

Optimization in Geotechnical Engineering: key topics and practical tools

Primož Jelušič

Associate Professor

University of Maribor

Faculty of Civil Engineering, Transportation Engineering and Architecture



INTRODUCTION



Importance of Optimization in Geotechnical Engineering

Role in Soil Mechanics

Optimization helps solve complex soil mechanical problems like failure surfaces and retaining wall embedment depths.

Reliability-Based Design

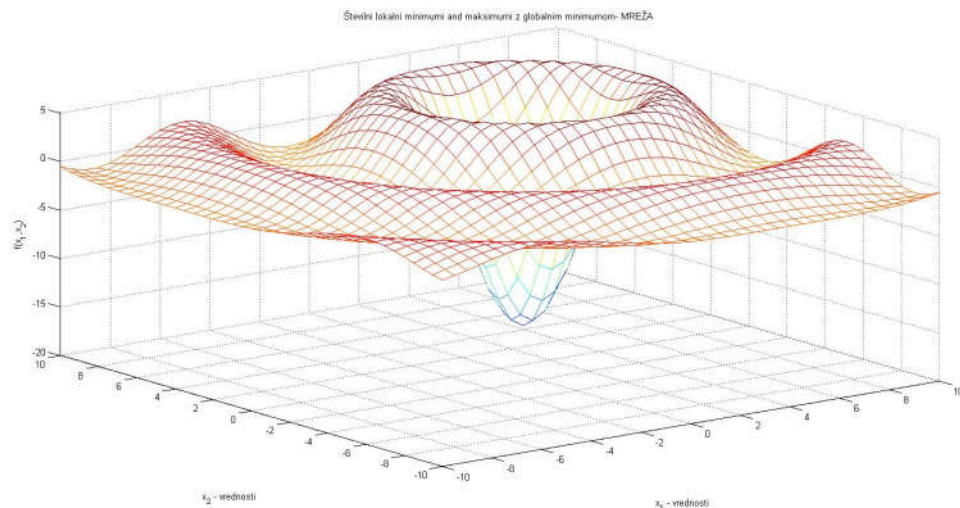
Optimization determines probabilities of failure to ensure sustainable and safe geotechnical designs.

Educational Approach

Structured teaching introduces fundamentals, computational techniques, and advanced applications for student excellence.



Key Topics in Optimization



Optimization Principles

Objective functions, decision variables, and constraints form the foundation of optimization in geotechnical engineering.

Types of Optimization

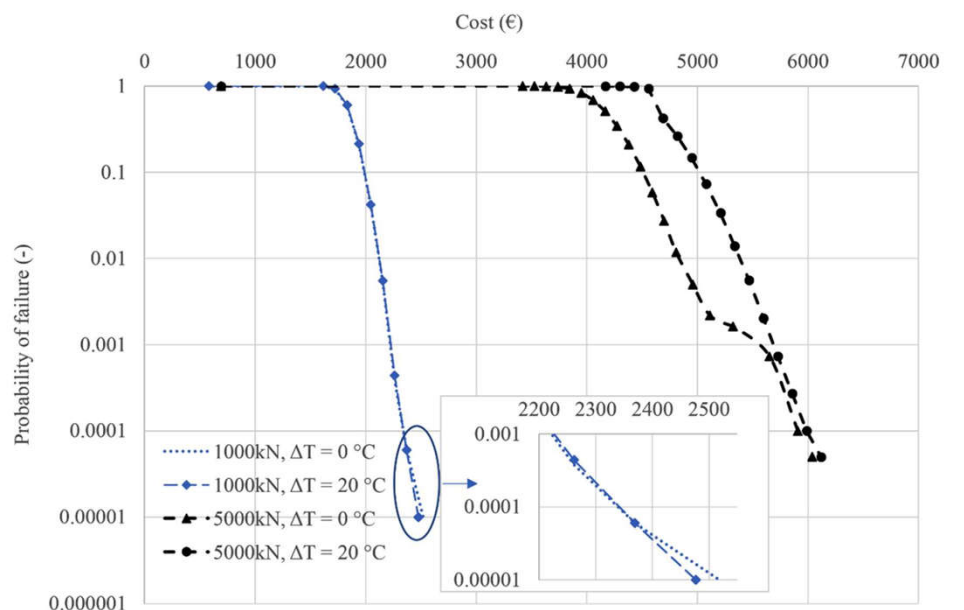
Optimization includes linear, nonlinear, integer, stochastic, multi-objective, and multi-parametric methods.

