How to model ballistics with the model Great Balls of Fire (GBF)

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Introduction The aim of the exercise is to familiarize with the model "Great Balls of Fire" (GBF), a dedicated software for the simulation of large clasts trajectories ejected from volcanic vents written by Sebastien Biass, Jean-Luc Falcone and Costanza Bonadonna (Biass et al., 2016). For those of you interested in modeling ballistics and the associated hazard assessment we warmly reccomend you to visit the webpage of GBF (*https://e5k.github.io/pages/gbf*).

In this exercise we will learn how to use the code and how different parameterizations of the input file affect the final output. No hazard assessment is treated in this exercise. The final goal of this one-hour exercise is to be capable of running the code, to understand the structure of the code and to learn basic concepts about the physics behind the trajectories of volcanic bombs and blocks.

1 Exercise

1.1 Getting started with GBF

The main folder of the exercise is "gbfCERG". Inside the folder you will find three subfolders: "doc", "post-processing", "simulator". Click on "simulator" and open the matlab file "forwardMainGBF.m". This is the main file from which we can set-up and modify the input needed for a correct simulation of the model.

The modified version of GBF created for the exercise consists of a single Java ARchive file (JAR) that reads the input file "listImpacts.dat" stored in "simulator/config". The output file of the simulation is instead "listImpacts.dat" and it is stored in "simulator/results". As a matter of fact, Matlab is simply used to create the input file required by GBF and to plot the final output.

EXERCISE 1.1

In this initial part of the exercise you are going to familiarize with the structure of the program and to run your first preparatory simulation.

1. Open the file "forwardMainGBF.m" in the folder "ballistics/gbfCERG/simulator". Type "pwd" in your command window to verify the correct path.
2. In your command window type: "outputTable = forwardMainGBF;". Verify that your simulation run correctly: can you see the map of Vulcano Island with the position of single clasts (in red)?

1.2 How to modify the input file?

Each simulation requires a specific input file in order to be correctly executed. Arbitrary settings for the input file can be defined modifying the lines 26-40 in "forwardMainGBF.m". In the following, we report a short list of the parameters that can be modified by the external user during the exercise:

- `data.N_objects`: number of clasts released from the vent in a single simulation.
- `data.density_mean`: mean value of the Gaussian distribution for clast densities $[kg/m^3]$.
- `data.density_std`: variance of the Gaussian distribution for clast densities $[kg/m^3]$. Clasts have a unique density if it is set to zero.
- `data.phi_mean`: mean value of the Gaussian distribution for clast sizes, expressed in phi-scale. We remember that the phi-scale is defined as: $d_{cm} = 0.1 \cdot 2^{-\phi}$, where d_{cm} is the clast diameter expressed in cm.
- `data.phi_std`: variance of the Gaussian distribution for clast sizes, expressed in phi-scale. Clasts have a unique size if it is set to zero.
- `data.velox_mean`: mean value of the Gaussian distribution for clast velocities $[m/s]$.
- `data.velox_std`: variance of the Gaussian distribution for clast velocities $[m/s]$. Clasts have a unique velocity if it is set to zero.
- `data.angle_tilt`: angle of the central line of the ejection cone measured from the vertical axis ($\theta = 0 \longrightarrow vertical$) $[deg\ °]$.
- `data.angle_spread`: spread of the ejection cone measured from the central axis of the cone.
- `data.angle_azimuth`: azimuthal angle of ejection measured from north to east, clockwise $[deg\ °]$.
- `data.wind_intensity`: constant velocity of the wind $[m/s]$.
- `data.wind_direction`: wind direction measured from north to east, clockwise $[deg\ °]$.
- `data.X_vent`: eastern coordinate of the vent $[m]$.
- `data.Y_vent`: northern coordinate of the vent $[m]$.
- `data.reduced_drag`: radius of the circle around the vent where a reduced drag formula is applied $[m]$.

