

## **LARGE-SCALE FINITE ELEMENT LANDSLIDE SIMULATIONS UNDER EARTHQUAKE LOADING**

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### **ABSTRACT**

When dealing with large-scale three-dimensional (3D) simulations of natural hazards, such as earthquakes and landslides, computations often exceed the capacity of current single-processor computers and conventional serial computing strategies are no longer possible then. One is to use parallel strategies instead, with multiple processing and memory units, in order to potentially reduce elapsed computation times and allow analysis of large-scale models with non linear constitutive modeling. In this case, traditional serial programs need to be redesigned in order to take full advantage of parallel distributed memory clusters. In this paper, we present the main features of the parallel version of the nonlinear finite element program used, as well as the computing strategy adopted for large-scale 3D non linear simulations under various loading conditions. Then, we present an application of this parallel program to simulate a natural slope under seismic activity, namely the Corniglio landslide (Northern Italy).

Keywords: Earthquake, Landslides, Finite Elements, Parallel Computations

### **INTRODUCTION**

Finite element programs for geotechnical and earthquake engineering purposes are generally serial application softwares working on single processor computers. When dealing with realistic 3D simulations of natural hazards, such as landslides triggered by earthquake and/or intensive rainfall events, computations often exceed the capacity (CPU, memory, storage) of current single-processor computers. It is no longer possible to use serial computing strategies then, and one is to use parallel strategies instead, performed on distributed memory systems, in order to potentially reduce elapsed computation times and allow analysis of large-scale models with non linear constitutive modeling. Thus, one is to redesign traditional serial programs in order to take full advantage of parallel clusters. The nonlinear finite element serial program called GEFDYN (Aubry and Modaressi, 1996), can be used for instance, to simulate 3D non linear response of soils and structures under various static (excavation, construction, slope movements, footing, etc.) or dynamic (earthquakes, fatigue, etc.) loading conditions. The parallel GEFDYN program takes advantages of a fully calibrated serial code for modeling of earthquake and geotechnical phenomena combined with advanced computational methodologies to facilitate the simulation of large-scale systems and broaden the scope of practical applications.

This paper first presents the main features of the parallel GEFDYN program. Then, the computing strategy adopted for 3D large-scale simulations is presented. Finally, the numerical results and computing performances obtained for the 3D parallel simulations of the "Lama" area in the province of Parma (Northern Italy) during the 1996 Correggio earthquake (Mw 5.44, October 15<sup>th</sup>, 1996) are

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discussed. The numerical simulations were performed on the Cluster parallel computers at BRGM (Intel Xeon) and at Ecole Centrale Paris (Intel Itanium2) in France.

## PARALLEL IMPLEMENTATION OF GEFDYN

### Short description of the GEFDYN non linear finite element program

In GEFDYN program, saturated materials are modeled using a coupled two-phase approach based on the macroscopic Biot's theory (Biot, 1962) for porous media. Various formulations are possible for earthquake analysis. In this research, the  $u$ - $p$  formulation is used, which take displacements of the soil skeleton and pore fluid pressures as the primary unknowns. Moreover, we assume infinitesimal strains and rotations and incompressibility of the soil grains.

The non linear constitutive modeling can be performed using various models, such as the cyclic multi-mechanisms elastoplastic Hujeux model (Aubry *et al.*, 1982). In this model, the plastic yield surface evolves within a volumetric hardening regime, which depends on the consolidation pressure (as in the *Cam-Clay* family models) and the plastic shear strains (shear-volumetric coupling in accordance with laboratory and field observations). A *Roscoe*-type non-associative flow rule is also used for the evolution of the plastic volumetric strain, which controls the dilatancy/contractance behavior of soil under shear loading.

More details of the theory of dynamics of saturated porous media, its extension into the nonlinear regime, and its implementation in the GEFDYN code can be found in Modaressi (1987) and Aubry & Modaressi (1996), along with numerical applications illustrating the capabilities of the numerical tool to deal with complex phenomena.

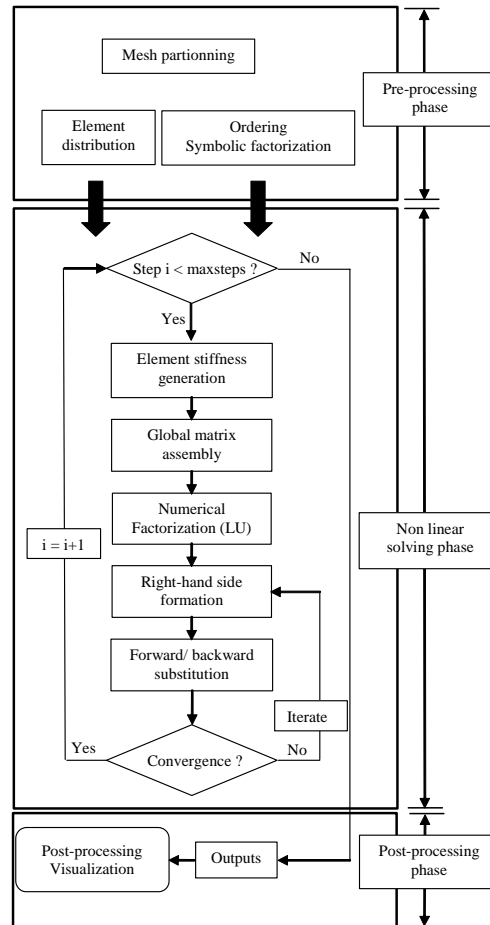
### Parallel implementation and computational procedure

