limitstate

analysis & design software for engineers

Application of Computational Limit Analysis & Design in the Middle East

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Managing Director at LimitState Ltd

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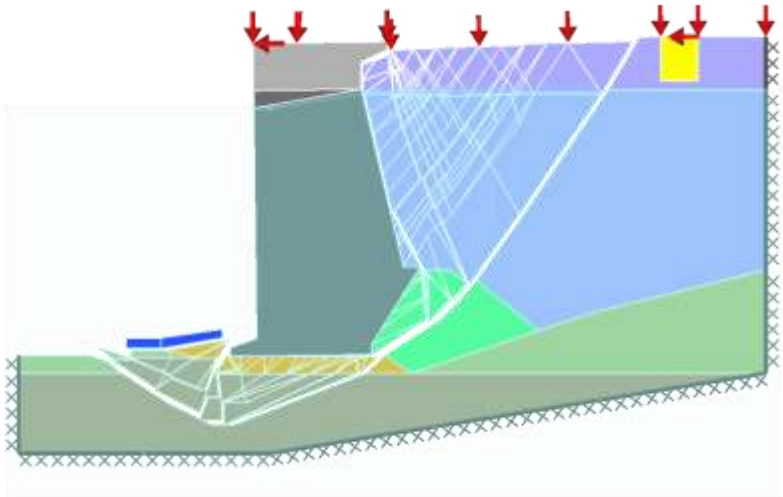
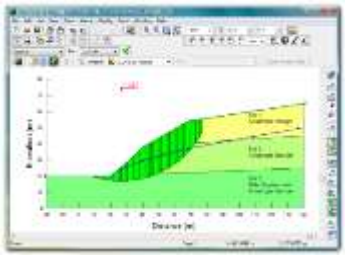


Background

Available geotechnical software

'Traditional': based on hand analysis solutions etc.



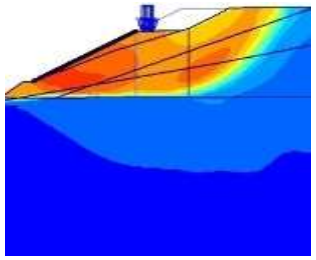
(potentially embedded in simple programs / spreadsheets etc.)

Gap…

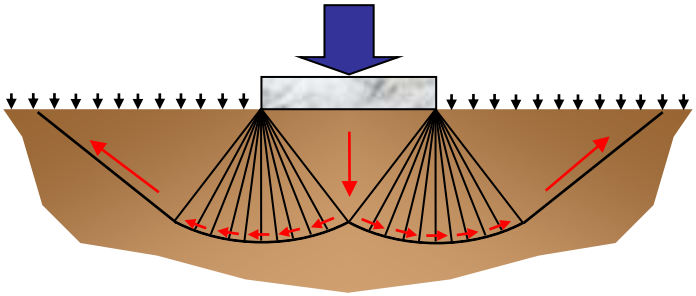
More:

- complex
- time consuming
- input parameters
- expertise required
- accurate [potentially at least!]

'Advanced': based on non-linear finite elements etc.



‘Traditional’ example



- Bearing capacity
  - Terzaghi equation:

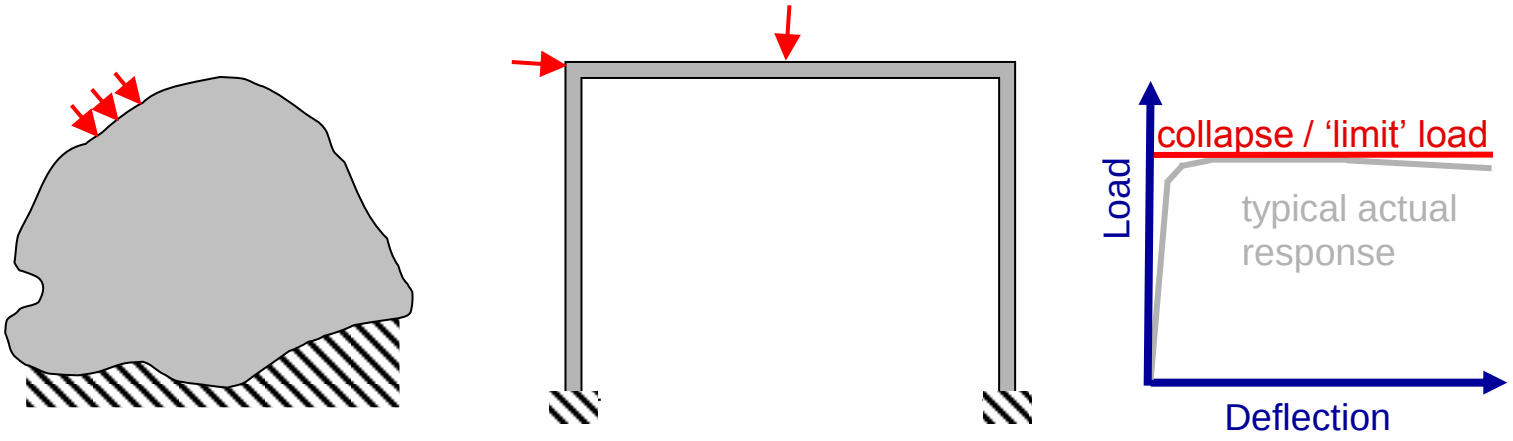
$$q = cs_c d_c i_c N_c + qs_q d_q i_q N_q + \tfrac{1}{2}\gamma B s_\gamma d_\gamma i_\gamma N_\gamma$$

[Approximate as terms in equation are not really additive – though addition always gives conservative result]

Issue: to handle embedded foundations, inclined loads, layered soils etc. it is necessary to apply additional modification factors. This becomes increasingly imprecise as more factors are used.

The role of limit analysis

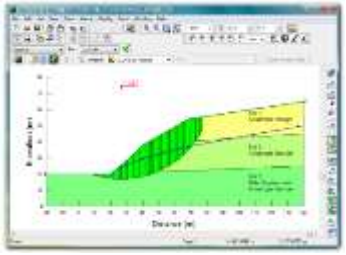
- Many ‘traditional’ methods use limit analysis
- Limit analysis allows direct estimation of the maximum load sustainable by a body or structure



- **Question:** can limit analysis be computerised?

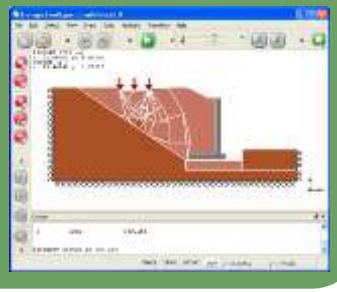
Available geotechnical software

'Traditional': based on hand analysis solutions etc.



(potentially embedded in simple programs / spreadsheets etc.)

'Mainstream': based on computational limit analysis(?)