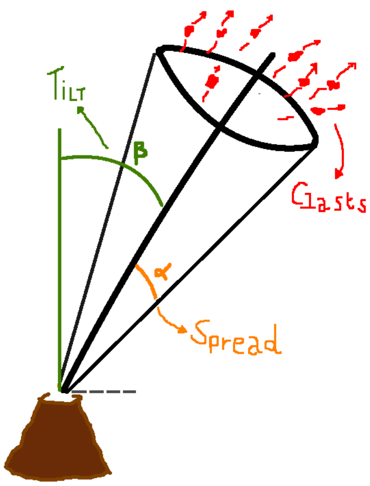

Figure 1: Sketch to clarify the meanings of tilt and spread angles.

EXERCISE 1.2
In this part of the exercise you are going to create your first input file.

1. Modify the input file in order to have 1000 clasts of 50 cm, with density 2000 kg/m^3, initial exit velocity of 200 m/s, with a tilt of 0° and a spread of 90°. No wind is required in this simulation. Set all the standard deviations equal to zero, except for the velocity (std velocity $= 50m/s$).
2. Do you think it is important to specify the azimuth of the simulation in the previous settings? Why?
3. Could you simulate an ejection of clasts that produces a straight line on the map, for example, at azimuth 90°? (hint: pay attention to the spread angle and the standard deviations).

1.3 Output of the simulation: table and plot

The model is executed simply typing "outputTable = forwardMainGBF;" in your command window. Two types of output can be obtained: first, a plot of the final position of the clasts over the DEM; second, the table "outputTable" where all the information of the ejected clasts is stored. This table will appear in workspace after the simulation. It is organized as follows:

- column 1: eastern coordinate of the i-esim clast [m].
- column 2: western coordinate of the i-esim clast [m].
- column 3: altitude on the DEM of the i-esim clast [m].
- column 4: mass of the i-esim clast [kg].
- column 5: diameter of the i-esim clast [m].
- column 6: kinetic energy of the i-esim clast at the impact [J].
- column 7: incident angle at the impact [degrees].
- column 8: ejection angle of the i-esim clast with respect to the vertical [degrees].
- column 9: azimuthal angle of ejection, measured from north to east clockwise [degrees].
- column 10: initial velocity of the i-esim clast [m/s].
- column 11: total time of flight of the i-esim clast [s].

EXERCISE 1.3
In this part of the exercise you are going to understand the output table.

1. Modify the input file in order to have 5.000 clasts of 75 cm, with density 1200 kg/m^3, initial exit velocity of 200 m/s, with a tilt of 0° and a spread of 90°. Wind is absent. Set all the standard deviations equal to zero, except for the velocity (std velocity $= 50m/s$).
2. Knowing that the eastern, northern and altitude coordinates of the vent are respectively (496634, 4250706) [m], what is the closest clast to the vent? And the furthest? (Hint: remember that the distance between two points on a plane is $d = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}$).
3. Using the function "hist" of Matlab, verify that the initial velocities are Gaussian distributed. (Hint: if you type "close all; hist(outputTable(:,number of the column for velocity))" ...).

4. In the output table no explicit information of the final velocities of the clasts is reported. Hoo do you think it is possible to derive this information? What is the highest impact velocity measured in your simulation? (Hint: create a vector with final velocities, derived from the output table. Then use the function "max" to calculate the maximum velocity at the impact).

1.4 Effect of the drag

The equation of motion solved numerically by the GBF is the following:

$$\vec{\boldsymbol{a}} = \vec{\boldsymbol{g}} - \frac{\rho_a \, A \, C_d \, |\vec{\boldsymbol{u}}| \, \vec{\boldsymbol{u}}}{2m} \tag{1}$$

The first term describes the effect of the gravitational force exerted by the Earth; the second term is the drag force exerted by the surrounding gas over the surface of the clast. The drag force is a function of: gas density ρ_a; projected area of the clast A; particle velocity $\vec{\boldsymbol{u}}$; particle mass m; drag coefficient C_d. The drag coefficient is a complicated equation that depends in turn on the particle Reynolds number of the clast. The GBF assumes $C_d \approx 0.1 - 0.5$, with a reduced drag for distances smaller than r_d (the reduced drag radius):

$$C_{d-eff} = \begin{cases} C_d \, (\frac{r}{r_d})^2, & \text{if } r < r_d \\ C_d, & \text{otherwise} \end{cases} \tag{2}$$

The reduced drag is justified under the assumption that at the beginning of the explosion clasts are ejected together with an expanding mass of gas. This results in a reduction of the effective drag around the object.