Geotechnical Applications

Optimization helps design foundations, stabilize slopes, plan retaining walls, and reinforce tunnels efficiently.

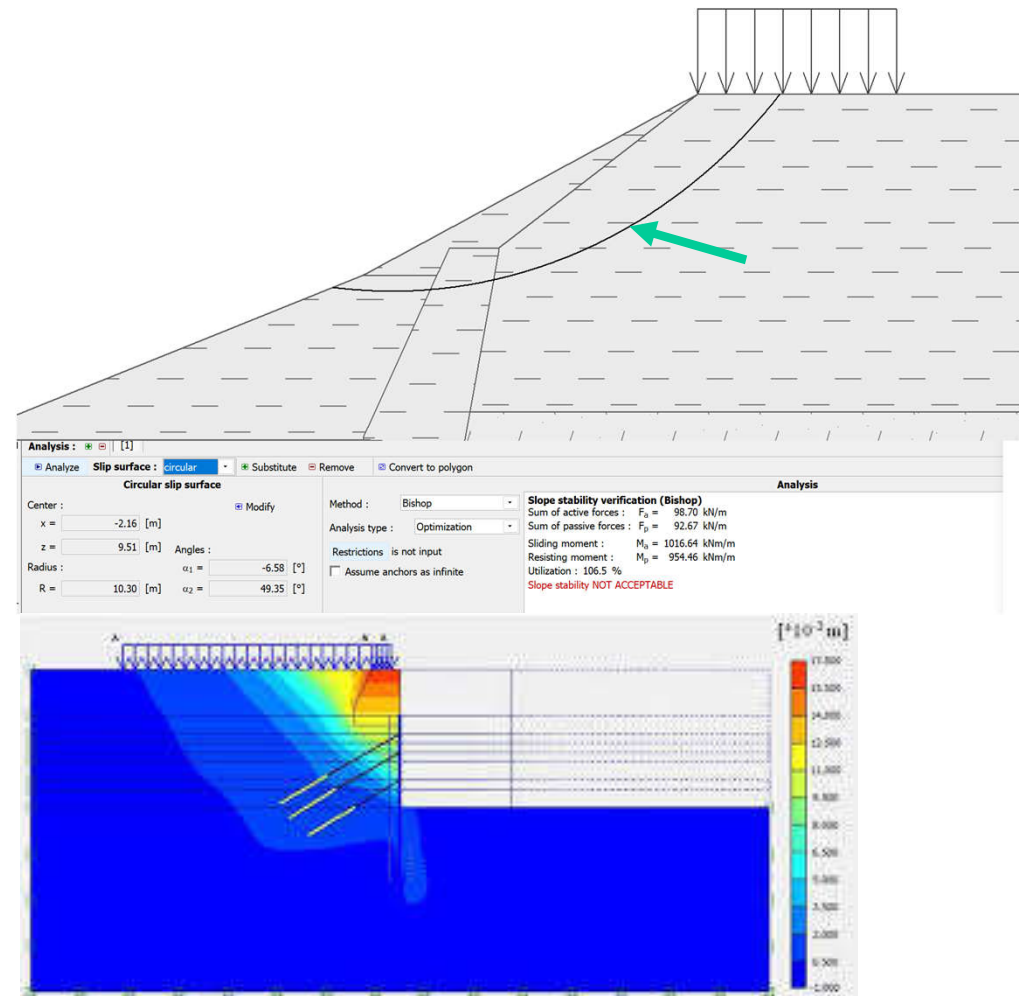
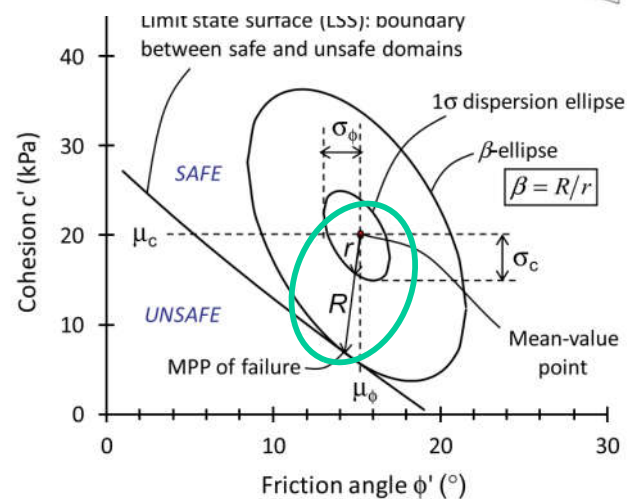
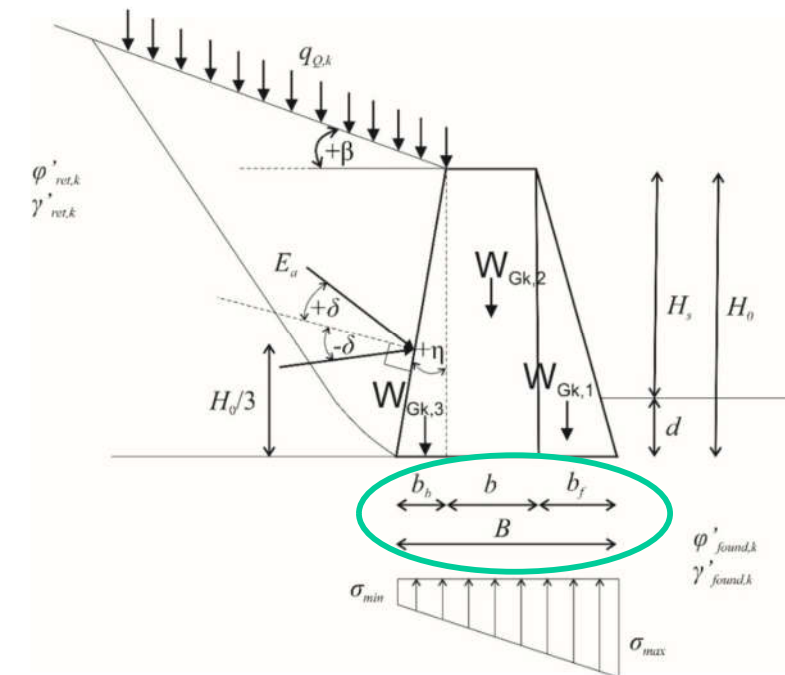
Cost and Material Efficiency