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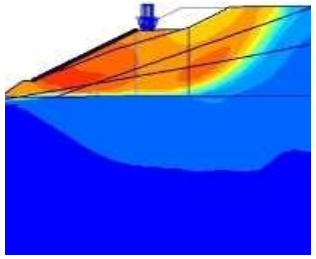
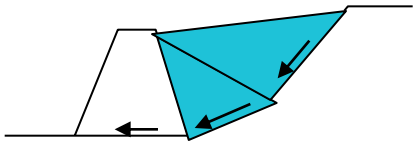
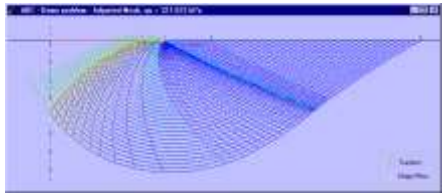


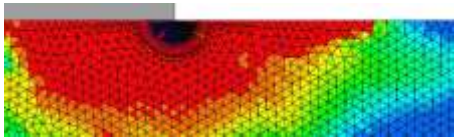
Computational limit analysis

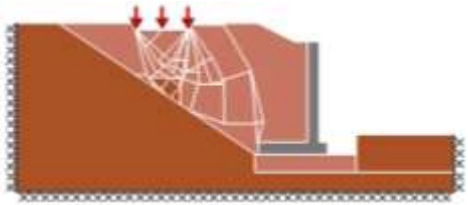
- Automated single application methods, e.g:
  - Foundations: slip-line field analysis
  - Walls: Coulomb wedge analysis

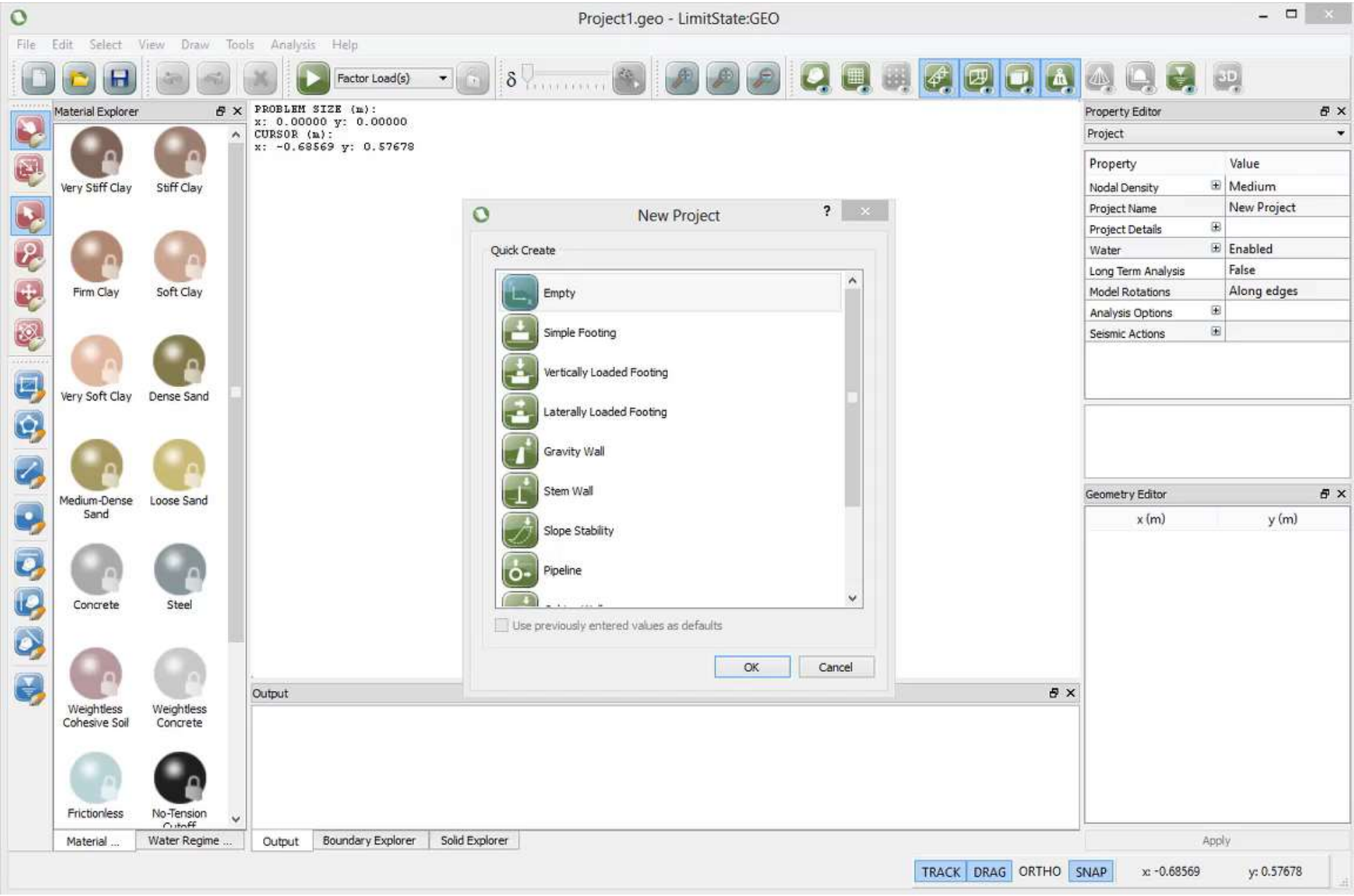


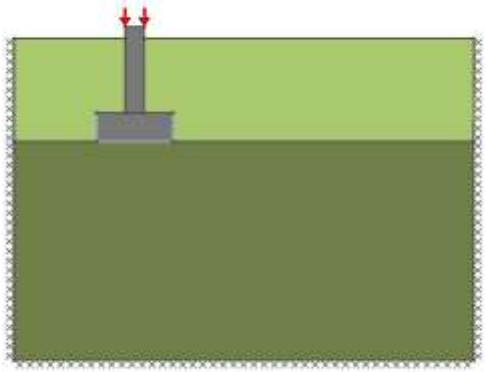
- Numerical methods
  - Method of characteristics
    - e.g. ABC software for foundations
  - Finite element limit analysis
    - Research tool only at present
  - Discontinuity Layout Optimization (DLO)
    - Now widely used in industry



