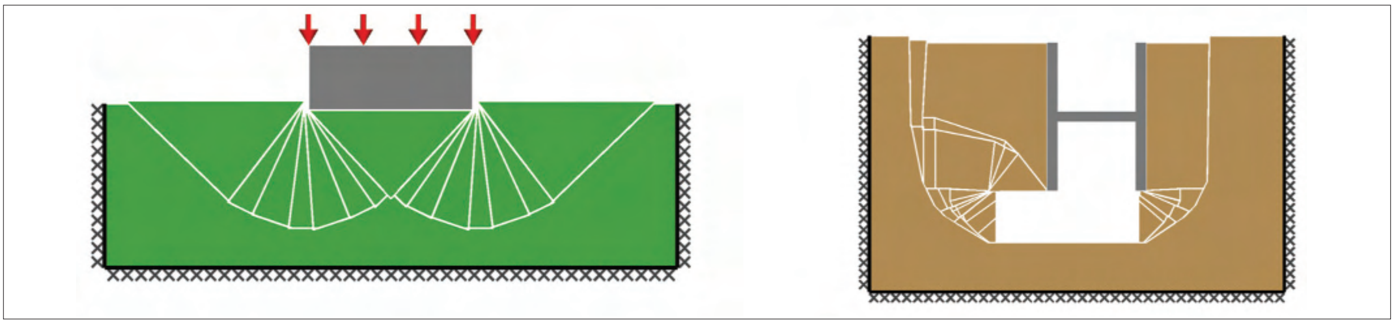
Technical note

Soil structure revolution

Dr Matthew Gilbert (M), LimitState Ltd, and Dr Colin Smith, Sheffield University, explain how new technology is dramatically simplifying ULS analysis of geotechnical and soil-structure interaction problems



1 Sample DLO failure mechanisms (footing and propped excavation)

Introduction

A new numerical analysis procedure which dramatically speeds up and simplifies the process of assessing the safety of foundations, retaining walls and a wide range of other soil-structure interaction problems has recently been developed. The new Discontinuity Layout Optimization (DLO) procedure can be used to identify clearly the form of the critical failure mechanism for problems of arbitrary geometry, helping the user to quickly gain an improved understanding of the likely mode of response (e.g. Fig 1).

Background

To assess margin of safety, engineers have typically had to rely either on basic 'hand-type' calculations (or 'automated hand calculation' software), or on complex software based on the finite element method or other comparable techniques. The drawback with these approaches is that they are either only applicable to a specific problem type or, in the case of the finite element method, can be very time-consuming and demanding of user expertise.

Though the range of applicability of 'hand-type' calculation methods can be extended by using various semi-empirical factors (e.g. depth factors and inclination factors in the case of the design of foundations), as the number of factors used increases, so the level of accuracy which can be expected decreases. This also leads to an opaqueness which can cause the engineer to lose sight of the underlying physics.

As a way of bridging the gap between 'hand-type' methods on the one hand, and significantly more complex tools on the other, so-called computational limit analysis techniques appear to have great promise. These potentially have wide applicability and use mathematical techniques to analyse quickly and robustly the ultimate limit state, without the need to iterate towards the collapse state (required e.g. when using non-linear finite elements). This article describes a recently developed computational limit analysis technique which is dramatically speeding up and simplifying the process of analysing the ultimate limit state (ULS) for geotechnical and soil-structure interaction problems.

A new numerical analysis procedure

Completely new numerical analysis procedures are not developed very often, and when they are, only a few then prove suitable for use in industry. However, the promise of DLO, developed at the University of Sheffield as part of an EPSRC funded research project (first described in a paper in the science journal *Proceedings of the Royal Society A* in October 2007), was such that the first DLO-based software application, LimitState:GEO, was launched less than a year later by University of Sheffield spinout company LimitState Ltd (see website: http://www.limitstate.com). Now numerous consulting engineers and contractors are taking advantage of the benefits the new technology brings.

How does DLO work?

Instead of modelling soil as a series of blocks or 'elements', the DLO procedure uses optimisation techniques to identify the most critical layout of slip-line discontinuities which transform a soil mass into a mechanism.

Fig 2 indicates diagrammatically how a problem is set up and solved using the DLO procedure. Nodes distributed across the problem domain are interconnected by potential slip-line discontinuities. Optimisation is then used to find the subset of slip-line discontinuities which are present in the critical collapse mechanism, and also the corresponding collapse load factor. To ensure that the mechanism obtained is compatible, and that the solution obtained is a true upper bound solution according to the theorems of plasticity, compatibility at nodes is enforced. Increasing the number of nodes increases the accuracy of the solution obtained.

