

Pyroclastic Flow from Soufrière Hills Volcano, Montserrat: Solid Block Model

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Abstract

The solid block model is applied to describe the motion of the pyroclastic flow under the joint action of gravity and Coulomb friction. Special attention is paid to characteristics of the pyroclastic flow generated by Montserrat volcano in likely directions. The critical friction angle of the flow propagation is evaluated empirically. Characteristic parameters of the pyroclastic flow (travel time and impact velocity) are well approximated by linear regressions. Proposed estimations of the parameters of pyroclastic flow are useful for the rough and express evaluation of its characteristics.

Keywords: Landslide Dynamics, Solid Block Model, Soufrière Hills Volcano

1. Introduction

The Soufrière Hills Volcano, Montserrat situated in the Caribbean (**Figure 1**) has been erupted since 1995. The activity of volcano has been carefully studied by [1-6]. Since 1995 three events have triggered the tsunami waves in December 1997 [7,8], July 2003 [9], May 2006 [10,11].

Various mathematical models were developed to describe the motion of the avalanche and the landslide dynamics [12-18]. The solid block model has been widely used [19-22] for rough estimations of landslide characteristics. Real and potential explosions of the Soufrière Hills Volcano were modeled using different models, see [7, 23-25].

In this paper special attention is paid to the characteristics of the pyroclastic flow generated by the Soufrière Hills Volcano. The travel time and the impact velocity of the pyroclastic flow are computed applying the solid block model in order to estimate potential debris avalanche hazard associated with the eruption of the Soufrière Hills Volcano.

2. Mathematical Model

According to the solid block approach, the pyroclastic flow is modeled as a solid block of a mass m sliding

down a tilted plane with a constant slope angle α , under the action of gravity mg , where g is acceleration of gravity, the friction F , and the normal force N . Let us consider a two-dimensional coordinate system XZ , **Figure 2**. The normal force N equals the component of the gravitational force:

$$N = mg \cos \alpha \quad (1)$$

The simple Coulomb friction law applied here is based on a constant basal friction angle δ that is an empirical property of the contacting materials:

$$F = \mu mg \cos \alpha, \quad \mu = \tan \delta. \quad (2)$$

The motion equation along x -coordinate is given by the second Newton's law:

$$\frac{d^2 x}{dt^2} = g \cos \alpha \sin \alpha - \mu g \cos^2 \alpha. \quad (3)$$

If we have the complex path of the pyroclastic flow which consists of several approximately constant slopes and the constant friction, the Equation (3) transforms into the set of equations

$$\frac{d^2 x_i(t)}{dt^2} = g \Psi_i, \quad \text{where } \Psi_i = \cos \alpha_i \sin \alpha_i - \mu_i \cos^2 \alpha_i, \quad (4)$$

and i is a number of the path. Previously, the equation of

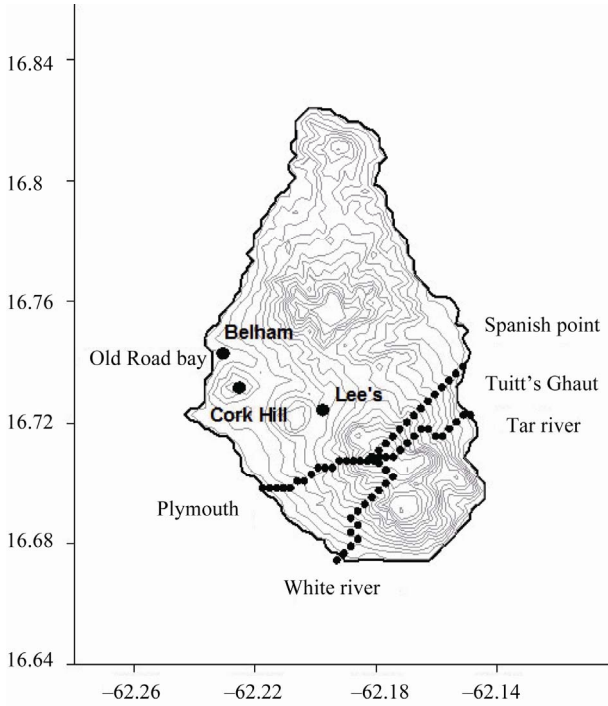


Figure 1. Montserrat Island, Lesser Antilles, Caribbean Sea.

