

Integration of physical simulation models in the frame of a GIS for the development of a volcanic risk assessment information system

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Abstract

Conventional volcanic risk assessment studies have usually appealed to complex calculation procedures in which a great variety of parameters are involved and large volumes of data from different sources have to be analysed. Both requirements have usually constrained the production of updated volcanic risk maps either because of the limited qualitative approach that has to be usually adopted to calculate risk or because of the long times required to gather and elaborate the data.

In this context, Geographical Information Systems and volcanic simulation physical models have provided the tools to give a first step towards the solution of these drawbacks. Making use of both of them, a dynamic and interactive methodology to analyse volcanic risk in the frame of a GIS has been designed and developed and a volcanic risk assessment information system for early prevention and management of volcanic crisis is currently being devised.

The main objective pursued by the incorporation of volcanic simulation models to the risk assessment process is to get advantage of their capability of producing "scenarios" or hazard maps where the potential distribution of the products of an eruption of certain characteristics is reflected. Hence, the possibility of identifying in advance the potential affected areas and the degree of affection makes them extremely useful tools for volcanic risk assessment, management and prevention purposes.

Nevertheless, volcanic simulation models have, till nowadays, usually made up independent programs with their own particular formats for data storage, retrieval and display. These characteristics have limited their use due to the constraints found when data exchange or interconnection with other phases of the classical risk assessment process has been tempted.

To achieve a complete integration of the models in the frame of the GIS, each of the models considered have to be adapted to the new operational environment. Therefore, before implementation takes place, there is the need to (1) identify the databases and parameters required for simulation, (2) analyse the kind of outputs provided, (3) establish the most convenient method to carry out the integration and, (4) specify the set of requirements that the models will have to fulfil in the new developing environment.

1 Introduction

The EU project Teide- European Laboratory Volcano (contract EV5V-CT93-0283) served as the frame for development of a methodology for volcanic risk assessment where the incorporation to the risk maps generation process of a specific set of computer based tools,- such as Geographical Information Systems and physical simulation models -, was for the first time considered as a feasible and realistic solution to the problems found by classical volcanic risk studies (Gómez-Fernández¹).

The lack of a widely accepted standard methodology to follow to carry out volcanic hazard and risk assessments prevented then us from having a departure development basis from which to select and adapt its most relevant features to the GIS working environment.

For this reason, there was the need to peer review the complete set of assessment methods followed by classical studies in order to identify the most significant elements required to carry out volcanic risk estimation and to devise a way to represent these elements into the GIS frame (Gómez-Fernández & Araña-Saavedra²).

The procedure followed to design the methodology was based on the principles and techniques proposed by *cartographic modelling* methodologies, that allowed us to decompose hierarchically the problem of risk assessment into each of its components.

In order to check the design of the calculation structure developed, a pilot study at Tenerife island (Canary islands, Spain) was carried out devoted to assess the risk posed by lava flows from the occurrence of effusive eruptions and to compare the extent of damage produced depending on the location of the eruptive vents selected and the socio-economic characteristics of the areas affected (Gómez-Fernández¹).

The results provided by the application of the methodology were discussed and analysed in order to identify the constraints of the method devised. Generally speaking, the methodology provided a way to surmount the constraints faced by classical assessments but, there were two features whose incorporation was considered as fundamental to provide an operational character to the assessments (Gómez-Fernández³).

First, there was the need to achieve a complete integration of the simulation models into the structure of the system as their independence slowed down the process of calculation, due to the need to create additional procedures to exchange data and parameters between them and the GIS.

Furthermore, it was stressed the need of an adequate user interface to provide communication between the users and the system as, without it, advanced technical skills to manage the tools devised were required, what made it a methodology difficult to master by inexperienced users.

In order to solve both constraints, the development of a near real-time information system (VRAIS) capable of providing a powerful and efficient tool for volcanic risk assessment was considered.

The project proposed, currently under development, has been structured in a series of interdependent and overlapping phases that have allowed us to: (1) analyse the feasibility of developing such a system; (2) formulate the set of requirements that it should fulfil, taking into account the users' needs; (3) establish a work-plan for its development and (4) design the system architecture and construct a prototype to test it.

An important task to be performed by the project is related with the implementation of the physical simulation models into the system's architecture. The review of the process followed to achieve this aim has been the object of this paper and is briefly introduced through the next sections.

2 Overview of the physical models simulation requirements

Physical models have provided the way to simulate eruptions and to obtain information on the extent and magnitude of their effects (Pareschi & Bernstein⁴), having already been considered the possibility of integrating them into the GIS architecture to help with hazard calculation (Lam and Swayne⁵).

The research carried out during the last years concerning the physical behaviour of eruptive phenomena has led to the development of sophisticated numerical models.