Using the procedure a mind-boggling number of possible mechanism topologies can be considered on a standard desktop PC (e.g. $2^{1,000,000,000}$ possible layouts can be considered, incredible given that there are only an estimated 2^{80} grains of sand on the earth!).

The DLO procedure was originally developed after observing similarities between the forms of the critical failure mechanisms encountered in soil mechanics problems and the layouts of truss bars in optimal 'Michell' trusses (in fact such similarities were first

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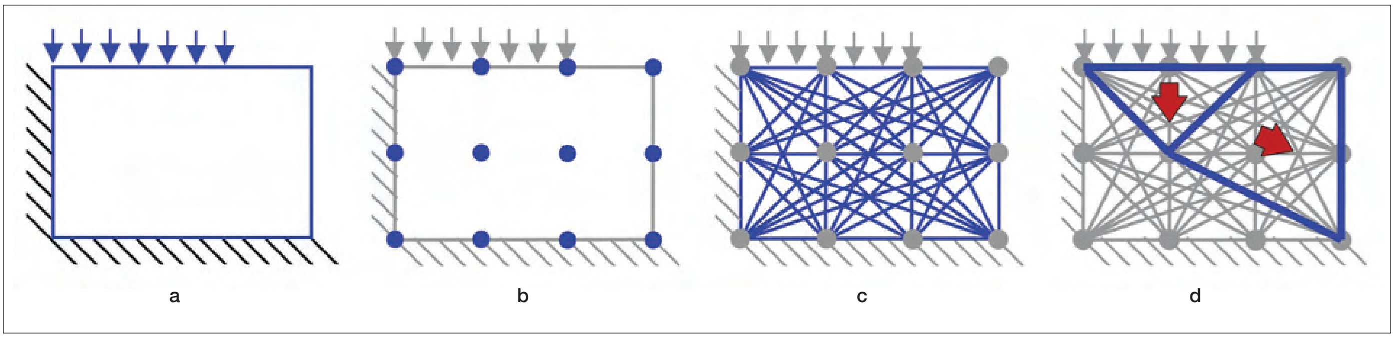

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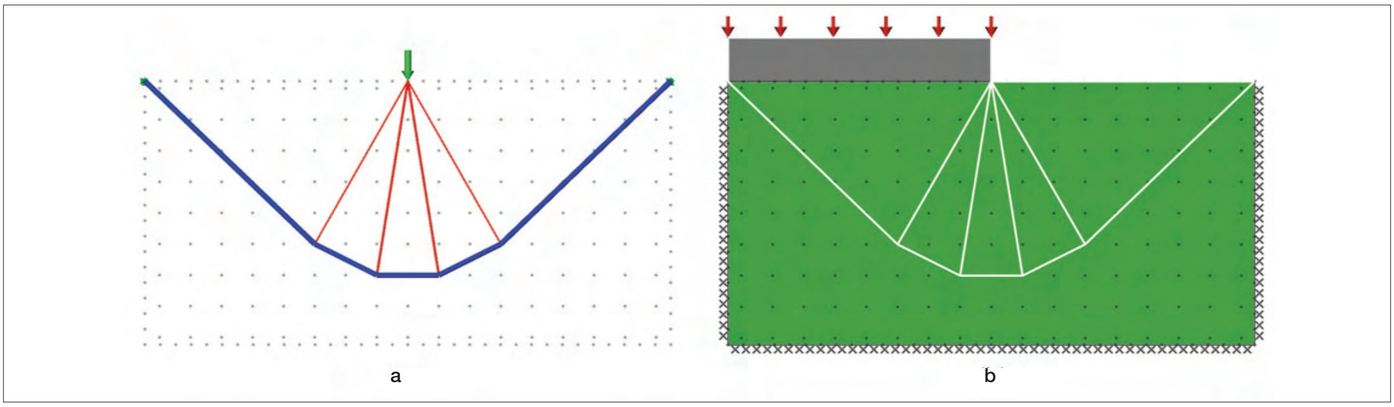