The GEFDYN program is well suited for non linear static or dynamic analyses of soils, but the use of the serial code is not possible, when dealing with large-scale 3D complex analyses, due to its current memory and storage behaviors and its prohibitive total elapsed simulation times in such analyses. On the contrary, the parallel version of GEFDYN is able to solve such problems, as it has been developed for distributed memory parallel computers, in which each processor of the parallel machine solves a partitioned mesh domain, and data communications among subdomains are performed through the MPI (Message Passing Interface) library (Snir and Gropp, 1998).

The computational procedure is illustrated in Figure 1. It can be divided into three phases: the initialization or pre-processing phase, the nonlinear solution phase, and finally, the post-processing phase. After reading the input files, the initialization phase consists of using METIS (Karypis & Kumar, 1997), in order to build a node-by-node weighed graph for partitioning of the finite element mesh and for workload balancing. Then, the symbolic factorization is performed to determine the non zero terms of the matrix factors. The domain decomposition and symbolic factorization are performed within each processor based on the global input data.

In the nonlinear solution phase, the program goes through an iterative process for each time-step, until convergence is reached, and using either the modified Newton-Raphson algorithm or the quasi-Newton BFGS method. The MUMPS software, a MUltifrontal Massively Parallel direct Solver (Amestoy *et al.*, 2001), is used for the Gaussian elimination ( $LU$  factorization) performed on the large sparse linear system. One of the advantages of this sparse solver is that it performs dynamic task creation and scheduling, in order to balance the work performed on each processor, thus improving memory management of the parallel multifrontal approach, but without increasing the numerical factorization time.

Finally, the last phase consists of collecting from the different processors, the results saved on nodes (e.g. displacements, accelerations, pore pressure, etc.) and on gauss points for the element outputs (e.g. strains, stresses, state parameters of the non linear constitutive model). Formatting of the results is then performed for post-processing and visualization purposes.



**Figure 1. Flowchart of Computational Procedures in parallel GEFDYN**

### Storage considerations

When performing large-scale simulations, the storage strategy plays a key role in the computing process, as it can dramatically increase the wall-clock simulation time, and it can also lead to the complete saturation of the hard disk devices, possibly causing computation break. In order to avoid such issues, a different strategy for nodal (displacements, accelerations, pore pressures, etc.) and gauss (strains, stresses, etc.) savings has been chosen in the parallel GEFDYN code. It consists in using different saving steps for the different results, as well as defining explicitly the nodes or zones (e.g. the ground surface) where the savings will occur. However, for very large problems, this strategy may not be sufficient, and we are still working on this issue.

## NUMERICAL SIMULATION OF THE CORNIGLIO LANDSLIDE

The three-dimensional (3D) simulations of the Corniglio landslide were conducted using the parallel version of GEFDYN on two parallel Clusters:

- the BRGM Cluster, which includes 24 Intel Xeon 3.06Ghz processors with 2GB of RAM per CPU and Ethernet Gigabit interconnection;
- the SGI Altix 350 Cluster at Ecole Centrale Paris, which is composed of 4 Non-Uniform Memory Access (NUMA) type machines including 50 Itanium2 64 bits Intel 1.5Ghz processors with 3GB of RAM per CPU and Infiniband interconnection.

### Presentation of the Corniglio landslide

The Corniglio landslide is a large mass movement over 3,000m long, 1,000m wide and up to 120m deep (surface:  $2 \times 10^6 \text{ m}^2$ , volume:  $200 \times 10^6 \text{ m}^3$ ) 1, stretching from 1,150m elevation to 550m a.s.l. and located 50km SW from the city of Parma, in the Emilia Romagna region (Northern Appennines, Italy), where the annual mean rainfall is about 1,500mm. It is classified as a slow, intermittent, complex and composite landslide.