Nevertheless, many of them require to have information on many parameters that are not available in time when a volcanic crisis takes place. This kind of models is fundamental to improve the knowledge of volcanic phenomena but is difficult to apply when fast results are needed, due mainly to the important computing requirements they have.

The scope considered for the development of the project (development of a near real-time information system) involves that the numerical models that would be considered for implementation have to fulfil three main conditions:

268 Risk Analysis

- They must be characterised by it fast performance (near real-time analysis).
- Their physical basis must be accurate but simple enough to allow implementation into the system.
- They must be widely accepted by the scientific community as a standard method for simulation.

Currently, there is a series of widely-applied models that fulfil these conditions, whose accuracy has been already tested. Nevertheless, these models are usually related with those eruptive phenomena whit a “simpler” to formulate behaviour such as lava flows, fall-out, ballistic projectiles or lahars.

On this basis, the parameters and databases required to carry out the numerical simulation of these phenomena and the kind of outputs that are obtained have been analysed. A summary of the results obtained from this analysis is presented through the next sections.

2.1. Lava flow models

The simplest available physical models require usually as input data the location of the eruption vent and the topography characterisation, in order to calculate the probable area that could be affected by the flows. Furthermore, depending on the model, other secondary parameters (e.g. maximum length, critical highness) can be also required for simulation.

The existing models represent the topography in vector (TIN networks) or raster format in the same proportion, depending on the preferences of the author or on the data available for the area where it has been applied initially (e.g. Macedonio et al.⁶)

2.2. Fall out models

These models require a more complex input that the previous ones. The simulation depends on the availability of data representing the location of the eruption vent, the distribution of winds with altitude, the particle sizes and density and the maximum volume erupted. They usually are built to operate on raster data and the outputs produced can make reference to the maximum depth of pyroclasts accumulated or to the load charge (in Kg per square metre) (e.g. Armienti et al.⁷).

It is desirable to have a complete record from which an statistical sample of a specific wind profile can be selected for simulation. This kind of models usually take only into account the distribution of winds coming

from one meteorological station (the closest as possible to the emission vent) so, the spatial distribution of vents in the area potentially affected by the products of the eruption is not considered.

2.3. Lahar models

The most common models make use of the topography, meteorological data (rainfall distribution) and the potential location of ice masses to identify the potential areas that could be affected by inundation (e.g. Macedonio & Pareschi ⁸).

2.4. Ballistic fall models

The simplest models take into account for calculation the topography, launch velocity and angle of the volcanic bomb, its shape, density and mass and the air density and resistance. The outputs provide information on the potential impact point of the projectile and the trajectory followed.

2.5. Other physical models

A great research effort has also been devoted to the development and improvement of numerical models capable of simulating the most physically complex eruptive phenomena like surges, pyroclastic flows or dispersion of volcanic gases. Nevertheless, these models present two main drawbacks for their inclusion into the system:

1. They require yet very long calculation times and are usually run on powerful computers what makes them hardly operational at the level considered for the current development of the system.
2. They are usually 2-D models, i.e. they consider exclusively the data coming from one topographic profile (the topography being a fundamental factor in the distribution of the products) what prevents to have an output where the spatial distribution of the parameters calculated by the model could be represented.

3 Physical models implementation strategy

As mentioned previously, physical eruption models have usually been devised as independent tools devoted to the analysis of the behaviour of the eruptive phenomena they represent.

270 Risk Analysis

Therefore, the possibilities of data exchange with external programs have been rather limited as usually they use their own internal data storage formats, what has rendered the communication with other programs difficult.

The integration of the physical models into the calculation structure of the volcanic risk assessment system could be achieved making use of two main methods: (1) the adoption of the data storage formats of the models to the one (usually more standard) used by the GIS package, keeping their independence in terms of communication with the user and calculation procedures or (2) the complete restructuring of their display, communication and storage characteristics in order to incorporate them into the system's architecture.

Regarding the first possibility, most of GIS packages allow the execution of external programs, although there would be still the need to develop routines to read the selected simulation parameters and to devise an interface common to the one used by the system in order to keep the coherence in the communication with the user. Furthermore, access to the system's databases from the model module would not be possible.

On the other side, the complete incorporation into the system might involve a longer programming task, due to the complex calculations that some of the models carry out, and still there would be the need to develop a common user interface, but the constraints related with the access to the system's databases and the transfer of simulation parameters would be avoided.

Taking into account the wide availability of accessible software development tools that can make feasible either the incorporation of the models' calculation routines into the GIS or the development of a user interface, the second method has been selected to implement the models.

The adoption of this approach means that the models have to be integrated in the system's architecture in such a way that could not be possible to distinguish them from the rest of the system. For this reason, their performance characteristics have to be defined according to the system's requirements.