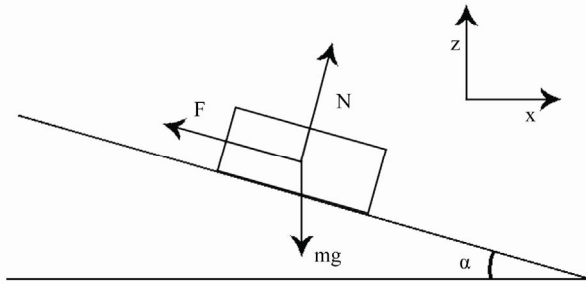


Figure 2. Model geometry: A block slides down a slope tilted α under the action of gravity force mg , friction F , and normal force N .

motion was solved numerically for paths of complex geometry for the snow-avalanche motion [26]. After integrating the Equation (4) we obtain the velocity of the pyroclastic flow in the end of the i -part:

$$v_i = g\Psi_i(T_i - T_{i-1}) + v_{i-1}, \quad (5)$$

where T_i is the travel time and v_{i-1} is the initial velocity on the start point of the i -part. The travel time is determined after the second integration of the Eq.(4)

$$T_i = T_{i-1} + \sqrt{B_i^2 + \frac{2L_i}{gF_i}} - B_i, \quad B_i = \frac{v_{i-1}}{g\Psi_i}, \quad L_i = x_i - x_{i-1}. \quad (6)$$

In case $\tan \alpha_i - \mu_i > 0$ the pyroclastic flow reaches

the sea, otherwise the pyroclastic flow stops if the initial velocity is not too high

$$v_{i-1} < \frac{\sqrt{2gL_i(\mu_i - \tan \alpha_i)}}{\cos \alpha_i}. \quad (7)$$

Of course, the Equation (3) can be easily integrated numerically for any mountain profile. In fact, all available digital maps have a resolution of several hundred meters, and the linear approximation of the profile is a natural spline. The approximation discussed here can be applied to study the dynamics of the pyroclastic flow if its horizontal scale of the pyroclastic flow is less than the length of each path.

Let us now apply this model to analyze the characteristics of the pyroclastic flow from the Soufrière Hills Volcano, Montserrat.

3. Characteristics of Pyroclastic Flow at Sea Entry

This simplified theoretical model is applied to calculate the parameters of the pyroclastic flow from the Soufrière Hills Volcano in directions of Tuitt's Ghaut, Plymouth, Tar River and White River valley, hereafter referred as likely directions.

To study the propagation of the pyroclastic flow, two parameters should be determined: Coulomb friction and initial velocity of the pyroclastic flow.

In fact, data of initial velocities of the pyroclastic flows from the Soufrière Hills Volcano is poorly documented. We can expect (see below) that the initial velocity has the same order as the mean velocity. Mean velocities of pyroclastic flows from the Soufrière Hills Volcano were measured earlier: 5 m/s - 30 m/s in 1996-1997 [27,28], 15 m/s in 2003 [2]. In fact, Calder *et al.* [29] suggested that velocity of dome-collapse flows was up to 10 m/s - 60 m/s. The simplified estimation of initial velocity can be done using the assumption that a dome collapses and falls as a free body in a crater achieving velocity $v_0 = \sqrt{2gh}$, where h is a height of lava dome. Assuming that it varies from 50 m to 100 m, the initial velocity attains 30 m/s - 40 m/s. These values argued with estimates by [29] are used in further calculations.