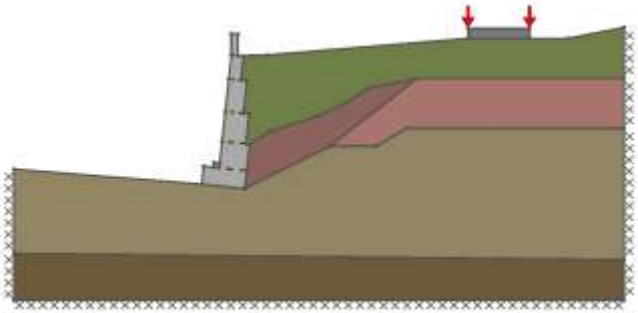




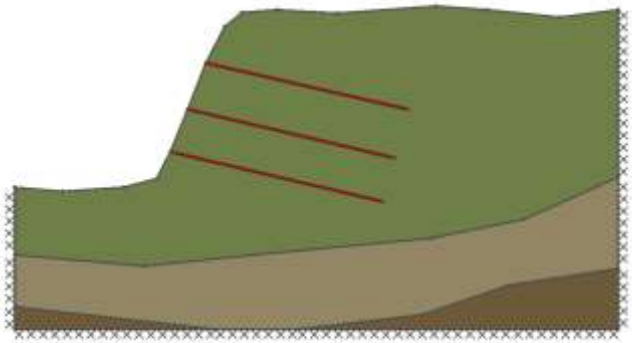

Project1.geo - LimitState:GEO
File Edit Select View Draw Tools Analysis Help
Factor Load(s)
Material Explorer
Very Stiff Clay
Stiff Clay
Firm Clay
Soft Clay
Very Soft Clay
Dense Sand
Medium-Dense Sand
Loose Sand
Concrete
Steel
Weightless Cohesive Soil
Weightless Concrete
Frictionless
No-Tension
Material ...
Water Regime ...
PROBLEM SIZE (m):
x: 0.00000 y: 0.00000
CURSOR (m):
x: -0.68569 y: 0.57678
New Project
Quick Create
Empty
Simple Footing
Vertically Loaded Footing
Laterally Loaded Footing
Gravity Wall
Stem Wall
Slope Stability
Pipeline
Use previously entered values as defaults
OK
Cancel
Output
Output
Boundary Explorer
Solid Explorer
Property Editor
Project
Property
Value
Nodal Density
Medium
Project Name
New Project
Project Details
Water
Enabled
Long Term Analysis
False
Model Rotations
Along edges
Analysis Options
Seismic Actions
Geometry Editor
x (m)
y (m)
Apply
TRACK
DRAG
ORTHO
SNAP
x: -0.68569
y: 0.57678



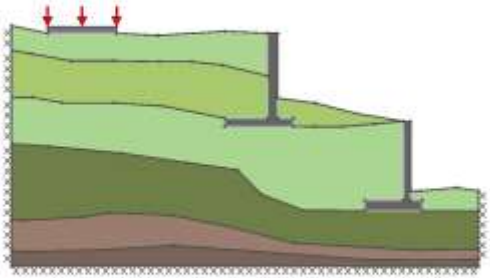
Footings



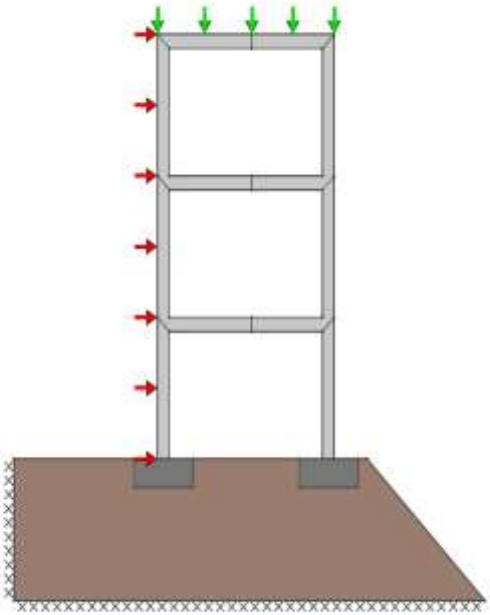
Retaining walls



Slopes



‘Combined’



Soil-structure interaction

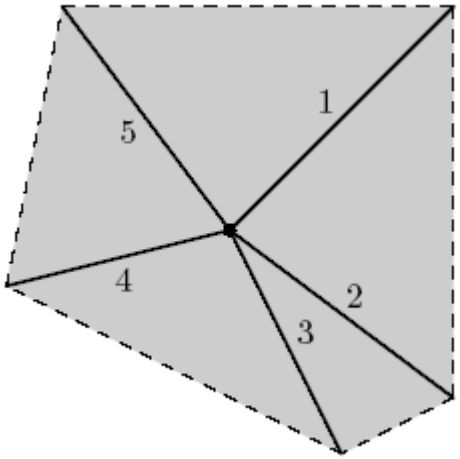
Discontinuity Layout Optimization (DLO)

Discontinuity Layout Optimization (DLO)

- Can be used to provide rigorous upper bound limit analysis solutions:
  - rapid and **direct** means of analysing the collapse state
  - outcome of 5 year **EPSRC** (UK Government) funded research project carried out at the **University of Sheffield**
  - key publication: Smith & Gilbert, *Proc. Roy. Soc. A*, 2007

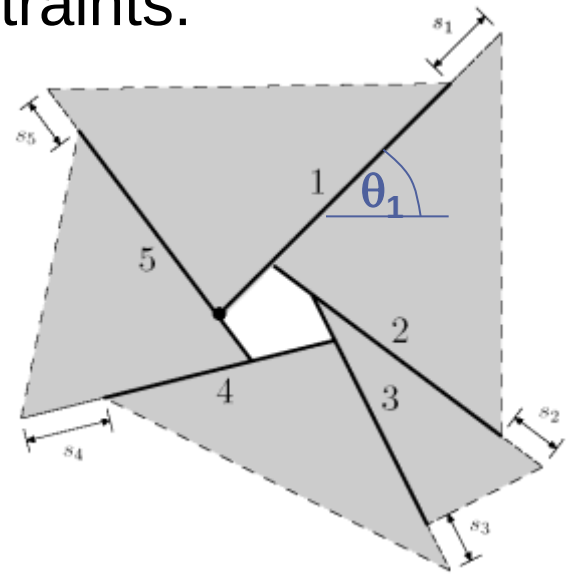
DLO: problem formulation

- Upper bound ('mechanism') formulation
  - Find minimum multiplier on specified loads (margin of safety, or 'adequacy factor')
  - Subject to nodal compatibility constraints:



