

Parallel three-dimensional finite element analysis of excavation

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ABSTRACT

Over the past few years, the authors have been working towards a generalised method of parallel finite element analysis based on an element-by-element solution strategy using iterative solvers. Until now, this work has focused on "fixed mesh" solutions. In some problems, geometry changes radically as the solution progresses. In geotechnical engineering, the construction process of excavation is a typical example. Change in geometry occurs when material is removed from the ground in either open excavations ("cuts") or in enclosed tunnels. In many real engineering situations, the natural geometry of geological units necessitates three-dimensional analysis, leading to a finite element representation with many millions of degrees of freedom. Algorithms for non-linear elasto-plasticity are needed to adequately capture the physical response of the soil each time material is removed. Large problem size and complex material behaviour lead to heavy computational demands, both in terms of storage (memory) and solution time. These can both be overcome by parallel computation. Once an analysis is complete, interpretation of the results presents a further challenge, benefiting from high performance visualisation techniques. In the context of solving and interpreting large three-dimensional excavation problems, this paper describes the authors' work in parallel computation and virtual reality visualisation. The ultimate aim of the research is to enable the geotechnical engineer to perform "Virtual Excavation".

INTRODUCTION

In this paper, the solution of a geometrically simple geotechnical problem is presented, namely the excavation of a large hole in the ground. In finite element terms, the soil is represented by a cubic domain of 20-noded hexahedral bricks. The base of the domain is fixed and the sides are on rollers. In total the model has around 1.5 million equations and more than 100,000 elements.

To make the problem more geologically realistic, the properties of the soil can be assigned statistically. In this way, the natural variation of weaker and stronger layers can be captured. In real situations, the use of stochastically generated soil properties implies that many “realisations” may be required for a single geotechnical design [1].

The program used was written using FORTRAN95 and is based on an element-by-element approach [2], [3]. A preconditioned conjugate gradient (PCG) solver was used together with a diagonal preconditioner to solve the system of equations. Plasticity was dealt with using a consistent return algorithm [2]. Parallelisation was achieved by simply inserting routines from the authors’ Open Source library, ParaFEM [4], into what was essentially a serial code. In the parallel program, each processor executes instructions according to the pseudo-code below:

```

Initialise
DO for local elements:      Calculate starting stresses
DO Excavate Layer
  DO for local elements:    Calculate excavation loads
  DO for local elements:    Calculate stiffness & preconditioner
  DO Apply Load Increment
    DO Apply Plasticity Increment
      Solve using Element-by-Element PCG
      DO for local elements
        Check yield surface & Update gauss point stress
        Compute bodyloads vector
      END DO
    END DO
  END DO
END DO
END DO
END DO

```

PERFORMANCE

The parallel software and libraries used in this study are fully portable across most modern computer platforms. Performance studies for the excavation problem were undertaken using three different machines currently hosted by the University of Manchester. The key characteristics of these machines are summarised in Table 1.

Machine and Number of Processors	Processor Type	Clock Speed Mhz	Flops Per Cycle	Peak Gflops Processor	Peak Teraflops Machine
IBM SP2 144	IBM Power3	375	4	1.5	0.216
SGI Origin 512	MIPSPro 4	400	2	0.8	0.400
SGI Altix 512	Intel Itanium	1300 & 1500	4	5.2 & 6.0	3.000

Table 1 Summary of Hardware Characteristics

In Table 2, a comparison is made here between the two SGI machines only. To give the reader an idea of the positioning of the IBM machine, the total solution time, using 32 processors, was 230 minutes.

The complete solution of the excavation problem involved removing 3 layers with 5 substeps per layer. This required a total of 50 plastic iterations, with an average of 404 iterations of the PCG solver for each one. When using one processor, 95% of the time

was spent in the solver, 4% was spent evaluating the plasticity algorithm and 1% in the rest of the program. The performance of PCG and the plasticity algorithm are shown in Table 2 as well as the total solution time.

There is a clear difference between scalability using the Altix and the Origin. They have essentially the same hardware for inter-processor communication. As the Altix has faster processors (see Table 1), the poorer speed-up at 128 processors compared with the Origin, shows that communication is starting to have a significant impact. Another feature to note is that the plasticity algorithm requires almost no communication between processors, which explains its impressive scaling.