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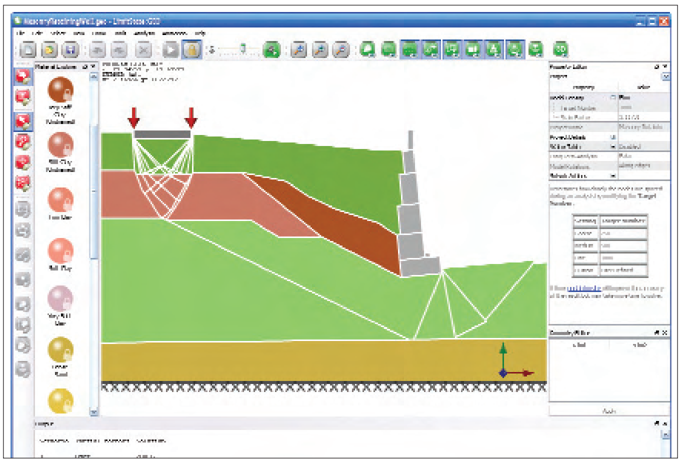

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2 Steps in the DLO procedure: (a) starting problem (surcharge close to a vertical cut); (b) discretisation of soil using nodes; (c) interconnection of nodes with potential discontinuities; (d) identification of critical subset of potential discontinuities using optimisation (giving the critical failure mechanism)

3 Problems for which (a) truss, and (b) geotechnical problems produce solutions of the same form (i.e. the optimal layout of truss bars is the same as the critical layout of slip-line discontinuities)

4. Combined problem solved using LimitState:GEO: footing behind a masonry retaining wall

observed several decades ago by intellectual luminaries such as William Prager and W. S. Hemp, but there appears to have been little follow up since). To investigate this further a cross-disciplinary research team was therefore established at Sheffield University to transfer existing expertise in truss layout optimisation to soil mechanics problems. A key finding was that the long established (though long neglected) truss layout optimisation technique originally developed by Dorn *et al.* (1964) could be modified and extended to tackle soil mechanics problems. For example, Fig 3 shows a problem for which the truss layout optimisation and discontinuity layout optimisation procedures produce solutions of the same form.

In geotechnical problems, the blocks of soil which lie between slip-line discontinuities can be identified after the optimisation process has been completed, meaning that DLO effectively fully automates the 'upper-bound' plastic analysis method initially put forward by Coulomb and others more than 2 centuries ago. However, whereas a Coulomb wedge analysis of a retaining wall problem only involves a single sliding soil block, a more critical mechanism might involve two, three or perhaps many hundreds of sliding blocks. The critical arrangement of these blocks previously had been very difficult to identify, but the fully general DLO procedure addresses this.

With DLO, the margin of safety for problems involving foundations, retaining walls, slopes, combined problem (e.g. Fig 4) and soil-structure interaction problems can be calculated directly. The only soil parameters required are the soil unit weight and the cohesion and angle of friction. Solutions comply with the fundamental theorems of plasticity, and the methodology fits in well with the limit state design approach used in Eurocode 7.

Eurocode 7

The imminent adoption of the Eurocodes demands a reappraisal of existing practices. With the limit state design methodology used by Eurocode 7, a key requirement is to identify the ULS, applying partial factors which are generic rather than problem specific. For example, this means that it may not necessarily be acceptable to only consider pure sliding and bearing failure mechanisms when analysing a foundation acted upon by an inclined load – since a combined mechanism involving sliding and bearing, as shown in Fig 5, may be more critical. This in turn means that general analysis tools are appropriate, and consequently are likely to find more widespread usage than has hitherto been the case. The DLO-based LimitState:GEO software allows the user to specify Eurocode load types and to apply inbuilt Eurocode 7 partial factors, simplifying the whole process.

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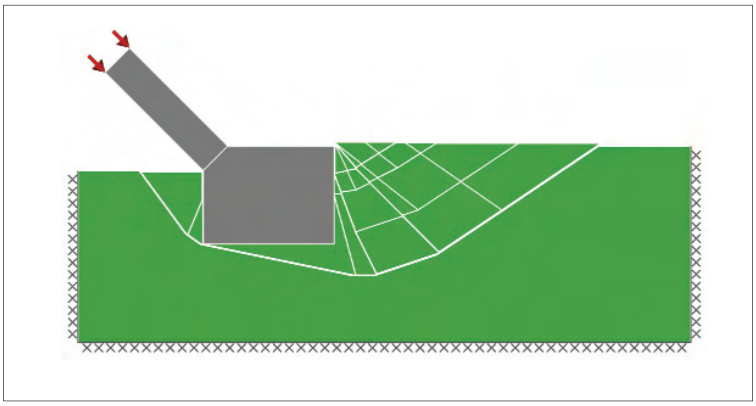