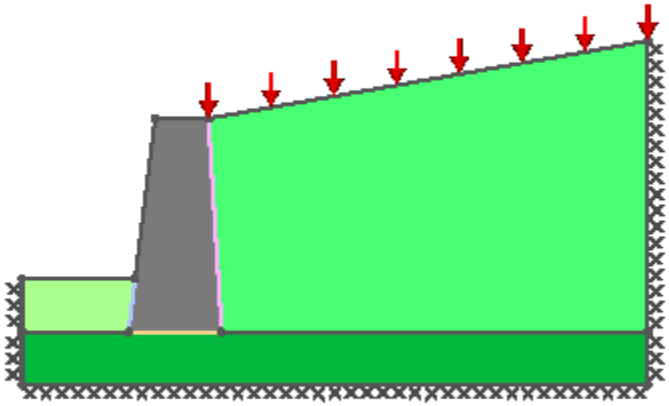
$$\sum_{i=1}^{5} s_i \cos\theta_i = 0$$

$$\sum_{i=1}^{5} s_i \sin\theta_i = 0$$



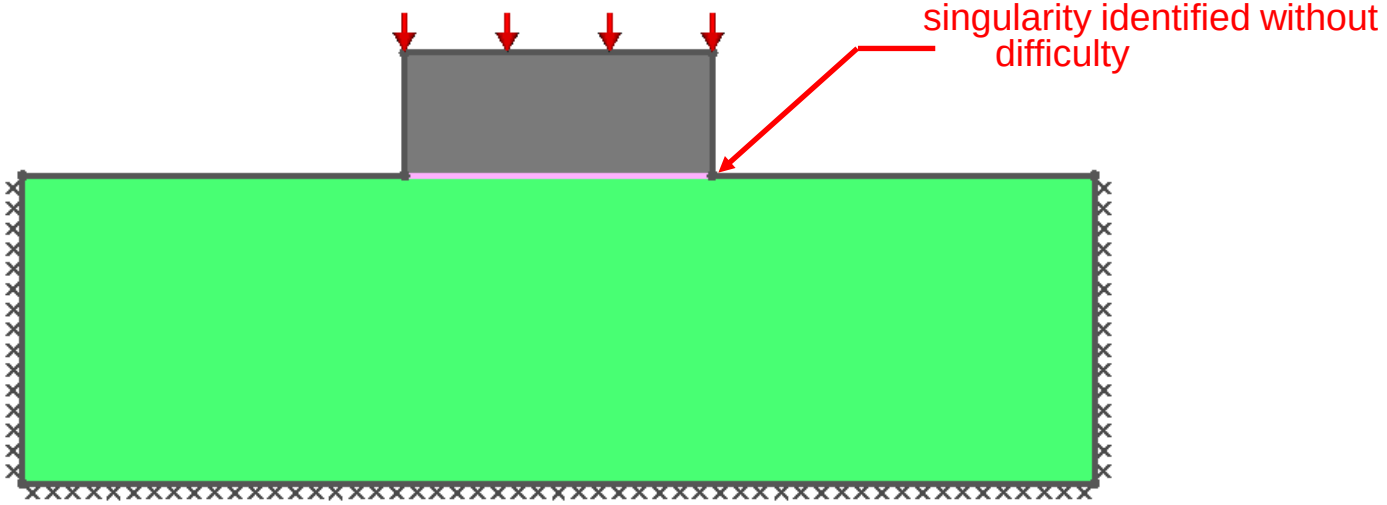
DLO: obtaining a solution

- Problem is a simple linear optimization problem (easy to solve)
- After solving can identify and then deform solid blocks to help interpretation:



Application to benchmark problems

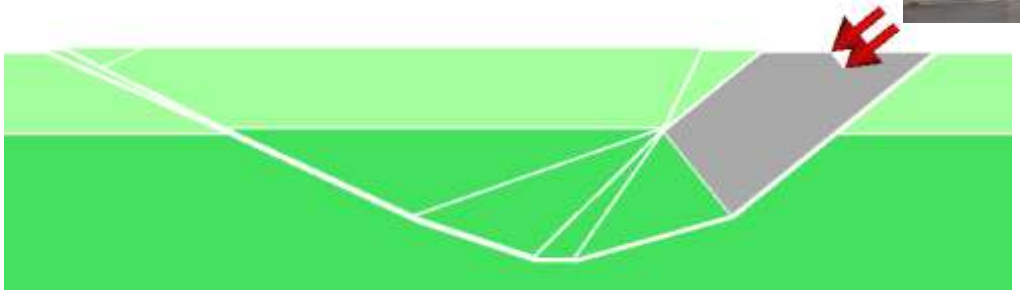
- For ‘Prandtl punch’ problem, solution within 1% of exact solution ($2+\pi$) in approx. 1 second:

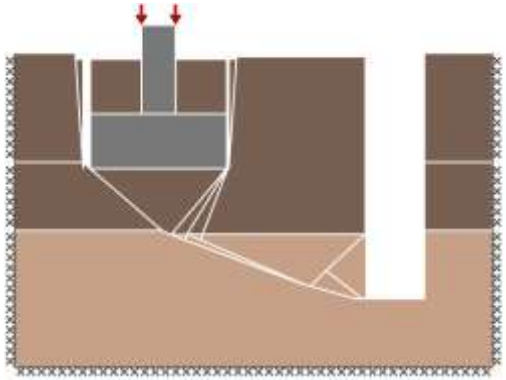


- Results for 100+ other cohesive-frictional benchmark plane strain problems available at: http://www.limitstate.com/geo/verification

Application examples

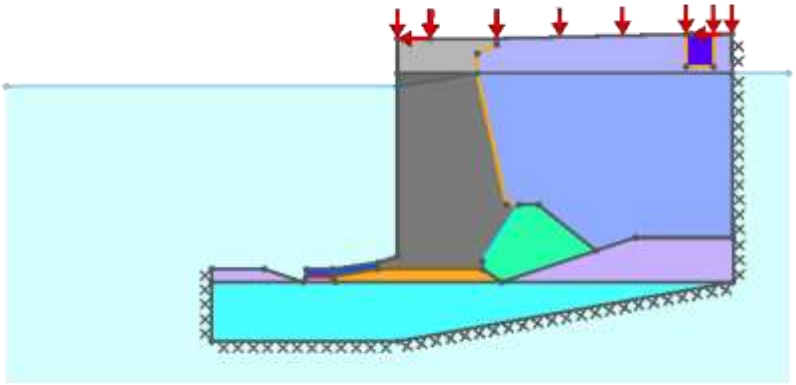
Inclined footing, carrying stadium roof loads



