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Research Paper

On the use of nonlocal regularisation in slope stability problems

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ABSTRACT

This study examines the use of nonlocal regularisation in a coupled consolidation problem of an excavated slope in a strain softening material. The nonlocal model reduces significantly the mesh dependency of cut slope analyses for a range of mesh layouts and element sizes in comparison to the conventional local approach. The nonlocal analyses are not entirely mesh independent, but the predicted response is much more consistent compared to the one predicted by local analyses. Additional Factor of Safety analyses show that for drained conditions the nonlocal regularisation eliminates the mesh dependence shown by the conventional local model.

1. Introduction

The modelling of slope failure in a strain softening material with conventional Finite Element models can be particular challenging. In a typical finite element analysis the strain developed along the shear bands is calculated using the displacement information computed at the nodes of the elements. This affects both the shear band thickness and the direction of its development [1]. The calculated strain is used to assess the degree of softening experienced by the material at that point. There can be a large difference, i.e. a high gradient, between displacement and therefore strain at neighbouring points. The potential strain concentration at one single point can lead to convergence problems and ambiguities in the development of the slip surface. In addition, the sizes of the elements in the mesh restrict the minimum size of the shear band to the distance between two points of known displacement, i.e. two nodes [2]. For example, if 8-noded two-dimensional elements are employed, the minimum shear band thickness is restricted to the width of half an element. These inherent limitations of the finite element method render the solution to be mesh dependent.

Several approaches have been proposed in the literature to try and regularize the numerical solution and model rigorously the shear zone and these can be divided into three main categories; Cosserat theories [3], gradient theories [3–6] and nonlocal approaches [1,3,7,8]. The present study focuses on the latter approach which is particularly attractive because it does not alter the fundamental governing equations, but it does introduce the calculation of a nonlocal strain as a variable by spatially averaging the local strains [9]. This makes the approach of nonlocal strain regularisation more straightforward to implement in an existing finite element code, compared to Cosserat and gradient theories.

The non-local method [10,11] adopts a distribution function which spreads the strain of the material at a point over a predefined surrounding volume. The local method calculates the extent of strain softening with reference to the strain at that point alone. To define the contribution of nonlocal strains to the yielding of the material requires the additional input of a characteristic length parameter, which controls the contribution of local strains to the nonlocal calculation depending on the distance of the local strains from the calculation point. In the present study the nonlocal model of Galavi and Schweiger [1] (G&S) is employed in a coupled consolidation problem of an excavated slope in a strain softening material aiming to investigate the performance of this nonlocal approach in terms of mesh dependence and computational cost. Furthermore the impact of the two nonlocal parameters, the defined length (DL) and the radius of influence (RI) on the numerical predictions is thoroughly investigated providing guidance for their use in boundary value problems. The defined length is an integral parameter of the G&S method which modifies the rate of softening, while the radius of influence is an optional parameter which makes the computation more efficient by reducing the number of local strains referenced in the nonlocal strain calculation.

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2. Mesh dependency of local strain softening slope stability analyses

As previously discussed, the modelling of slope failure in a strain softening material with conventional Finite Element models can be particular challenging, as the solution can be very sensitive to the adopted mesh discretization. For an assumed problem geometry, different element layouts can be employed and the mesh is usually refined around the areas of potential strain concentration leading to varying element sizes within the FE model. The sensitivity of a local strain softening model on these two aspects (i.e. the element size and the elements' layout) is first demonstrated, before exploring the use of nonlocal regularisation in strain softening materials. A parametric study employing both biaxial compression analyses, as well as slope stability analyses was carried out for this purpose. The biaxial compression analyses first examine the role of element size within a uniform mesh discretisation, while in the slope stability analyses both aspects of mesh discretisation are investigated. All the analyses presented in this paper were carried out in plane strain with the Finite Element code ICFEP (Imperial College Finite Element Program) [12], using a strain softening variant of the Mohr-Coulomb model [13]. This is an elasto-plastic model in which softening behaviour is facilitated through a variation of the angle of shearing resistance φ', and the cohesion intercept c' with the deviatoric plastic strain invariant, as shown in Fig. 1. The limits for peak (φ_p', c_p') and residual (φ_r', c_r') strength are specified in the model by a percentage value of the deviatoric plastic strain invariant ($E^p_{d,p}$, $E^p_{d,r}$, respectively) which is defined in Eq. (1):