This landslide has repeatedly affected the old village of Corniglio (altitude: 700m a.s.l.), causing damages to many buildings, roads, aqueducts and other infrastructures (see the topographic map of the landslide and immediate surroundings on Figure 2). The movements are mainly attributed to the increase of pore-water pressures, after periods of intense rainfall, to the weathering process, causing the deterioration of the geomechanical properties, and finally, to seismic activity. In the “Lama” sliding zone, velocities have reached a maximum value of about 50 m/day during the two recent reactivations of the 1994-96 and 1997-1999 periods, whereas in the “Coniglio Village” zone, maximum speed has reached about 1.5 cm/day (LESSLOSS, 2006).

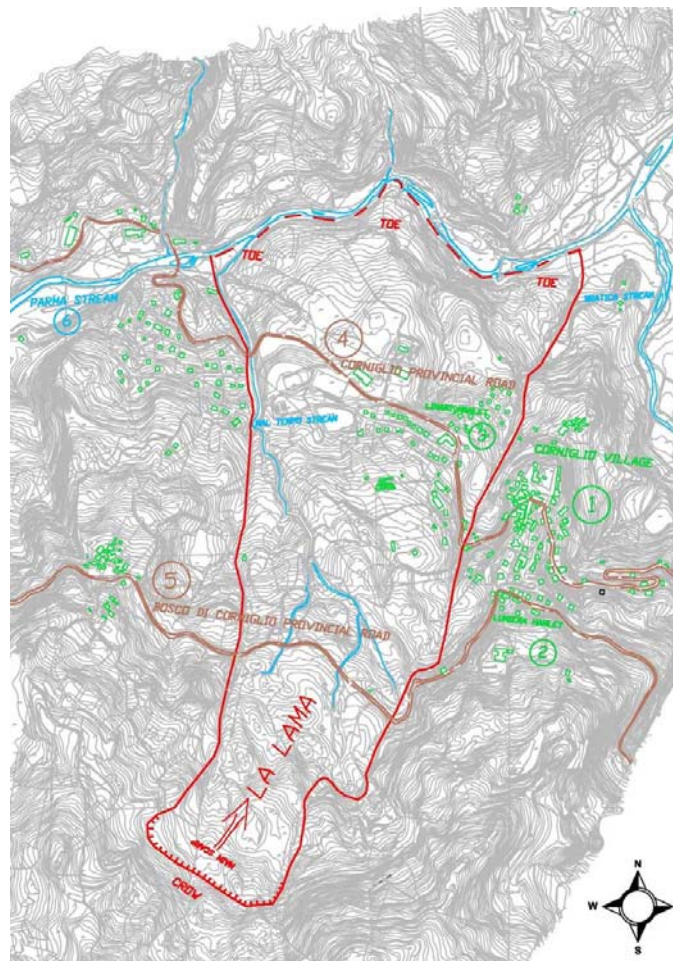


Figure 2. Topographic and orientation map (after SGI in LESSLOSS, 2006)

During the damaging Mw 5.4 Correggio (Parma) earthquake of October 15<sup>th</sup>, 1996, a reactivation of the landslide occurred, despite the fact that the earthquake epicenter lies at 60km from the Corniglio site. The accelerograms used for this study were recorded at the Novellara station (epicentral distance of 8 km), where peak horizontal ground acceleration (PGA) value was close to 0.2g. The horizontal (EW and NS) components of the input Novellara acceleration were scaled to represent the motion at Corniglio, that is a horizontal PGA of 0.0216g (LESSLOSS, 2006).

### Numerical modeling

The simulations of the landslide presented in this paper, were performed using the above-described 3D parallel finite element program GEFDYN. The aim was here to assess the difficulties and thus, the feasibility of such large-scale dynamic analysis, in order to improve the modeling process for further realistic analyses.

As shown in Figure 3 and due to geometrical symmetry considerations, only half of the landslide area (including the Corniglio village zone) was considered for analysis. This area is nonetheless about 3700m long, 1310m wide and 140m deep. The horizontal components of the input Novellera acceleration were entered as a global accelerogram to simulate a rigid base motion (Fig. 4). The model was discretized using 4-node tetrahedral elements.