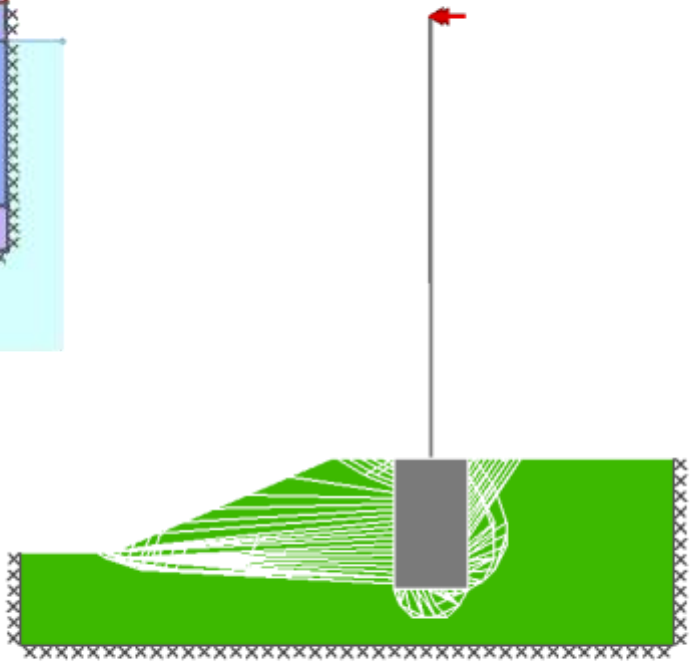


Trench excavation near footing

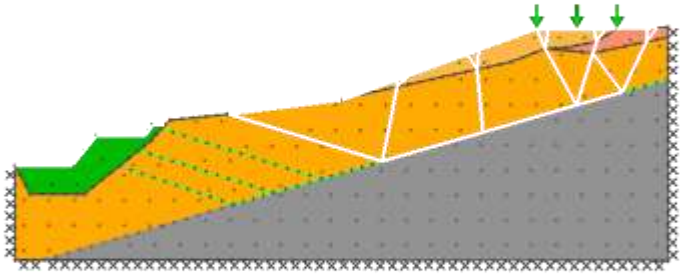
Application examples



Quay wall

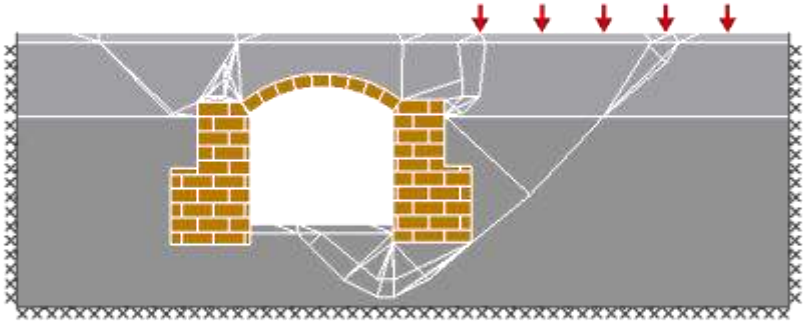


Mast foundation

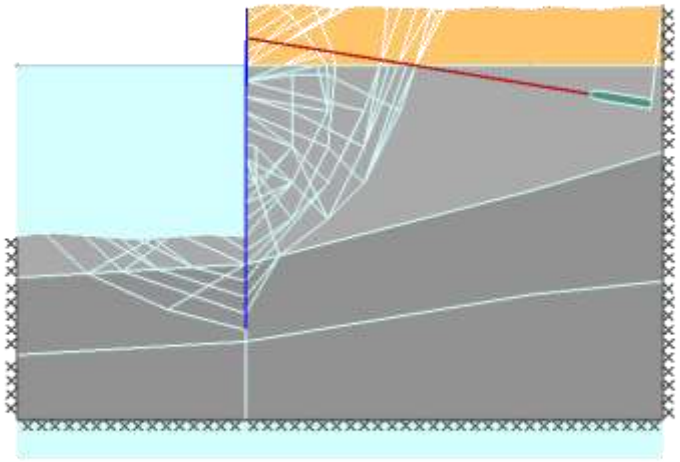


Slope remediation

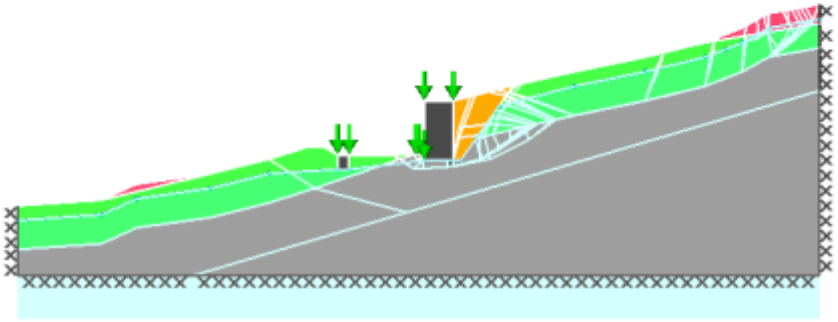
Application examples



Masonry arch stability



Anchored sheet pile wall



Construction on slope

Application in practice

- Once embedded in a modern software application, methods such as DLO takes the work out of analysis and allow the engineer to focus on:
  - Interpreting and understanding the ground conditions
  - Developing innovative designs
  - What if/parametric studies

limitstate geo

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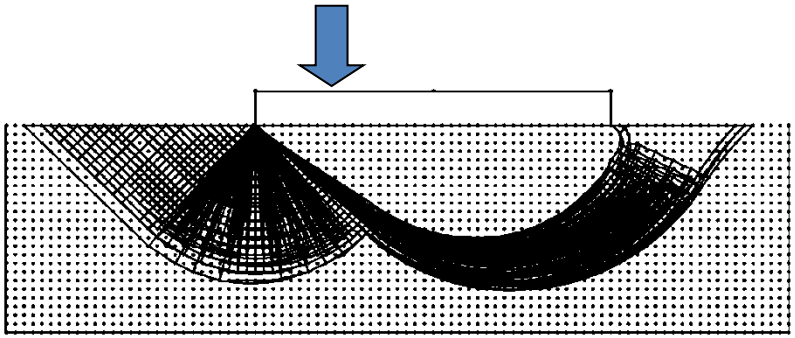
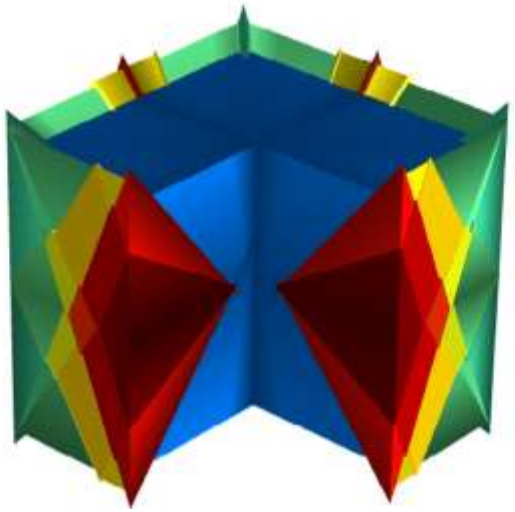
Recent academic developments

- Curved slip-lines to model rotational failures
  - Smith & Gilbert, *Géotechnique,* November 2013



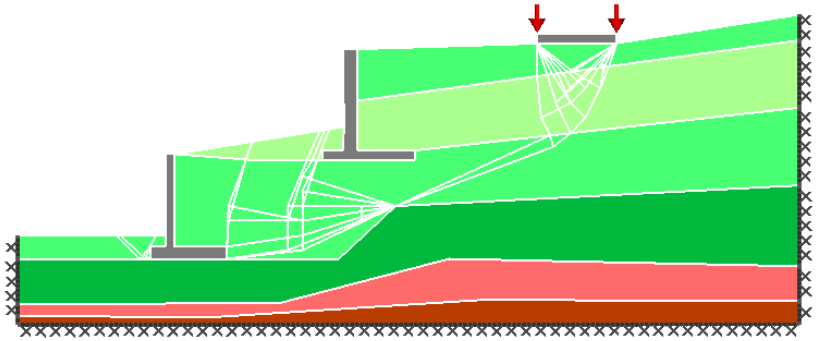
- 3D DLO
  - Hawksbee, Smith & Gilbert, *Proc. Roy. Soc. A*, July 2013



Application in design

Application in design

- DLO provides engineers with a fully general-purpose *direct* ULS analysis capability.