3.1. Models performance requirements

Taking into account that there is a variety of parameters and databases that the models to be implemented use to carry out the simulations and that each of them follow a different way to carry out the calculations, a series of general common requirements to be fulfilled by all the models has been identified as a first step towards implementation.

From this basis, particular implementation requirements will have to be considered for each of the models according to their characteristics.

The general requirements have been identified taking into account the performance and communication issues that users can ask from the system and the possible tasks related to the simulation process. The most significant ones are the following:

- All the models to be implemented will make use of a standard communication interface to avoid that the users will have to learn on the particulars of each of them.
- They must incorporate full display capabilities in order to help users to select the area where the simulation is to be run.
- Each of them will have to provide the users with an easy and interactive way of selecting the required simulation parameters, that will have also to be clearly identified in the interface.
- They must provide the possibility of accessing, when needed, the information available in the system's databases in order to get help regarding any variable that might have a weight in the definition of the simulation scenarios.
- They must be able to generate risk scenarios in near real-time.
- They will store information according to the system's data storage formats, allowing the free flow of data from and to the GIS platform selected.

4 Models implementation

Once the main models' performance requirements have been established, the next development stage regards their incorporation to the calculation structures.

As an initial implementation phase, the incorporation of a lava flow and a fall-out simulation models has been carried out. The selection of these phenomena as the first to be incorporated is based on criteria such as the tested models' accuracy, the code availability, the high frequency of occurrence of these phenomena and their potential damaging effects on the human environment.

To carry out the implementation, the code of each of the models had to be translated to the programming language selected to develop the system (Visual Basic 5 Pro) and the corresponding interface had to be designed.

In order to test if the models, once implemented, fulfil each of the requirements established in the previous phases of the study, the

272 Risk Analysis

databases required for simulation and, information regarding the most adequate simulation parameters were gathered from active volcanic areas where one or both phenomena have occurred in the past.

This way, a set of data from Tenerife (Canary islands, Spain) has been used to check the lava flow model and data from the area of Campi Phlegrei (Italy) has been gathered to work with the fall-out model.

As the models implemented have already been tested previously for performance at the study areas selected and the pieces of code where the simulation algorithms are described have not been modified, a detailed analysis of the simulation results has not been carried out.

4.1. Lava flow model general characteristics

The lava flow model implemented has been built taken into account the design and calculation characteristics of the model developed by Felpeto et al.⁹.

In this model, it is assumed that the topography plays the main role in the definition of the path that will be followed by the flow and the calculations are carried out in raster format.

From the pixel that represents the emission vent (to be provided), it is considered that the flow can propagate to any of its neighbours. The probability that the lava will flow onto a certain pixel is proportional to the difference in highness between both of them, taking into account that there is no possibility for the flow to propagate against the slope.

Applying a Monte Carlo algorithm, the model calculates one possible path for the lava flow. This process is repeated a great number of times and, finally a recount of the times that each pixel has been selected.

4.2. Fall out model general characteristics

The fall out model implemented has been built taken into account the design and calculation characteristics of a model developed by Macedonio et al.¹⁰.

The model is based on a physical model which describes diffusion, transport and sedimentation of particles (ash) in two dimensions from one or more point sources. The dispersion of the particles in the atmosphere takes place under turbulent diffusion and wind transport (a reasonable assumption at large distances from the crater), whereas the fallout is controlled by the particles settling velocity, resulting from the action of the gravity force and the air drag.

The model can be used either to simulate the mass distribution of the deposit if a wind profile is given ("deposit mode"), or to define the probability of a given accumulation of mass on the ground if multiple wind profiles are provided ("probability mode").

It needs to run the definition of the physical system: spatial distribution of the point sources, total erupted mass, grain size distribution, wind velocity profile, atmospheric turbulent diffusion coefficients. The output values are expressed in terms of the mass accumulated on the ground or the probability of mass accumulation depending on the calculation mode selected.

5 Future model implementation issues

In order to complete the modelling capabilities of the system, the implementation of models representing other volcanic phenomena will be taken into account into the future and new volcanic datasets will be incorporated into the system.

A main task to be carried out in order to develop an operational system is the establishment of full interconnection capabilities with the rest of the elements or modules that will make part of the system devised to carry out volcanic risk assessment, in order to assure that the troubles found in our first stages of development have been completely solved

The main constraint related with the implementation of the models in the system arises from the fact that most GIS packages have their own data storage formats, what means that the routines devised will be tightly linked to the characteristics of the GIS software package selected for implementation. The solution of this constraint falls out of the scope of the current project, but will be considered in future developments.

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274 Risk Analysis

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