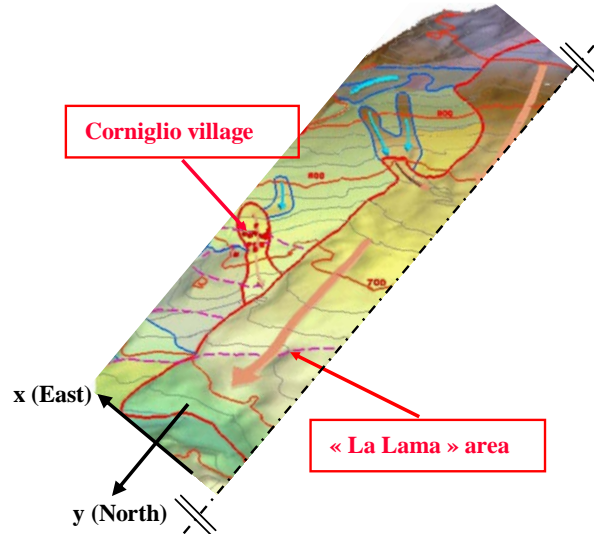


Figure 3. Landslide model

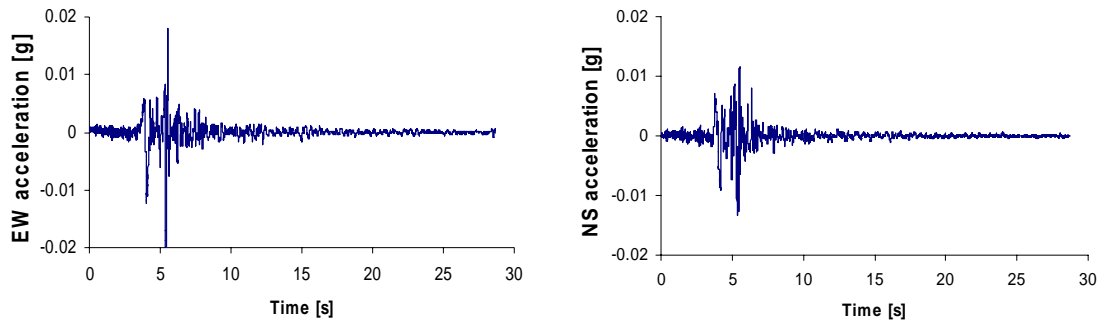


Figure 4. Horizontal components of the input acceleration used in simulations

Two materials were considered for analysis: one “soft” surficial material, which corresponds to the slope and slide deposits (sandy silty gravels with sandy clayey silt layers), and one “hard” material, which essentially groups marls and sandstones. The mechanical characteristics (wave velocities, bulk density, friction angle, cohesion) of these materials are given in Table 1.

A static application of gravity (model own weight) was performed before the seismic excitation. The resulting soil stress state served as initial conditions for the subsequent earthquake analysis.



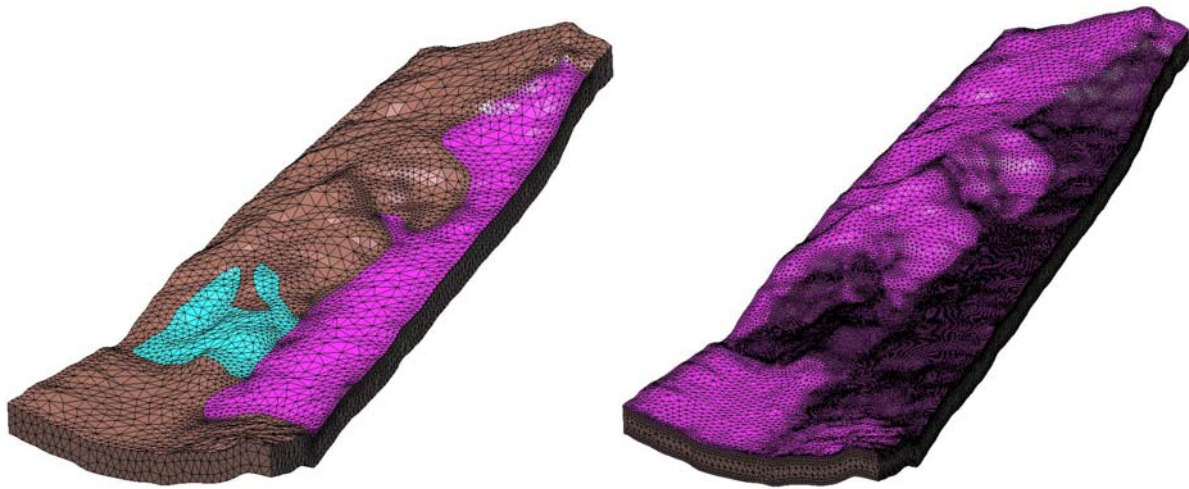
**Table 1. Mechanical characteristics of the soil layers considered for analysis**

Materials	Constitutive type	$V_S$ (m/sec)	$V_P$ (m/sec)	Bulk density (kg/m <sup>3</sup> )	$\phi'$ (°)	$C'$ (kPa)
Slope and slide deposits	Elasto-plastic	120	240	1900	30	50
Marls and sandstones	elastic	440	870	2200	-	-

Different simulation cases were conducted in order to assess the performances of the parallel code: one with coarse meshing, which allows a maximum frequency of about 2Hz, and one with refined meshing, allowing a maximum frequency of 5Hz (see Table 2 and Fig. 5).