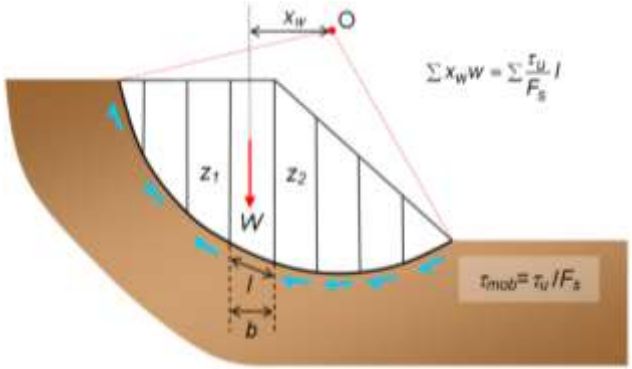


- How can this be used with existing and new design codes, including limit state codes such as Eurocode 7?

Slope stability

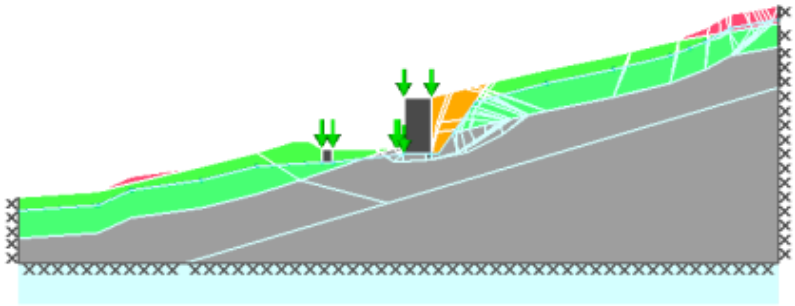
Conventional approach:

- Factor on strength averaged over length of **assumed** slip surface.



General approach:

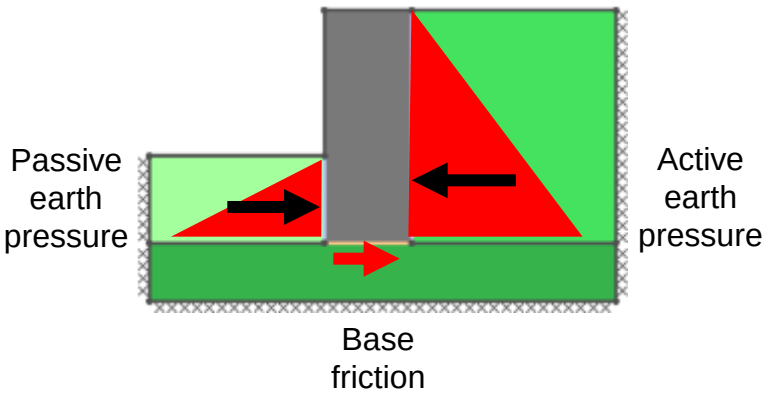
- Factor on strength applied to whole soil domain. Software **automatically determines** critical failure mechanism.



Retaining walls

Conventional approach:

- Active and passive earth pressures are **assumed** to act on the wall. K_a and K_p determined from factored soil strength.



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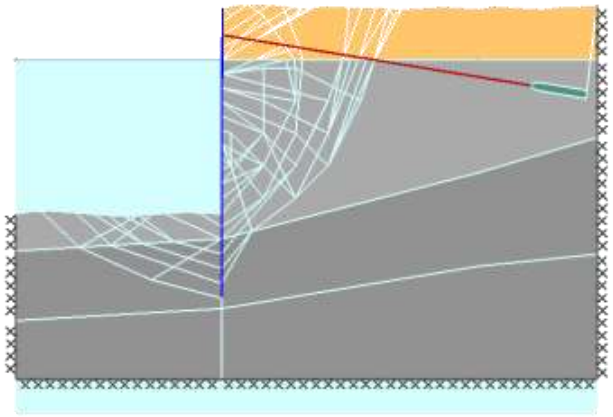
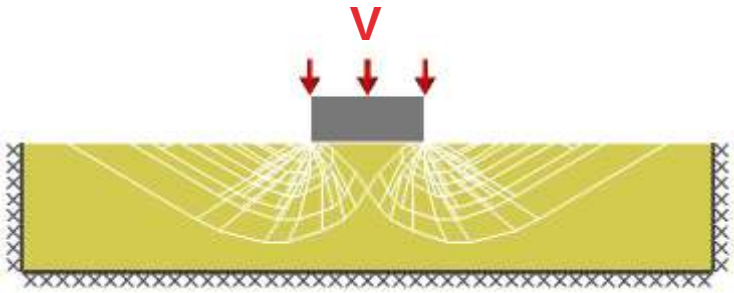


Foundations

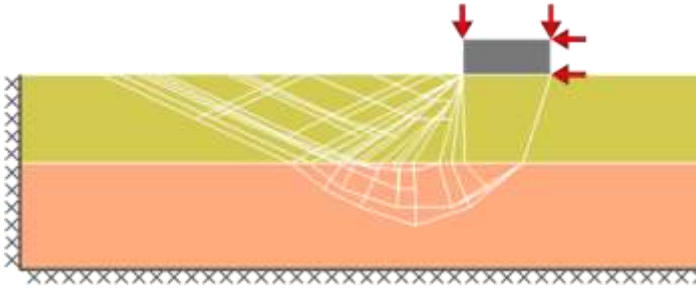
Conventional approach:

- Determine collapse load using Terzaghi's bearing capacity equation (implicitly **assuming** a specific collapse mode). Factor load by 3.



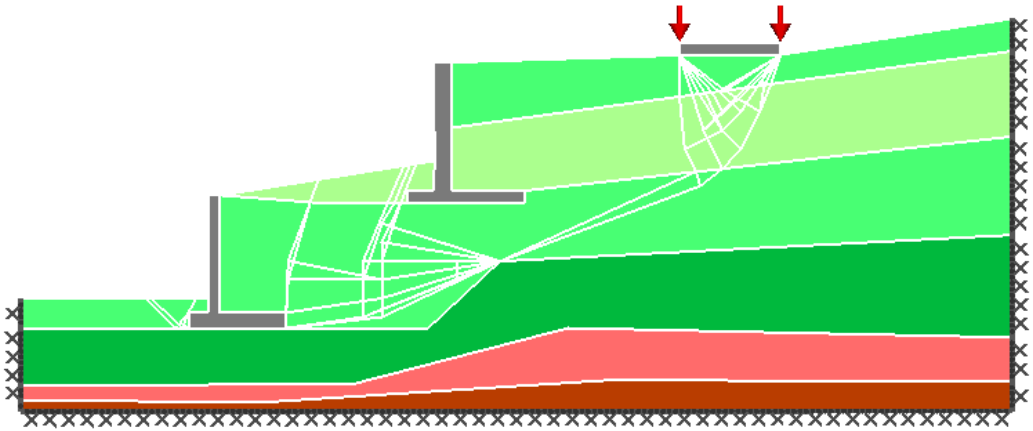
General approach:

- Determine collapse load from **automatically determined** critical failure mechanism. Factor load by 3.