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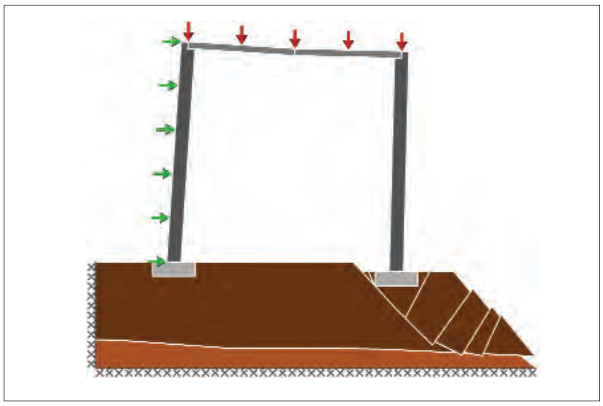

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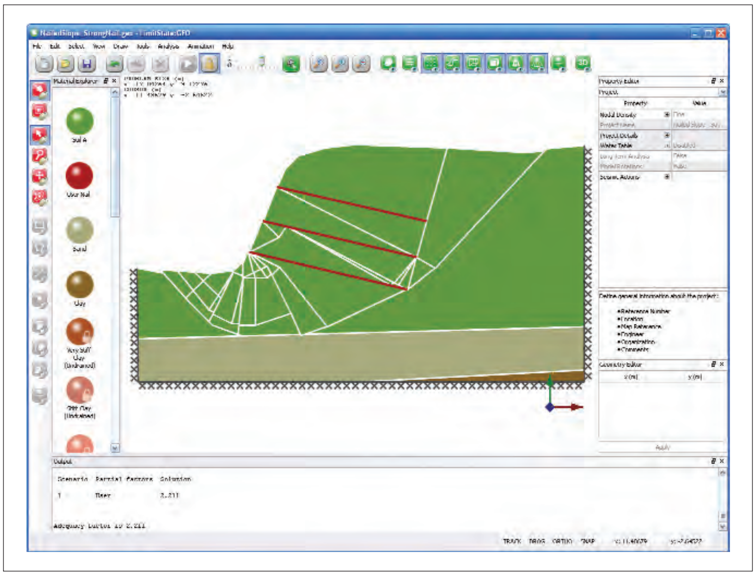

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5 Combined sliding and bearing failure of a footing
6 Simple soil–structure interaction problem involving failure of both soil and structural elements
7 Nailed slope problem solved using LimitState:GEO

Soil-structure interaction problems

The new DLO analysis procedure also makes it possible to tackle the sort of soil-structure interaction problems that could previously only be analysed using far more complex techniques (e.g. non-linear finite elements). Fig 6 shows a simple example, which involves failure of structural elements of a building and also the underlying soil.

Practical DLO software tool

The LimitState:GEO software uses DLO to provide a rapid and easy to use ULS analysis tool for engineers. The software, currently at version 2.0, has been designed to:
– find the critical failure mechanism and margin of safety without having to pre-determine the type of problem being solved, or the mode of failure;
– identify solutions that are typically much more accurate than those found using traditional 'automated hand calculation' software;
– rapidly analyse problems containing multiple partial factor sets, such as Eurocode 7 Design Combinations 1 and 2;
– allow complex problems to be modelled, e.g. involving multiple material models, water and soil nails (Fig 7), seismic actions;
– allow 'sanity checking' of the results of an analysis, through the production of simple free-body diagrams which can be checked by hand.

Furthermore:
– the software interfaces with other industry standard software applications (e.g. CAD packages) and can potentially replace a number of existing 'problem specific' analysis software programs and/or in-house spreadsheets;
– results have been benchmarked against a wide range of problems. In many cases a solution within a few percent of the known exact solution can be obtained in a matter of a few seconds from the website: (www.limitstate.com/geo/verification) to see how output compares with benchmark solutions for >100 problems);
– although designed principally as a practical tool for use in industry, the software is being made freely available for academic teaching and research use, and lecturers from a number of Universities have reported that the software is bringing geotechnical and soil–structure interaction problems to life, leading to increased student engagement. Some examples of teaching usage are available at:
(http://www.geotech.shef.ac.uk/trac/wiki/TeachingResources).
A sample implementation of the DLO procedure written in a short MATLAB script is also available at:
(http://www.cmd.shef.ac.uk/dlo).

References

Dorn, W. S., Gomory, R. E., and Greenberg, H. J.: 'Automatic design of optimal structures', *Journal de Mechanique*, 3, 1964, p 25–52

Smith, C.C. and Gilbert, M.: 'Application of discontinuity layout optimization to plane plasticity problems'. *Proc. Royal Society A: Mathematical, Physical and Engineering Sciences*, 463 (2086), October 2007, p 2461-2484