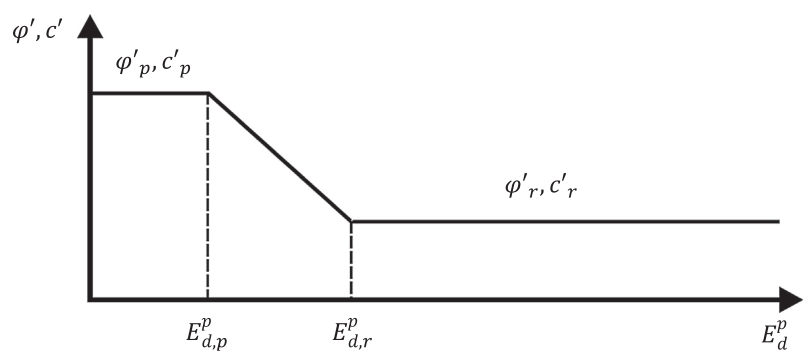

Fig. 1. Variation of the angle of shearing resistance φ' and the cohesion intercept c' with the deviatoric plastic invariant E^p_d adapted from Potts et al. [13].

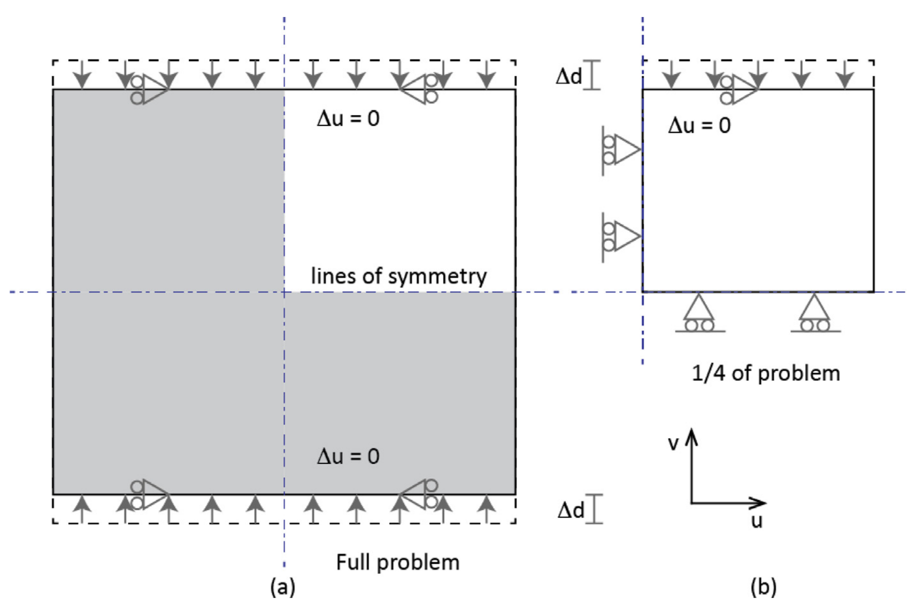

Fig. 2. Boundary conditions for biaxial compression.

Table 1
Summary of biaxial compression analysis for local and nonlocal strain softening models.

Mesh identification & element arrangement	Element size (m)	Local model:strain rate peak to residual (%)	Nonlocal model:DL values		
			0.525 m	1.05 m	2.1 m
			Ratio of DL over element size		
10 × 10	2.1	5–20	–	–	1:1
20 × 20	1.05	10–40	–	1:1	1:2
40 × 40	0.525	20–80	1:1	1:2	1:4