As for the basal friction angle, usually it is considered to be equal to $17^\circ - 30^\circ$ for the sand-textured debris [24] and $20^\circ - 40^\circ$ for the granular debris avalanche [30]. Previously the debris avalanche from Caribbean volcanoes was actively modeled [24,30,31] and appropriate basal friction angle was suggested to be rather small ($5^\circ < \delta < 8^\circ$ for Mt Pelée, Martinique and $13^\circ < \delta < 35^\circ$ for the Soufrière Hills Volcano, Montserrat). Earlier Heinrich *et al.* [24] suggested that the best agreement between calculated and theoretical data was

obtained when the small basal friction angle $13^\circ < \delta < 15^\circ$ is used. Furthermore, the motion of real landslides is governed by low values of the friction angle [24-30]. Considering these studies, values $8^\circ - 17^\circ$ are chosen to estimate the characteristics of the pyroclastic flow in the present study.

Below the pyroclastic flow from the Soufrière Hills Volcano is studied in likely directions.

3.1. Tar River Direction

According to results of the marine geophysical survey on the flanks of Montserrat, deposits are located 15 km offshore the Tar River valley [32]. During a period of heavy rainfall on 29 July 2001 the low volume pyroclastic flows in the Tar River Valley continued for five hours before intensifying into large pyroclastic flows with surges [2]. Totally, three large lava dome collapses occurred in the Tar River Valley between November 1999 and July 2003 [2]; in July 2003 the pyroclastic flows impacted the sea and produced tsunami [9]. Small pyroclastic flows also occurred in the Tar River Valley in November-December 2009 [33].

Different splines of the volcano profile in the Tar River direction are demonstrated in **Figure 3**. The original spline represents 3'' resolution map presented in [34], **Figure 3(a)**. Various splines are used in order to study the sensitivity of the results to the resolution, see **Figures 3(b)-(d)**. First and second volcano profiles consist of 14 and 7 paths correspondingly, and a zone of an easy slope ($5^\circ - 12^\circ$) is clearly observed. The use of the small friction angle ($13^\circ - 15^\circ$) recommended previously by Heinrich *et al.* [24], and initial velocity of 30 - 40 m/s leads to deceleration and stop of the pyroclastic flow in the area of the top. Then, a long-distance steep zone with a maximum slope angle of 34° begins; and finally, a third easy zone 2000 m - 2250 m off the volcano peak is characterized by the moderate slope angle ($1^\circ - 12^\circ$). So, the first (original) and the second (approximated) profiles can be divided into three zones characterized by the different average slope angle, **Figures 3(a)** and **(b)**.

The third profile (**Figure 3(c)**) is rather homogeneous in terms of the slope angle; it varies smoothly from 15° to 5° . The last profile (**Figure 3(d)**) represents a linear approximation of the original one; the slope angle is equal to 14° . Calculations with the use of the initial velocity (30 m/s - 40 m/s) and the moderate slope angle ($\alpha < 17^\circ$) show that neither third nor fourth profiles "obstruct" the propagation of the pyroclastic flow; and it reaches the sea.

Thus, results are sensitive to the resolution of the profile, and the use topographic maps of low resolution can lead to improper conclusions.