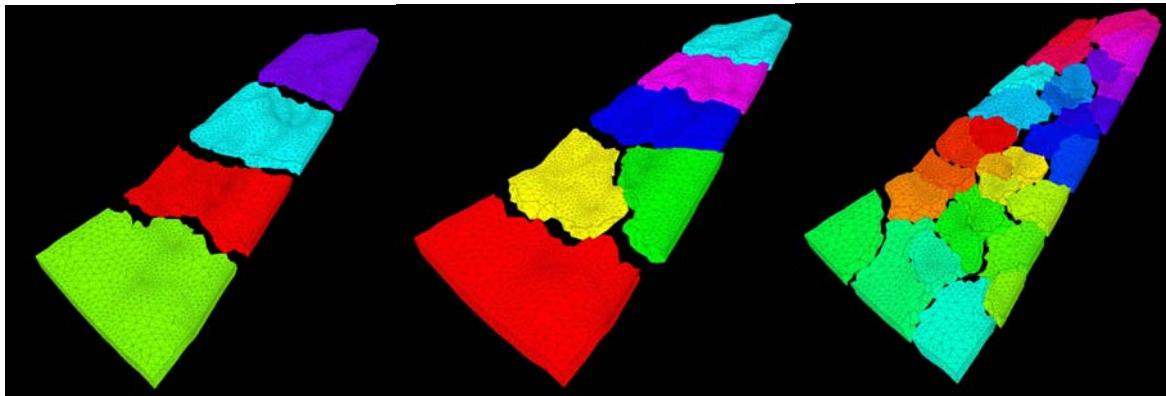
**Table 2. Computing features for the seismic simulations**

Simulation case	Number of nodes	Number of elements	Max. Frequency (Hz)
Coarse	9,722	38,859	2
Refined	781,970	525,998	5

**Figure 5. Meshes for coarse (9,722 nodes) and refined (781,970 nodes) simulations.**

The coarse mesh runs were conducted on the BRGM Cluster, using 4 and 6 processors. The refined mesh run was conducted on the SGI Cluster, using 32 processors. Figure 6 shows the domain partitions used for the different cases.

For the coarse mesh cases, it was possible to perform a total of 4000 time steps of 0.005 second per step, whereas only a total of 2000 time steps of 0.005 second per step was performed for the refined mesh, due to storage and network communications issues.

**Figure 6. Mesh Partitions for 4, 6 and 32 CPUs.**

### Computing results and discussion

The total wall-clock execution times, used RAM and volumes of storage (results) for each case are detailed in Table 3. For the coarse mesh cases, we note that it was possible to perform a binary storage of all the nodal and gauss results at each time step, which explains the quite high wall-clock times. A different strategy had to be envisaged for the refined case, due to storage and network communication issues. Nodal results for the whole mesh could be saved every 4 time steps only, whereas surface displacements and accelerations could be saved at each time step. No gauss results could be saved in this case.

**Table 3. Computing performances for the seismic simulations**

Simulation case	Total wall-clock time	RAM/CPU used for the run	Storage volume	Number of CPUs	Number of time steps
Coarse	16h 9min	80MB	65GB	4	4000 (~ 20 sec of shaking)
Coarse	11h 33min	53MB	65GB	6	4000 (~ 20 sec of shaking)
Refined	17h	2.5GB	39.5GB	32	2000 (~ 10 sec of shaking)

Figure 7 presents the comparison between the x-displacement time histories obtained at the same location inside the village, for the coarse and refined mesh cases. We see that in both cases, the main features are the same, except for the peak amplitudes which tend to be smaller in the refined mesh case. This differences may be explained by the numerical dispersion introduced by the coarser mesh, which spatial step in this region is about 12m, instead of 5m for the refined case.

Figure 9 shows the computed peak horizontal accelerations occurring in the Corniglio village zone after about 5.5 seconds of shaking, for the coarse mesh run with 6 CPUs. In this case, a slight amplification of the input motion can be observed near the village zone for both components.

Figure 8 displays the coutour fill of the displacement norm and vectors obtained after 20 seconds of shaking for a large zone of the coarse mesh (6CPU run), whereas figure 11 displays the computed time histories of displacement and acceleration fields obtained at node 5805 located within the village zone (Fig. 10). We see that in both case, the maximum displacement value obtained in the village zone, which seems to be in the x-direction (West), is about 8mm. This value is to be compared to the 2-4cm values of permanent displacements found in the same zone (LESSLOSS, 2006). This difference may be explained by the  $\phi'$  and  $C'$  parameters considered in this analysis, which were rather optimistic for the slope and slide deposits and they should be decreased. Moreover, it would be better to perform a refined analysis with pore-water evolution in order to obtain more realistic behavior of the sliding materials.

