



# Parallelization of the TRIGRS model for rainfall-induced landslides using the message passing interface



M. Alvioli <sup>a,\*</sup>, R.L. Baum <sup>b</sup>

<sup>a</sup> CNR-IRPI, Via Madonna Alta 126, I-06128 Perugia, Italy

<sup>b</sup> U.S. Geological Survey, P.O. Box 25046, Mail Stop 966, Denver, CO 80225-0046, USA

## ARTICLE INFO

### Article history:

Received 31 October 2015

Received in revised form

15 March 2016

Accepted 1 April 2016

Available online 11 April 2016

### Keywords:

TRIGRS

Shallow landslides

MPI

Slope stability

## ABSTRACT

We describe a parallel implementation of TRIGRS, the Transient Rainfall Infiltration and Grid-Based Regional Slope-Stability Model for the timing and distribution of rainfall-induced shallow landslides. We have parallelized the four time-demanding execution modes of TRIGRS, namely both the saturated and unsaturated model with finite and infinite soil depth options, within the Message Passing Interface framework. In addition to new features of the code, we outline details of the parallel implementation and show the performance gain with respect to the serial code. Results are obtained both on commercial hardware and on a high-performance multi-node machine, showing the different limits of applicability of the new code. We also discuss the implications for the application of the model on large-scale areas and as a tool for real-time landslide hazard monitoring.

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## Software

Name of software TRIGRS v2.1

Developers R. Baum, M. Alvioli

Contact [massimiliano.alvioli@irpi.cnr.it](mailto:massimiliano.alvioli@irpi.cnr.it), [baum@usgs.gov](mailto:baum@usgs.gov)

Software required FORTRAN compiler, MPI libraries

Software availability <http://geomorphology.irpi.cnr.it/tools/trigrs>

<http://dx.doi.org/10.5066/F73J3B27>

<http://dx.doi.org/10.5066/F7ZW1J08>

## 1. Introduction

The widespread availability of high resolution Digital Elevation Models (DEM) for large areas opens the possibility of

applying physically based models, originally designed for use in restricted areas or even to single slopes, to much larger scale. With increasing size of the study area and resolution of the DEM, the required computing time for each run of the model increases proportionally to the number of grid cells in the study area. The aim of this paper is to present a new parallel implementation of TRIGRS, an open-source FORTRAN program designed for physically-based modeling of the timing and distribution of shallow, rainfall-induced landslides. The spatial distribution of landslides is obtained computing transient pore-pressure changes, and attendant changes in the factor of safety, due to rainfall infiltration and using a simple infinite-slope description on a cell-by-cell basis. Time dependence is implemented in the model by time-dependent rainfall infiltration, resulting from storms that have durations ranging from hours to a few days. The results are obtained using analytical solutions for partial differential equations that represent one-dimensional, vertical water flow in isotropic, homogeneous materials for either saturated or

\* Corresponding author.

E-mail addresses: [massimiliano.alvioli@irpi.cnr.it](mailto:massimiliano.alvioli@irpi.cnr.it) (M. Alvioli), [baum@usgs.gov](mailto:baum@usgs.gov) (R.L. Baum).

unsaturated conditions, which are modeled separately in the code. The variable rainfall input is represented by step-function series, while a simple runoff routing model allows the user to divert excess water from impervious cells onto more permeable downslope cells. The computation of the factor of safety in unsaturated soils is modeled by an approximate formula for the description of effective stress in unsaturated materials. Horizontal heterogeneity is accounted for by allowing material properties, rainfall and other input quantities to vary from cell to cell.