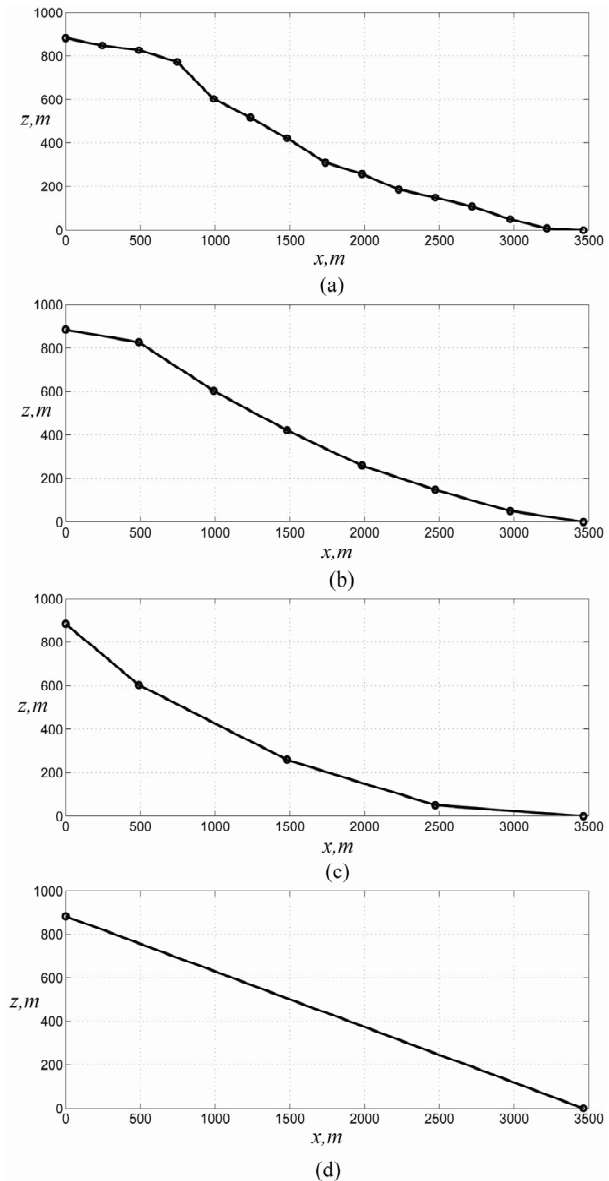


Figure 3. Profile of Tar River valley in different resolutions: original (a), small (b), moderate (c), linear approximation (d).

The use of small friction angle ($8^\circ - 15^\circ$) and the initial velocity of 40 m/s permit us to observe some peculiarities of the pyroclastic flow: in terms of the spatial and temporal variation of the velocity, it is described rather fairly when the first and second profiles are used (250 m and 500 m); the effect of the easy slope that decelerate the pyroclastic flow, is observed 500 m - 700 m from the volcano peak, **Figure 4**. Then, the velocity decreases slightly hundred meters off the shore.

As for the travel time, it does not exceed 2 minutes, **Figure 4**. The pyroclastic flow stops on the top of the volcano when the initial velocity of 30 m/s - 35 m/s is

used. A case of maximum initial velocity is specially studied here because it permits to estimate the minimum travel time that is important in terms of time alert. As mentioned, results are sensitive to the resolution of the profile, and the moderate (250 m and 500 m) and the original resolution (250 m) is used in order to obtain reasonable data.

Let us study the critical parameters of the pyroclastic flow for moderate resolutions (250 m - 500 m). As discussed earlier, the pyroclastic flow stops when the moderate resolution is applied. The proposed range of unknown parameters (the initial velocity and the friction angle) is used to identify the “behavior” of the pyroclastic flow. The critical values of the friction angle vary from 12° to 15.5°. The pyroclastic flow stops when the critical value is exceeded (other conditions being equal). For example, the pyroclastic flow does not reach the sea when the initial velocity is 33 m/s and friction angle exceeds 13° in case of moderate resolution, see **Figure 5(e)**. The critical friction angle is evaluated empirically from the performed calculations for the moderate resolution, and the linear regression has the following form:

$$\delta_c = 0.3 \cdot v_{int} + 2.5, R = 0.94, \quad (8)$$

where v is in m/s, hereinafter R is a coefficient of correlation.

Two parameters of the propagation of the pyroclastic flow (the travel time and the impact velocity) are specially studied for the original resolution. Calculations are produced for different initial velocity (30 m/s, 35 m/s and 40 m/s), and a wide range of the friction angle (8° - 17°), **Figure 5(i)**. In general, the travel time does not exceed 2 minutes. The travel time is can be approximated by the following equation:

$$T_{Tar\ River} = 5 \cdot \delta + 13 \quad R = 0.79, \quad (9)$$

where T is in seconds, the friction angle δ is in degrees. In all cases the impact velocity does not exceed 100 m/s. A minor rise of the basal friction angle reduces significantly the velocity of the pyroclastic flow. For example in a case when the initial velocity is 40 m/s, the sought parameter decreases twice (from 80 m/s to 40 m/s) while basal friction angle increases from 10° to 14°, **Figure 5(m)**. The impact velocity v can be fitted by

$$v_{Tar\ River} = -10 \cdot \delta + 175, \quad R = 0.98, \quad (10)$$

where v is in m/s.