Processors	Speed up PCG		Speed up Plasticity		Total time (minutes)	
	Origin	Altix	Origin	Altix	Origin	Altix
1	-	-	-	-	5205	1556
32	26	30	31	32	206	52
64	51	56	62	59	109	28
128	98	76	117	86	61	20

Table 2 Performance Comparison

RESULTS

The results of the simulation were analysed using the multipipe edition of AVS/Express (MPE) [5]. There are several attractions to using MPE, particularly for this study which produced a sequence of large 3D datasets (more than 500MB). Firstly, a number of key graphics algorithms have been parallelised so that large graphics objects can be rendered interactively. Secondly, support is provided for easy output into immersive Virtual Reality facilities.

One potential drawback of using AVS/Express, and a common criticism, is that it is not designed specifically for post-processing finite element analyses. In particular, it lacks some of the functionality expected by FEA practitioners - for example interpolation using finite element shape functions. That said, AVS does provide its own visual programming language and the advanced user can write specific modules to deal with such shortfalls.

The response of the homogeneous ground to the removal of the soil is illustrated in Figure 1. Results involving non-homogeneous ground will be presented at the conference. Here, the images show a cross-section through the domain as the interest lies in the deformation of the excavation walls. The magnitude of displacement varies greatly from one step to the next, therefore the images are not plotted to the same scale. In the first set of images, arrows are used to indicate the direction of the ground movements. As the excavation is deepened, the initial uplift at the surface and heave at the base of the excavation is followed by downward flow and eventual collapse. The second set of images show the magnitude of the displacements. The colour map used consists of a number of evenly spaced black stripes, which appear as isocontours on the volume. In the gaps between the black stripes there is a continuous graduation of colour which indicates the magnitude of the isocontours. A black stripe on the volume which has a

very light surround is data with a high magnitude of displacement while a black stripe on the volume with a dark surround is data with a low magnitude of displacement.

Why use black stripes? Removal of the stripes would leave a grey-scale shading that is typical of contemporary FEA visualisation. The stripes serve to highlight the variation in displacement that the eye cannot pick up with the greyscale shading alone.

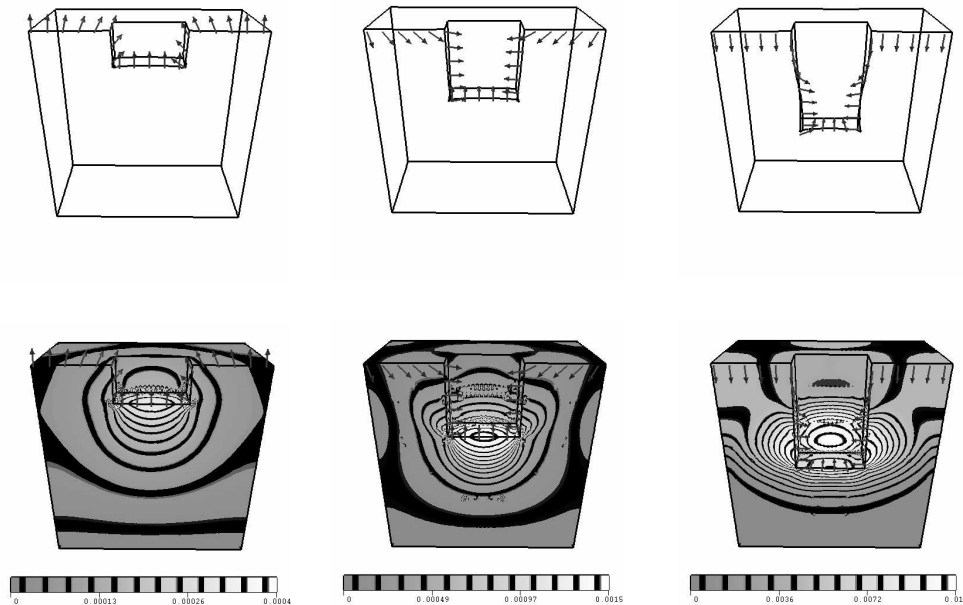


Figure 1 Displacements for the three different excavation stages

In conclusion, the authors note that these are not particularly large analyses. Systems of more than 500 million equations have recently been described [6] using up to 4088 processors.

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