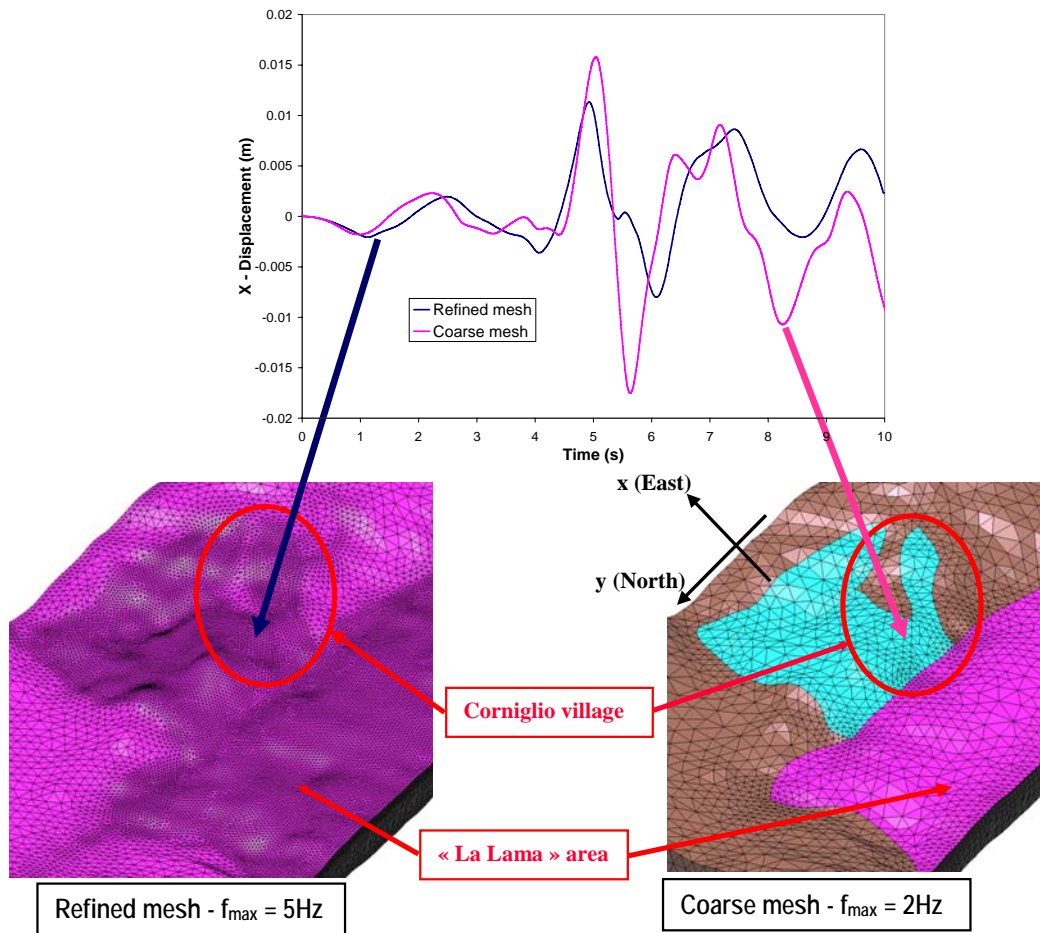


Figure 7. Comparison of computed x-displacements between the coarse and refined mesh cases