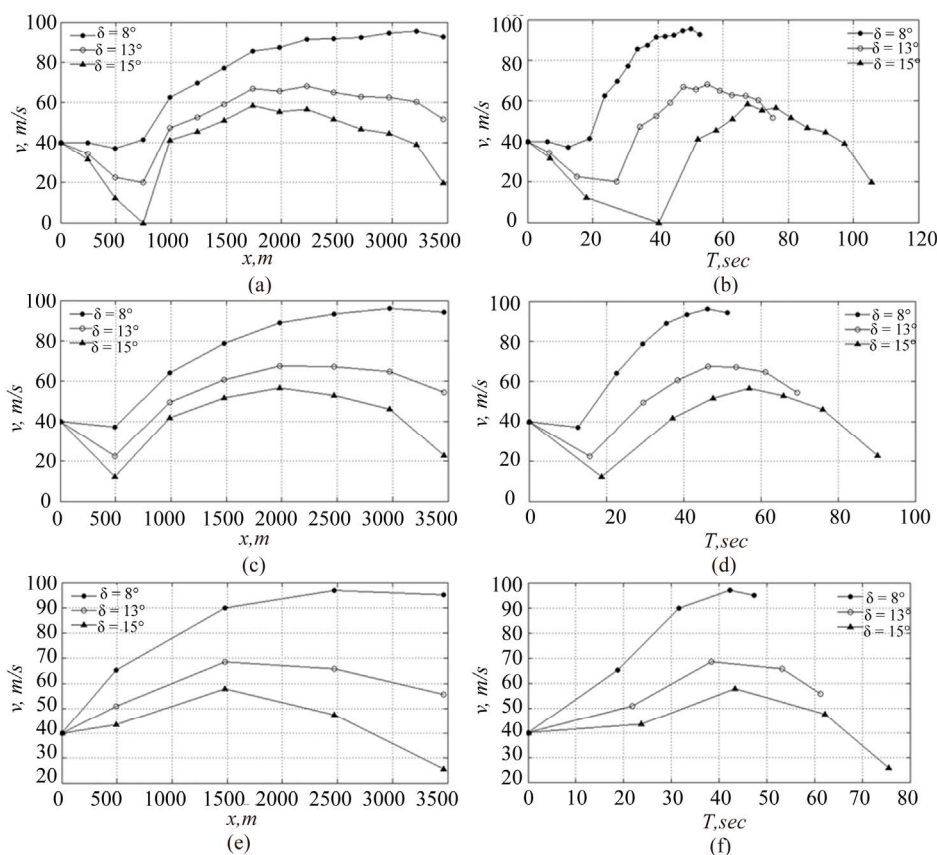


Figure 4. Velocity of the pyroclastic flow along the Tar river profile for the original (a,b), small (c,d) and moderate resolution (e, f): Velocity versus distance (left column) and velocity versus time (right column).