Ground improvement and soil investigations benefit from optimization by minimizing materials and controlling costs.



Key Topics in Optimization

- minimum dimensions (B , d)
- MPP of failure (by finding minimum distance R)
- critical failure surface





Practical Tools for Teaching Optimization

Optimize

solution, objectiveValue = Minimize test using ga solver

Specify problem type

Objective

Linear Quadratic Least squares Nonlinear Nonsmooth

Examples: $f(x, y) = x/y$, $f(x) = \cos(x)$, $f(x) = \log(x)$, $f(x) = e^x$, $f(x) = x^3$, Solve $F(x) = 0, \dots$

Unconstrained Lower bounds Upper bounds Linear inequality

Constraints

Linear equality Second-order cone Nonlinear Integer

Examples: $x \geq 0, x \leq 2$

Solver

ga - Genetic algorithm

Select problem data

Objective function

Local function test New...

Number of variables

nvar

Constraints

Lower bounds From workspace lb $\leq x$

Upper bounds From workspace ub $\geq x$

Specify solver options

Display progress

Text display

Final output

Plot

Distance Genealogy Selection Score diversity

Scores ☒ Stopping criteria Max constraint violation ☒ Best fitness

Best individual Expectation value Range

Software and AI Integration

Commercial Engineering Software

PLAXIS, GeoStudio, and Geo5 are widely used for geotechnical modeling and analysis in education and practice.

Programming Environments

MATLAB and GAMS enable implementation of custom optimization algorithms for advanced problem solving.

Optimization with Excel Solver

Excel Solver offers an accessible tool for linear and nonlinear optimization tasks in teaching.

AI Tools Integration

AI tools like Copilot, ChatGPT, and MATLAB AI chat assist students with interactive problem solving and code generation.



Pedagogical Strategies by Educational Level

Undergraduate Level

Basic Optimization Concepts

Focus on foundational optimization principles using simplified examples like retaining walls and slopes.