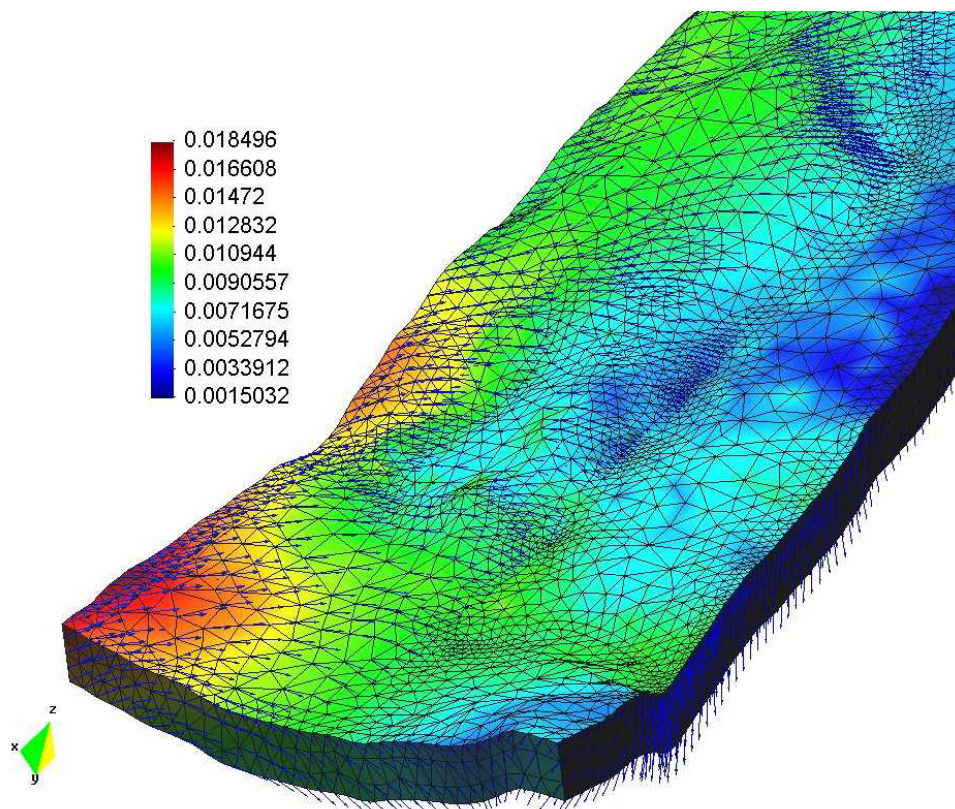


Figure 8. Computed contour fill of the displacement norm and vectors after 20 seconds of



shaking (6 CPUs - coarse mesh run)

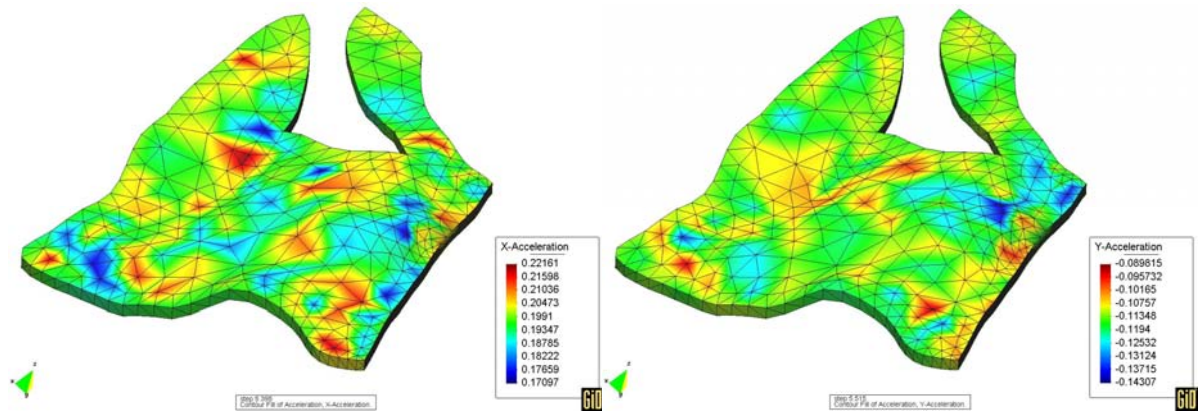


Figure 9. Computed horizontal accelerations in the village zone (6 CPUs - coarse mesh run)