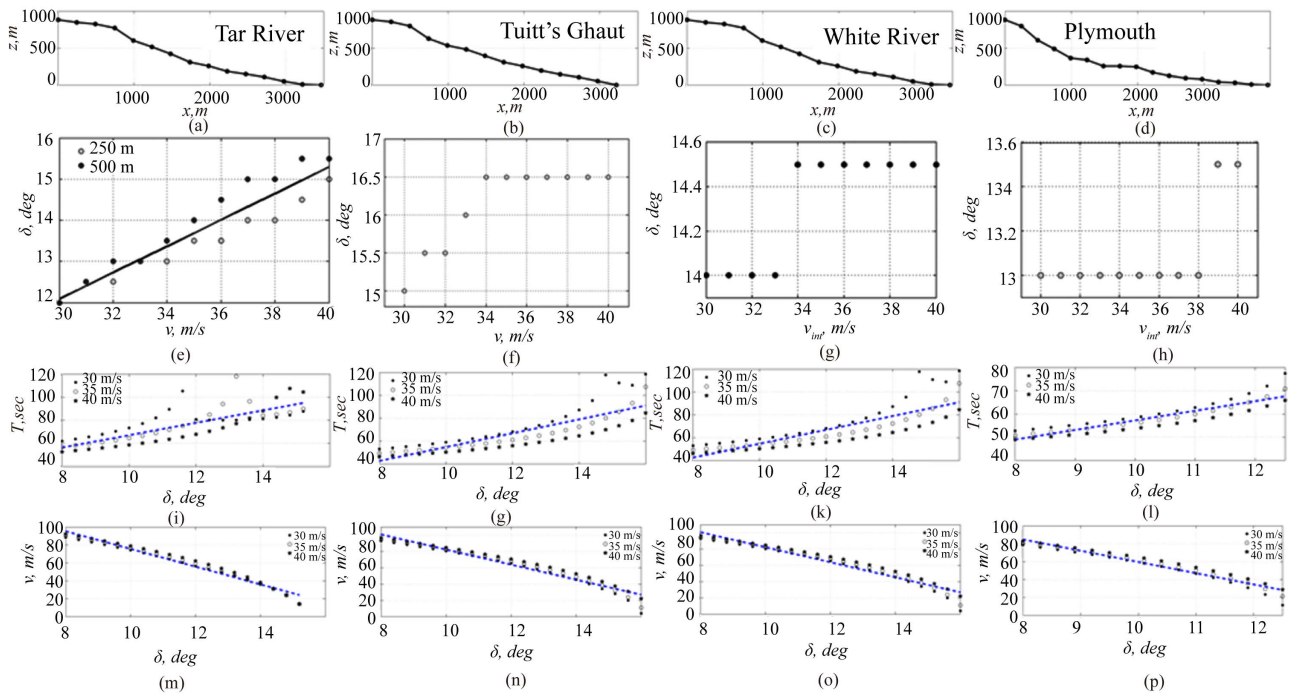


Figure 5. Parameters of the pyroclastic flow in likely directions: the original profile (a–d); the critical friction angle of the propagation (e–h); travel time (i–l); impact velocity (m–p).

3.2. Tuitt's Ghaut Direction

Since 1995 the northern side of the volcano has been strongly affected by the surge, by main and derivative pyroclastic flows [29]. Debris torrents occurred in Tuitt's Ghaut in mid-November, 2009 when a moderate flow was observed; followed by numerous torrents in the end of November. In December the runout distance of pyroclastic flows reached 2 km from lava dome; after several weeks of large pyroclastic flows, helicopter observations showed that the head of Tuitt's Ghaut was full of pyroclastic deposits [33].

Based on the topography data presented in [34], the splines of different resolution are examined, the original one is given in **Figure 5(b)**. It is interesting to mention that Tuitt's Ghaut is located close to the Tar River profile described in the previous section. Both profiles have a characteristic feature that influence the propagation of the pyroclastic flow: a zone of the steep slope is clearly observed 500 m from the top. This peculiarity makes the pyroclastic flow decelerate. In general, the Tuitt's Ghaut profile is rather homogeneous, with average slope angle 15° .

The study of critical characteristics appears to be very conclusive, see **Figure 5(f)** where calculated data for the original resolution of 250 m is given; the same values are obtained for the moderate resolution of 500 m. The critical angle varies from 15° to 16.5° being almost constant for the initial velocity more than 34 m/s.

Mean values of the significant parameters are studied using the same approach as described in the previous section. It takes about 50 - 100 seconds to cover a distance of 3200 m, **Figure 5(j)**. It bears repeating that time alert up to 1 - 2 minutes is rather short to claim the alarm. The deviation between values of the travel time obtained for different cases is rather big. The travel time can be approximated by a simple linear regression:

$$T_{Tuitts\ Ghaut} = 6 \cdot \delta - 6 \quad R = 0.82, \quad (11)$$

where T is in seconds, friction angle δ is in degrees.