What about limit state design?

- Limit state design codes such as Eurocode 7 (EC7) are written in a general way, often tying in with general purpose analysis approaches



- e.g. EC7 Design Approach 1 (DA1) Combination 2 allows direct use of general purpose numerical limit analysis

What about limit state design? [2]

- Before undertaking an analysis partial factors are applied to loads and/or materials
- An adequacy factor is then applied to load(s) or material strength(s) to trigger collapse:
  - If the adequacy factor >= 1.0 then the system is stable.
  - If the adequacy factor < 1.0 then the system is unstable.

Middle East examples

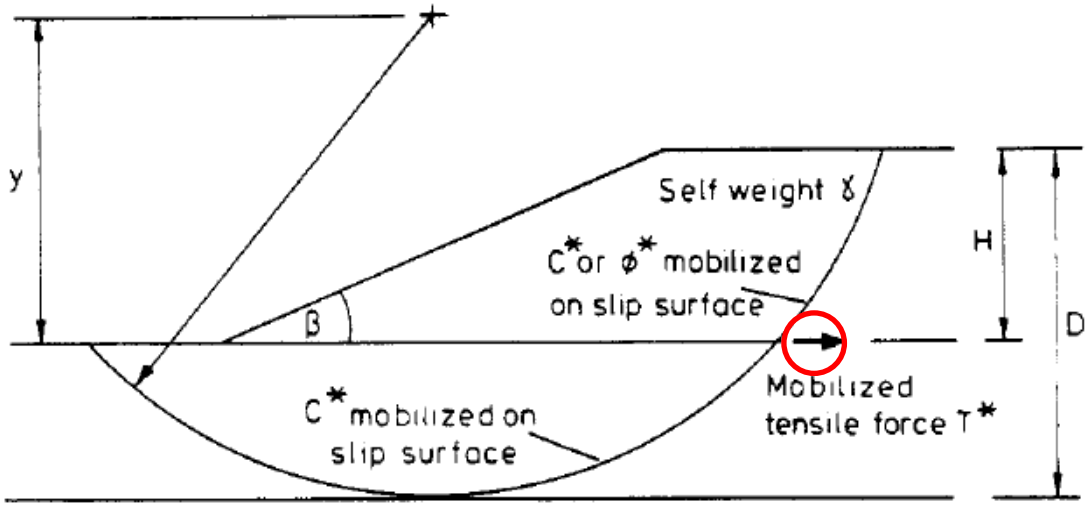
Example 1: embankment on soft soil

- Soft soils are common in the region:

(Photos from Benmebarek et al., TAJSAT, 2013)

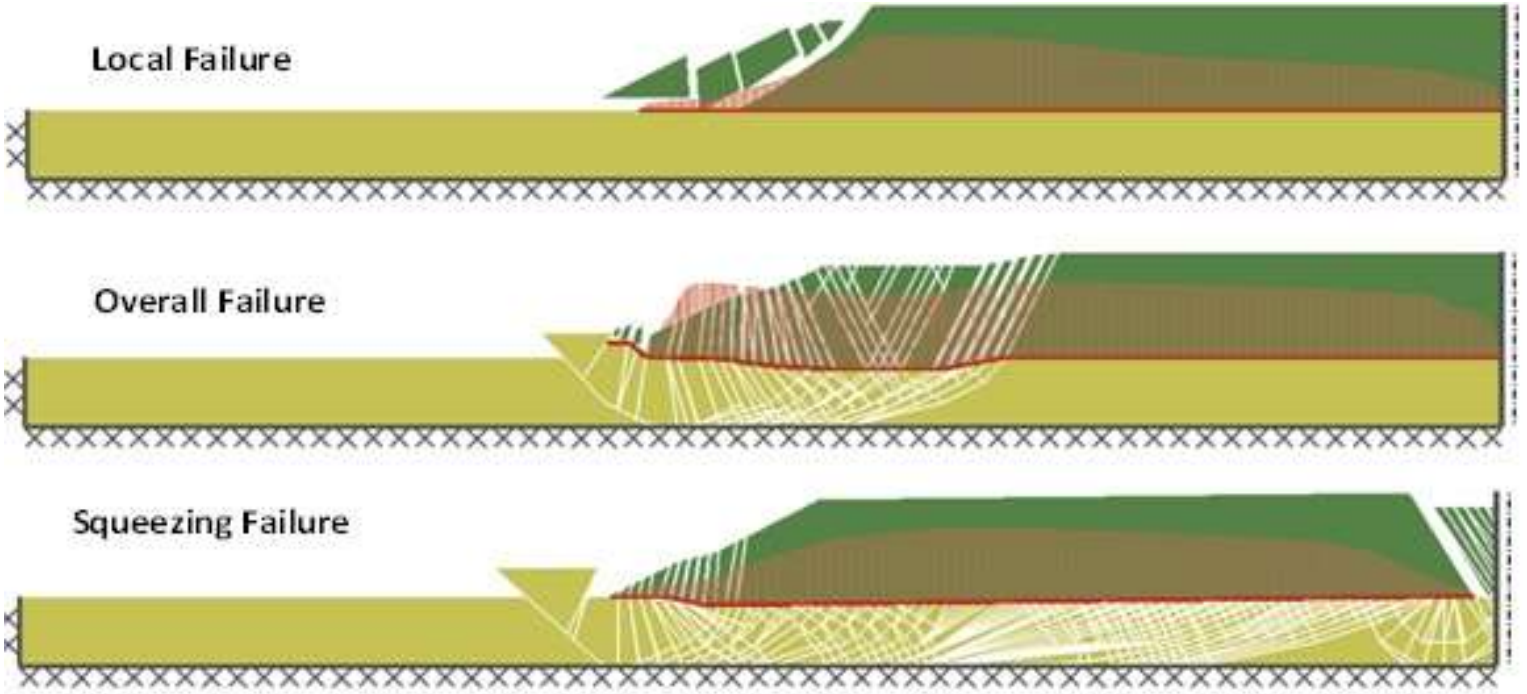
'Traditional' model

- Traditional methods of analysis rely on assumed mechanisms
- e.g. Hird (1986):