Master's Level

Advanced Optimization Methods

Techniques like genetic algorithms and multi-objective optimization are explored in depth at the Master's level.

Project-Based Learning

Case studies and project-based learning prepare students to integrate technical, economic, and environmental factors in their work.

PhD Level

Advanced Research Topics

Doctoral students focus on metaheuristics, sustainability optimization, and novel algorithms for geotechnical challenges

Original Research Contributions

PhD assessments emphasize original research with publications and development of innovative tools in geotechnical engineering.

Basic Optimization Concepts

Focus on foundational optimization principles using simplified examples like retaining walls and slopes.

Interactive Learning Tools

Use of tools such as Excel to demonstrate linear programming in an accessible and user-friendly way.

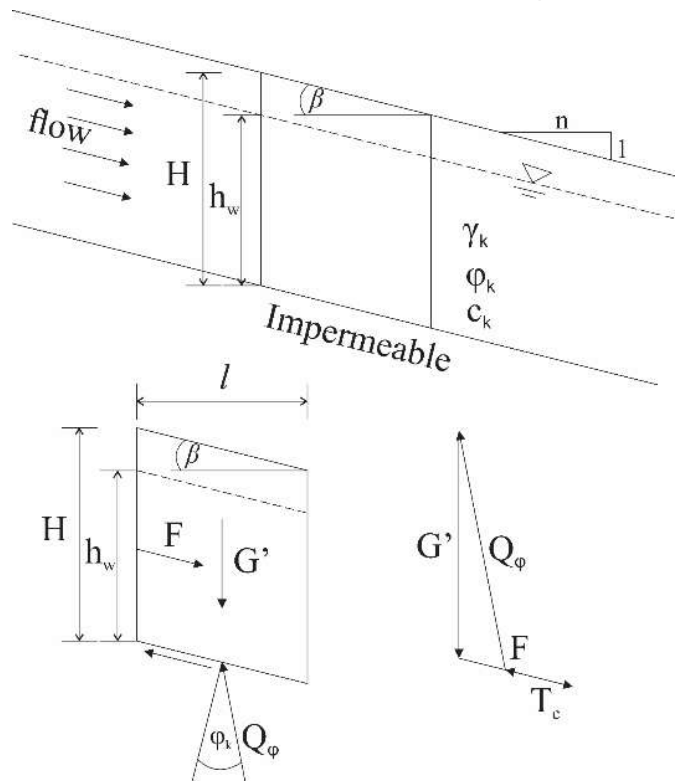
Real-World Application

Linking theory to practice through geotechnical case studies and scenarios.

Collaborative Assessments

Problem-solving exercises and mini-projects to promote teamwork and critical thinking.

Example: Optimization model



Slope Stability Analysis

Slope Stability Model

The model analyzes an infinite soil slope on impermeable rock including groundwater seepage effects parallel to the rock surface.

Optimization Approach

Optimization ensures vertical and horizontal force equilibrium by defining objective functions and constraints mathematically.

Practical Implementation

Model implemented in Excel Solver using soil properties and slope parameters to calculate a safety factor of 1.1825.

Comparison with FEM

Finite element modeling yields a slightly different safety factor, validating the optimization technique accuracy.

$$\varphi'_d = \text{atan}\left(\frac{\tan \varphi'_k}{SF}\right) \quad (1)$$

$$c'_d = c'_k / SF \quad (2)$$

$$s = \sqrt{1^2 + n^2} \quad (3)$$

$$i = 1/s \quad (4)$$

$$G' = (H - h_w) \cdot \gamma_k + h_w \cdot (\gamma_k - \gamma_w) \quad (5)$$

$$F = i \cdot h_w \cdot \gamma_w \quad (6)$$

$$T_c = c'_d \cdot (1/\cos \beta) \quad (7)$$

$$\sum V = 0: G' + F \cdot \sin \beta - T_c \cdot \sin \beta - Q_\varphi \cdot \cos(\varphi - \beta) = 0 \quad (8)$$

$$\sum H = 0: F \cdot \cos \beta - T_c \cdot \cos \beta - Q_\varphi \cdot \sin(\varphi - \beta) = 0 \quad (9)$$