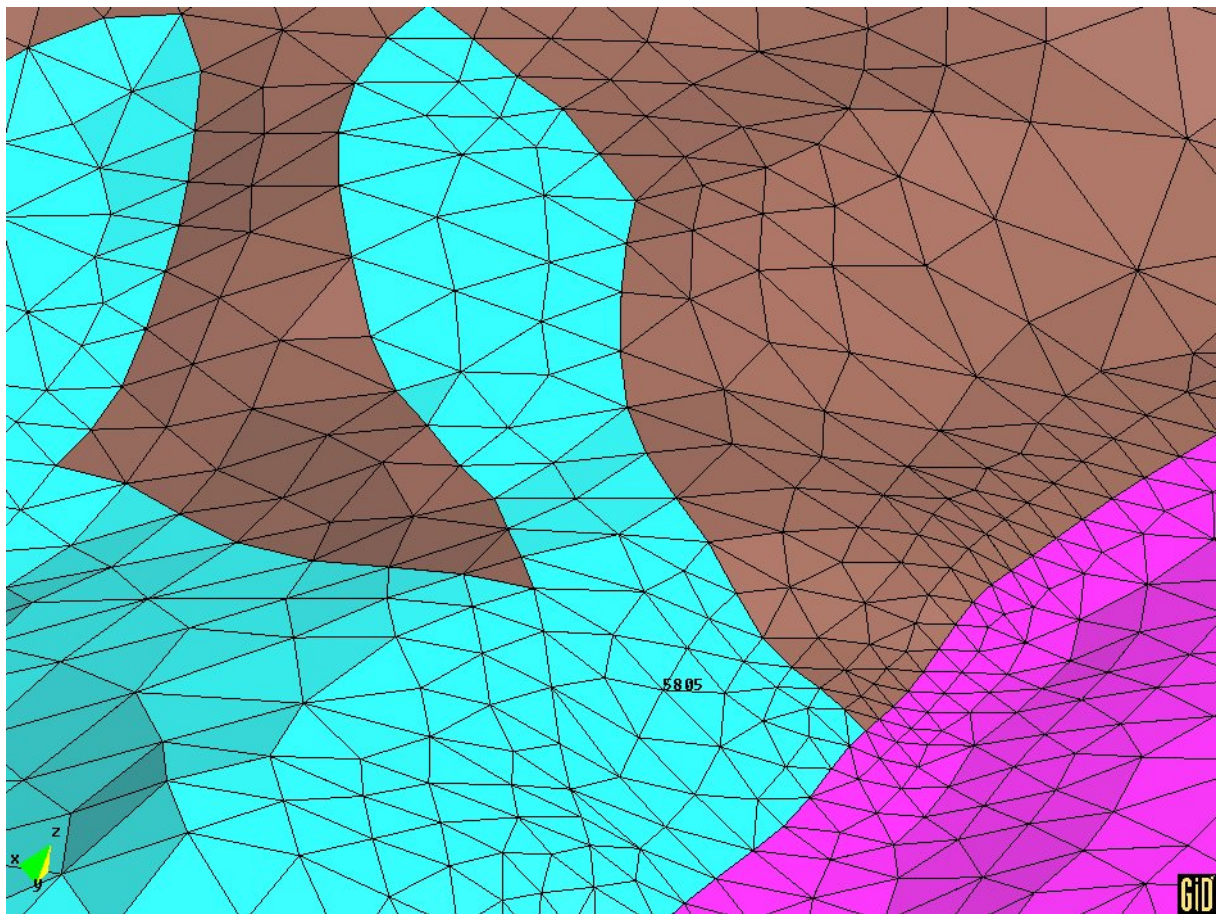
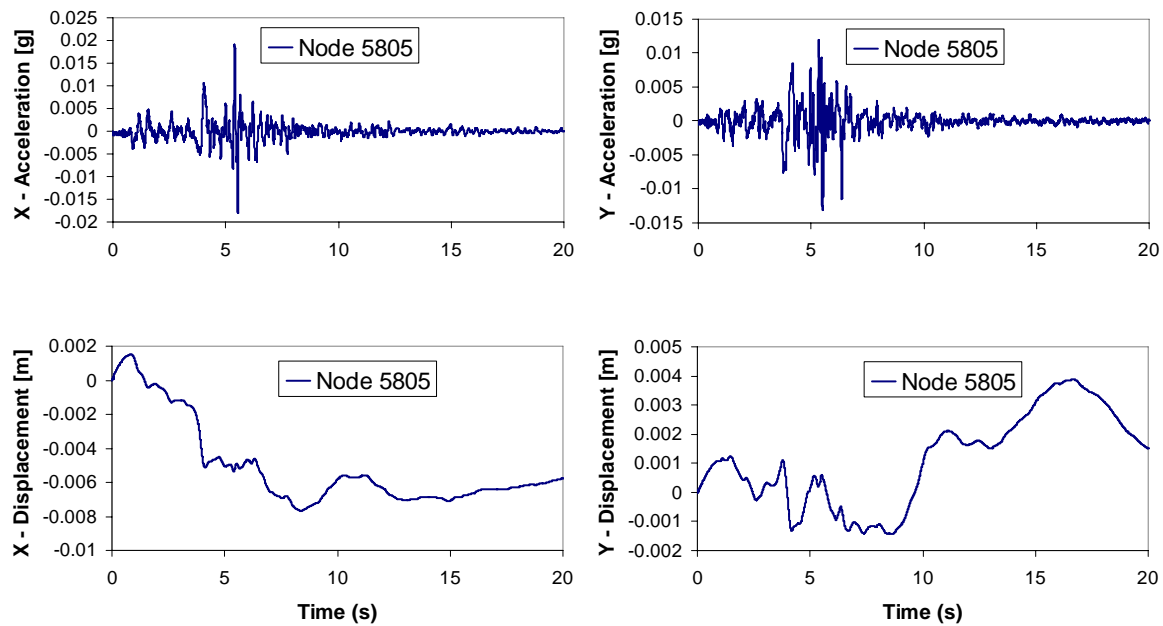


Figure 10. Position of node 5805 located in the village zone, for time histories (coarse mesh run)



**Figure 11. Computed acceleration and displacement time histories at node 5805 (6 CPUs - coarse mesh run)**

## SUMMARY AND CONCLUSIONS

3D large-scale FEM earthquake simulations of an active landslide on parallel computers was presented in this paper. The code employed for analysis is the parallel version of an existing nonlinear finite element program, GEFDYN. The computational performances and results are presented and discussed, focusing on the storage issues for such large-scale analysis with heterogeneous materials. The aim of the simulations presented in this paper, was to assess the difficulties and thus, the feasibility of such large-scale dynamic analysis, in order to improve the modeling process for further realistic analyses. Further coupled two-phase analyses are underway, which consist in using the earthquake simulations as initial state for static landslide non linear simulations considering intense rainfall events, in order to assess the role of pore water pressures in the instability process for the studied landslide.

## ACKNOWLEDGEMENTS

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