8.1 Step Definition

Both saturated and unsaturated analyses use quasi-static loading to approach drained conditions:

```
% Step Definitions
@Step 2:
@@StartStep: 1
@@StepTime: 1.0e15
@@ModernAutoInc: Yes
@@SolverType: Direct
@@MaxIterations: 10
@@OutputInterval: 100
@@InitialStepIncrement: 1e-3
@@UseModifiedNewton: No
@@OutputTypes: Displacement EffStress VoidRatio PoreWaterPressure
DegreeOfSaturation
@@Geostatic: No
@@MinTimeStep: 1e-7
@@MaxTimeStep: 1.0e0
@@ErrorTarget: 1.0e-3
@@UL: No
@@SimMode: Static
%%%
```

1.8.2 Prescribed Displacement

The same downward displacement of -0.4 m is applied under the footing:

```
% Prescribed Values
@PrescribedValue Displacement 1
@@DOF: DisY
@@Amplitude: -0.4
@@LoadType: Ramp
@@StartStep: 2
@@Frequency: 0.0
@@DampingFactor: 0.0
@@PhaseLag: 0.0
@@NodeIds: 776 782 808 807 817 827 825 828 837 839 841
@@Propagate: Yes
%%%
```

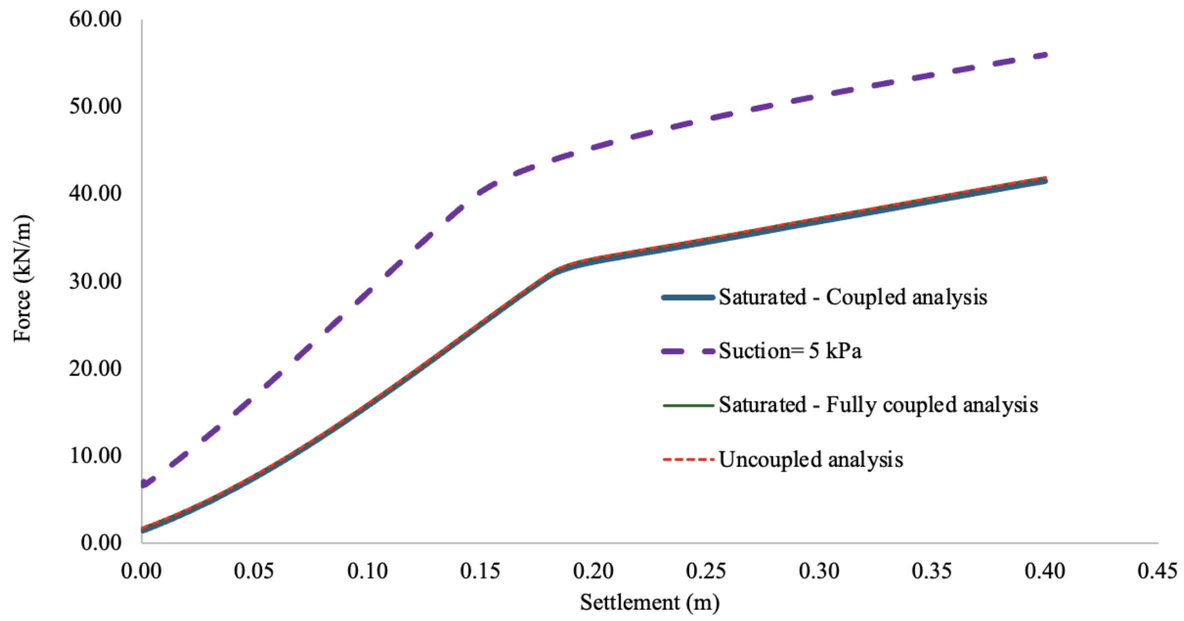

Figure 1: Load–deflection comparison for saturated and unsaturated soils

1.9 Results

1.9.1 Load–Deflection Response

The figure below compares the **load–deflection** response for three cases: 1. **Saturated soil** ($p_c = 0$ kPa) — fully coupled analysis 2. **Saturated soil** ($p_c = 0$ kPa) — uncoupled analysis (from rigidfootinggcc.md) 3. **Unsaturated soil** ($p_c = 5$ kPa) — fully coupled analysis

Figure 1. Load–deflection comparison: effect of matric suction on bearing capacity. The saturated cases (coupled and uncoupled) match closely, validating the coupled formulation. The unsaturated case with $p_c = 5$ kPa exhibits significantly higher bearing capacity compared to the saturated cases, demonstrating the strength increase due to matric suction.

1.10 Discussion

The three cases show excellent agreement for the saturated analyses (coupled and uncoupled), confirming that the fully coupled formulation correctly reduces to the drained limit under quasi-static loading conditions. The unsaturated case with $p_c = 5$ kPa exhibits significantly increased bearing capacity compared to the saturated cases, demonstrating the strength enhancement due to matric suction.