EXERCISE 1.4

In this part of the exercise you are going to think more in detail about the meaning of the drag force and its effects on the trajectories of the clasts.

1. Modify the input file in order to have only 1 clast of 100 cm ejected, with initial exit velocity of 200 m/s, a tilt of 35° and a spread of 0°. Wind is absent. Set all the standard deviations equal to zero (also for velocities). Try three different values of `data.reduced_drag`: 200 m (the default value), 2 m, 20 m. What do you observe on the final distances of the clast? Why?

2. Now run the same simulation as in the previous point, but change the input file in order to have only 1 clast of 20 cm. What do you observe?

3. Compare the final distances on the map for the 100 cm and 20 cm clasts (just focus on `data.reduced_drag` = 200 m). Which object travelled further? Why?

1.5 Analyzing the energies of the impacts

An important aspect related to ballistics is the quantification of the kinetic energy associated with the impact. This point is crucial for hazard assessment, both for the structural damage of the buildings and the phyisical consequences to people (see for example Tab.1).

Roofing material	Impact energies required for penetration (J)
Glass skylights/windows	0.15-2
Tile (clay or terracotta)	10-80
Fibre reinforced concrete sheet	20-85
Timber boards	60-500
Metal sheet	400-1000
Reinforced concrete slab	4000-12000

Table 1: Likely ranges of impact energies required by to penetrate a range of roof types, assuming typical thickness and average condition (from (Jenkins et al., 2016)). In addition, biomechanical experiments have shown that a dynamic load (such as a falling clast) can cause skull fractures at energies of around 28 J (Yoganandan et al., 1995).

EXERCISE 1.5

In this part of the exercise you are going to set a complete simulation for a large number of ballistics and display the final results in a histogram. The typical velocities tested in this simulation are characteristic of moderate Vulcanian explosions ($\sim 80 - 400\ m/s$).

1. Modify the input file in order to have 50.000 clasts of 70 cm (std $= 0\ cm$) and density 2000 kg/m^3 (std $= 0\ kg/m^3$), with initial exit velocity of 200 m/s (std $= 80\ m/s$), a tilt angle of 0° and a spread of 80°. Wind is absent. Using the function "hist", display the distribution of final kinetic energies before the impact. What is the mode of the distribution? And the minimum and maximum values? [Hint: create a vector with the final kinetic energies; use the functions "max", "min", "mode"].
2. Repeat the previous point with clasts of 25 cm of diameter (std $= 0\ cm$).
3. Repeat the previous point with clasts of 25 cm of diameter and a constant wind of 15 m/s and direction east. Do you see any major differences respect to the previous point?
4. Considering the range of impact energy you have obtained, which elements listed in Tab.1 would be affected?

References

Biass, S., Falcone, J.L., Bonadonna, C., Di Traglia, F., Pistolesi, M., Rosi, M., Lestuzzi, P., 2016. Great Balls of Fire: A probabilistic approach to quantify the hazard related to ballistics - A case study at La Fossa volcano, Vulcano Island, Italy. J. Volcanol. Geotherm. Res. 325, 1-14.

Jenkins, S. F., Spence, R. J. S., Fonseca, J. F. B. D., Solidum, R. U. and Wilson, T. M.: Volcanic risk assessment: quantifying physical vulnerability in the built environment, J. Volcanol. Geotherm. Res., 276, 105-120, doi:10.1016/j.jvolgeores.2014.03.002, 2014.

Yoganandan, N., Pintar, F. A., Sances, A., Walsh, P. R., Ewing, C. L., Thomas, D. J. and Snyder, Ri. G.: Biomechanics of skull fracture, J. Neurotrauma, 12(4), 659-668, doi:10.1089/neu.1995.12.659, 1995.