The program is operated by providing an input text file. The file contains many lines, and it is described in the README file bundled with the software, which is free for download and use. A full description of the previous version of the software and its user manual can be found in (Baum et al., 2008). In particular, the input file is used to specify the numerical values of the input parameters, location of input grids in the filesystem, rainfall intensity and duration pattern. The minimal inputs of the model are a DEM, the corresponding slope grid, a duration-intensity rainfall pattern and numerical values of geotechnical parameters. Additional details are provided by specifying different zones for any of the input parameters, corresponding to homogeneous areas, and a number of other grids to specify initial conditions, soil depth and other parameters affecting the accuracy of computations. The more details are provided as inputs, the longer is the running time of the code, mainly because the time needed to read the additional details into the program increase. The user can also specify different outputs, which may vary in the kind and number of output grids, since they can be output at various intermediate times during the simulated storm. The number of time steps specified in the input rainfall pattern, the number of time steps and the number of points along the vertical direction required to solve the model equations in each cell, the type of output required by the user and the number of times at which the outputs are required by the user represent additional factors contributing to the overall running time. In this work we analyse the different contributions of the various factors to the running time of the code in order to reduce the major time-demanding operations and parallelize the computing-intensive part of the code.

The model equations, their time- and space-discretized versions and their implementation into the FORTRAN code have been published in the version 2.0 manual (Baum et al., 2008) and will not be repeated here. We will focus, instead, on new features of the code, providing the corresponding new model equations where applicable, and on the code parallelization strategy and performance gain. We have fully parallelized the serial code using the Message Passing Interface (MPI) protocol (MPI Forum, 2012), and tested the new parallel code in a vast study area in Colorado. The great advantage of using the MPI libraries is that the code is parallelized at low level, so that the changes are essentially transparent to previous users of the code, and that it may be run on any MPI-enabled machine, ranging from conventional multi-core workstations to large, multi-node supercomputers. Examples of successful applications of the MPI standard to environmental software are found in hydrology (Yiping et al., 2013; Tiejian et al., 2011), flood inundation (Yu, 2010) and ocean science (Jordi and Wang, 2012; Wang and Shen, 2012), to name a few.

The paper is organized as follows. The general structure of the existing code is outlined in Section 2. Since an effective speedup of the code running time can only be achieved by optimizing the serial code first, the optimizations are described in Section 3 along with many changes and bug fixes. The subsequent parallelization with MPI libraries is described in detail in Section 4. The performance of the new code was assessed in a rather large area in Colorado, presented in Section 5, where our choices for soil parameters are motivated, the rainfall pattern time intervals are discussed and model results are presented. We discuss the results and draw conclusions in Section 7.

## 2. Serial code structure

In order to illustrate the MPI implementation details we need to outline the relevant parts of the existing serial code. All the numerical values of the input parameters of the code are provided in the initialization file, the mode of execution (saturated or unsaturated soil, finite or infinite soil depth) is specified there, and the paths to the input grids are given. The grids are checked for consistency, so that the NODATA cells match in all of them. Before the calculation starts, excess water from infiltration in each cell is directed to the neighboring cells according to the runoff directions prepared separately; this is done to prepare the values at each user-requested time step and, after this is accomplished, there is no more need to know information regarding neighboring cells during the core computation. As a result the computation of the factor of safety and the other outputs of the code are performed independently for each cell, which is a great advantage for parallelization purposes. In each of the core computation subroutines, hereafter referred to as SAT-INF (Saturated-Infinite depth), SAT-FIN (Saturated-Finite depth), UNS-INF (Unsaturated-Infinite depth) and UNS-FIN (Unsaturated-Finite depth), the cell-by-cell calculations are performed in such a way that one loop over the different cells and one over the different times-steps, exist. By virtue of each cell's stability calculation being performed independently of all the others, we have parallelized the outer loop, as described in Section 2, namely the loop over the valid grid cells in the study area. To illustrate the structure of the serial code, we outlined the UNS-FIN algorithm in pseudo-code in Algorithm 1. The other execution modes have similar structure, at least as far as parallelization changes are concerned. The pseudo-code refers to both the serial and parallel structure; the points in which the relevant MPI modifications and function calls were made are highlighted and will be commented in a dedicated Section.

## 3. New features of the serial code

The TRIGRS model is freely available as FORTRAN source code; the latest published version is described in (Baum et al., 2008). The new version presented in this work is a revised one, including many bug fixes and improvements. In this section we will describe in detail the differences with respect to the serial code in the previous version and the parallelization scheme we have implemented.

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