Example: Optimization model

Slope stability

Input data

Geometry

H (m) = 5

h_w (m) = 4

l: n = 4

Soil

γ_k (kN/m³) = 20

ϕ_k (°) = 25

c'_k (kPa) = 2

Water

γ_w (kN/m³) = 10

s (m) = 4.12

i = 0.243

Calculation

SF = 1.1825

β (°) = 14.036

G' (kN/m²) = 60

F' (kN/m²) = 9.701425

c_d (kN/m²) = 1.691379

ϕ_d (°) = 21.14224

T_c' (kN/m²) = 1.74343

Q_ϕ' (kN/m²) = 62.41

SUMV: 0.00

SUMH: 0.00

Solver Parameters

Set Objective: $\$B\25

To: ☐ Max ☐ Min ☒ Value Of: 0

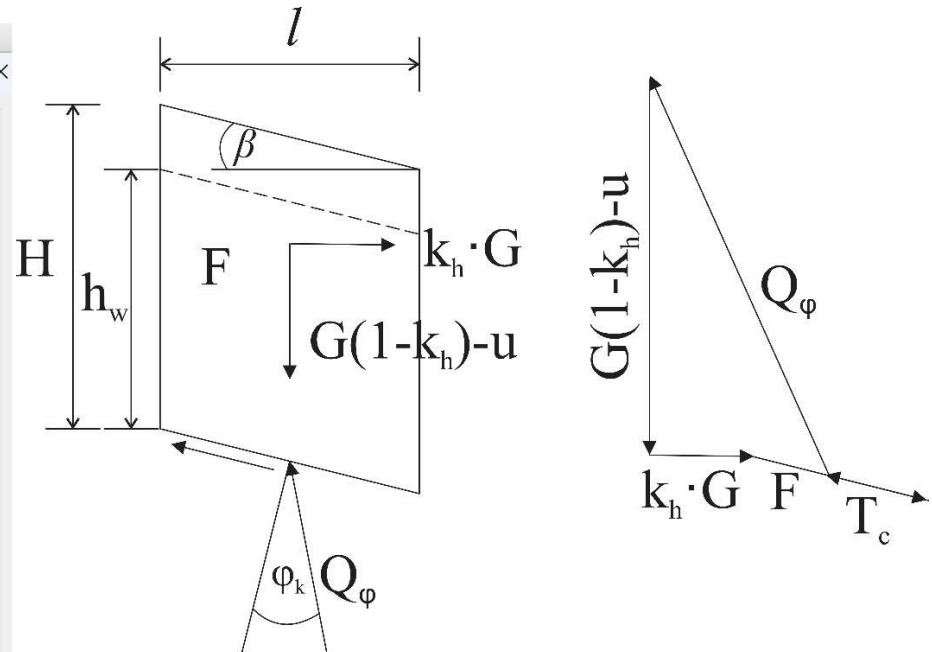
By Changing Variable Cells: $\$B\$17, \$B\24

Subject to the Constraints: $\$B\$26 = 0$

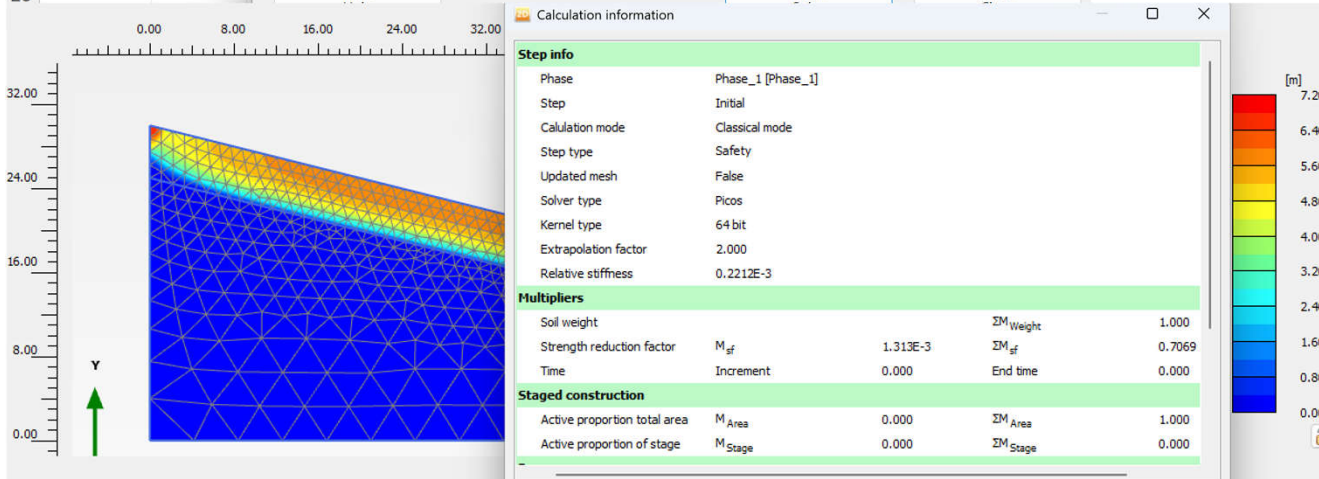
☒ Make Unconstrained Variables Non-Negative