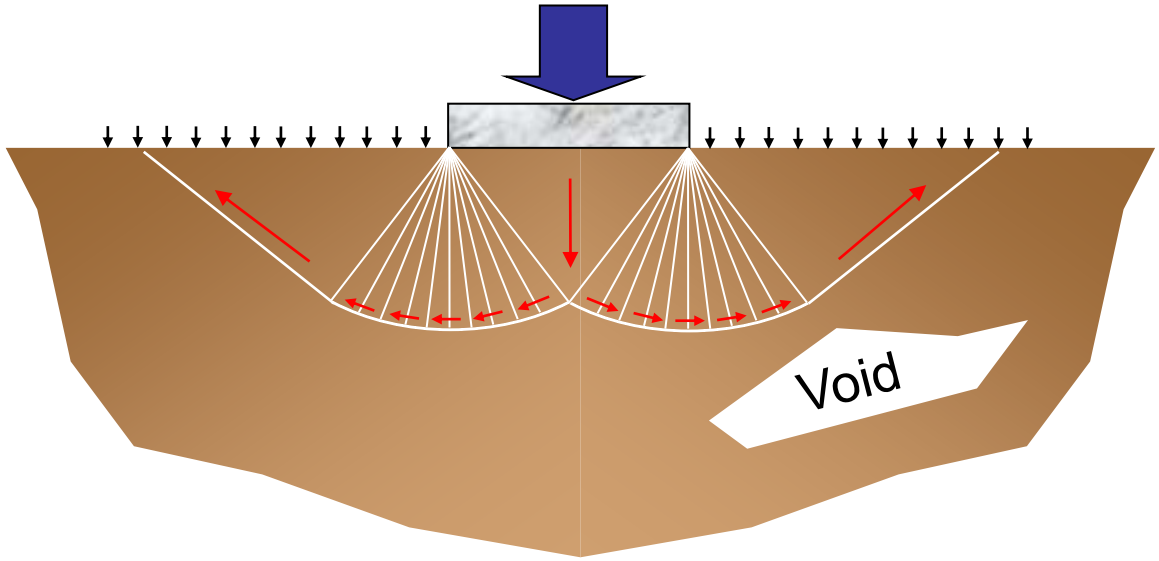
LimitState:GEO model

- Key point: able to identify a wider range of mechanisms than traditional methods, e.g:



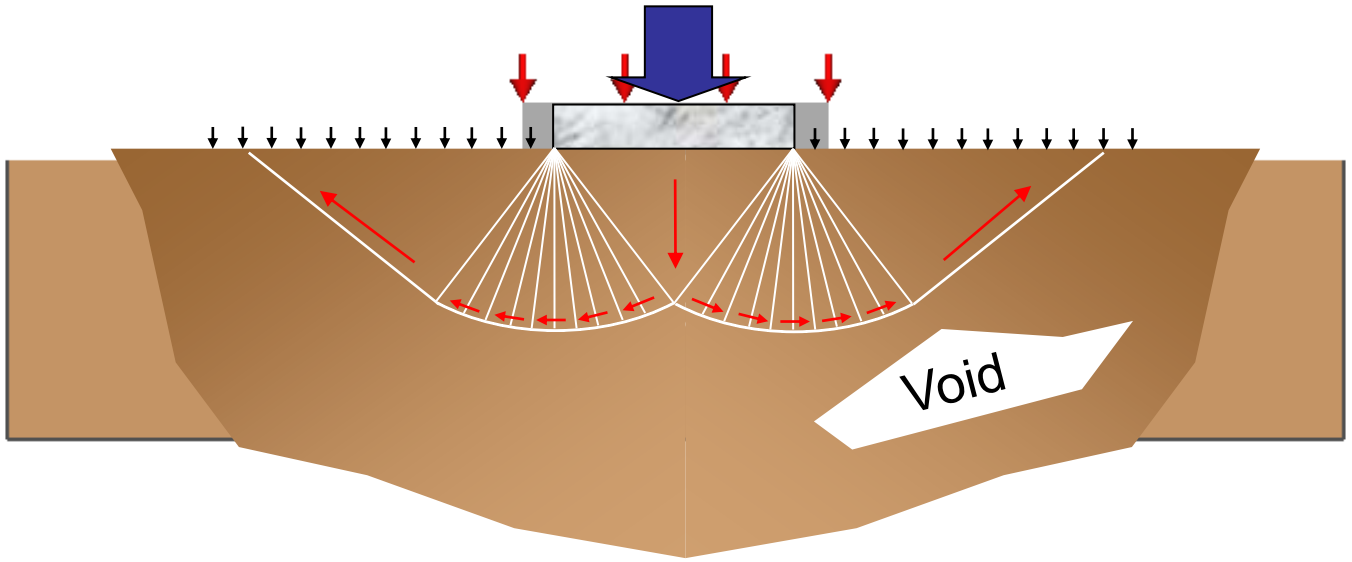
Example 2: foundation close to cavity

- Dissolution cavities common in the region



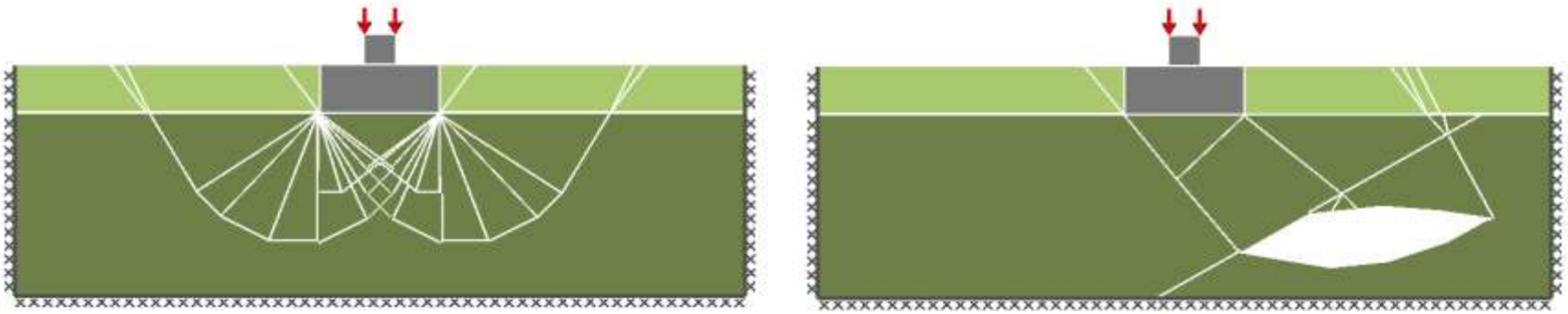
- Problem: difficult to model these using traditional methods!

Example 2: foundation close to cavity



LimitState:GEO model

- Easy to model effects of arbitrary features, such as voids



(assuming their location & extent are known!)

Other applications

- Modelling of soil improvement methods
  - Cut and fill
  - Stone columns
  - Ground mixing
  - Etc, etc…

Conclusions

Conclusions

- Computational limit analysis fills the gap between ‘traditional’ and ‘advanced’ tools:
  - Generally applicable methods fit in well with the philosophy of limit state codes such as Eurocode 7
- DLO is a quick and easy to use general method:
  - Automatically identifies the critical mechanism
  - Eliminates the need to separately consider sliding, bearing failure etc, or to try to fit a problem to a known solution
- Flexibility to model non-standard features / geometries is important for many Middle East applications

Acknowledgements

- LimitState credits:
  - Dr Wael Darwich, Dr Tom Pritchard

- University of Sheffield credits:
  - Dr Colin Smith, Dr Sam Hawksbee, Alireza Tatari, Ahmed Babiker
  - EPSRC (UK Government Research Council)