Select a Solving Method: GRG Nonlinear

Solving Method: Select the GRG Nonlinear engine for Solver Problems that are smooth nonlinear. Select the LP Simplex engine for linear Solver Problems, and select the Evolutionary engine for Solver problems that are non-smooth.



	Normal condition	Earthquake $k_h=0.1g$
Safety factor (SF)	1.1825	0.7793
Analitical (optimization)	1.1640	0.7069
FEM		



Summary and Future Directions

Role of Optimization



Optimization enables efficient and sustainable solutions in geotechnical engineering construction projects.

Structured Curriculum



Integrating theory, practice, and research prepares students for success in academics and industry.

Modern Educational Tools



Using AI tools like Copilot, ChatGPT, and MATLAB enhances student engagement and learning experience.

Copilot   **MATLAB**

Future Skill Development

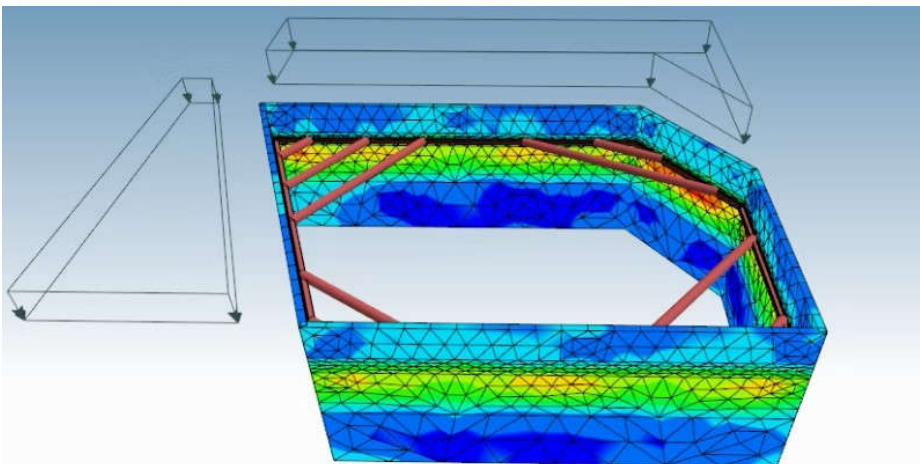


These technologies support computational skills development to meet evolving engineering demands.

Copilot (based on GPT-4) and ChatGPT-5 can be powerful allies in solving **optimization problems**, especially when integrated with tools like **Excel**, **MATLAB**, **Python**, and other platforms. Here's how they can help across different environments:

They can assist with:

- Formulating optimization problems (linear, nonlinear, integer, multi-objective)
- Explaining algorithms (e.g., simplex, gradient descent, genetic algorithms)
- Suggesting suitable solvers (e.g., fmincon, linprog, Solver in Excel)
- Debugging code and improving performance
- Visualizing results (plots, sensitivity analysis)
- Interpreting outputs and suggesting next steps



Summary and Future Directions

- Conventional Finite Element Method (FEM) serves primarily as an analysis tool, offering responses to predefined design configurations.
- It does not inherently seek optimal solutions, making it less suitable for design exploration or optimization tasks.
- Each iteration in an optimization process typically requires multiple FEM analyses, which can be computationally intensive.
- This highlights the need for more efficient and integrated approaches when combining FEM with optimization techniques.