According to calculations, the impact velocity varies from 30 to 100 m/s, **Figure 5(n)**. Considering the fact that during the period of high volcanic activity in November–December 2009 no pyroclastic flow reached the sea in this direction, it would appear reasonable to suppose that either real basal friction angle is bigger than 16° or initial velocity of the pyroclastic flow is less than 30 m/s. Deviation between obtained values of the impact velocity for different cases is rather insignificant, and a linear regression can be used to approximate this parameter,

$$v_{Tuitts\ Ghaut} = -9 \cdot \delta + 175, \quad R = 0.97, \quad (12)$$

where entrance velocity v is in m/s, friction angle δ is in degrees.

3.3. White River Direction

In December 1997 a debris avalanche and a pyroclastic

flow with a volume of $55 \cdot 10^6 \text{ m}^3$ were produced in White River valley [29]; this lateral blast is associated with the tsunami inundated 80 m inland at the Old Road Bay [7,8,35], see **Figure 1**; this event was actively studied [7,24,36]. This tsunami might have reached the neighbor island (Guadeloupe) situated about 50 km from Montserrat. Zahibo *et al.* [37] suggested that the eruption of Soufrière Hills Volcano represents a potential danger of distant tsunami. In October 2009 the pyroclastic flow deposits extended 3 km down the White River. In November - December 2009 small pyroclastic flows occurred in the White River valley. In November 2009 pyroclastic flows moved down Gingoos Ghaut (SSW from White River valley) to within 200 m of the sea [33].

Geographically, the White River profile is divided into 2 paths of different slope angle, the first one stretches for 500 - 700 m and is characterized by a big slope angle (up to 30°) that is followed by a steep path with a mean slope angle about 11° . The latter decelerates significantly the propagation of the pyroclastic flow [34], see **Figure 5(c)**.

Computed critical characteristics of the propagation of the pyroclastic flow (250 m resolution) are presented in **Figure 5(g)**. According to calculations, the pyroclastic flow does not stop and reaches the sea when splines of other resolutions are used. This peculiarity can be explained by the fact that there are no sudden changes of the slope angle and the pyroclastic flow is not decelerated.

For all profiles in the White River direction mean values of the travel time and the impact velocity are determined, **Figure 5(k)**. The travel time can be approximated by a following linear regression

$$T_{\text{White River}} = 4 \cdot \delta + 16, \quad R = 0.91, \quad (13)$$

where T is in seconds, the friction angle δ is in degrees. The impact velocity is also examined, and it is shown that the impact velocity decreases considerably when the basal friction angle is slightly modified, **Figure 5(o)**. A simple regression (14) is characterized by a high value of the coefficient of correlation R :

$$v_{\text{White River}} = -11 \cdot \delta + 178, \quad R = 0.97, \quad (14)$$

where v is in m/s.

3.4. Plymouth Direction

A former capital of Montserrat, Plymouth was abandoned after the eruption of the Soufrière Hills eruption in 1997. In June 1997 pyroclastic debris entered the Belham Valley, when a portion of the surge cloud detached to travel westwards of Cork Hill [4], see **Figure 1** for locations. Since then a partial dome collapse with pyroclastic flow activity has occurred once: on 8 January 2007 pyro-

clastic density currents were observed in Gages Valley.

The original geographical profile in the direction of Plymouth [34] is given in **Figure 5(d)**. It is characterized by a complicated geometry; it consists of several paths of different inclination. The first steep path that stretches for 1000 m is described by a big slope ($19^\circ - 38^\circ$), then another path begins ($6^\circ - 18^\circ$), after that a plain and extended zone is located. One more path is observed 2000 m from the volcano peak ($\alpha < 17^\circ$).

In **Figure 5(h)** critical characteristics of the propagation of the pyroclastic flow for the original resolution are presented; the same values are obtained for the resolution of 500 m. For a wide range of the initial velocity (30 - 38 m/s), the critical friction angle is the same (13°).

Let us discuss briefly peculiarities of the impact velocity and travel time, related with the geometry of the profile in the direction of Plymouth. The pyroclastic flow traverses 4000 m, from the top of the volcano to the sea shore, in a short period of time (50 - 80 seconds), but calculated values have a wide scatter, **Figure 5(l)**. As for the impact velocity, it depends significantly on the friction angle, **Figure 5(p)**. Both parameters can be approximated by linear regressions:

$$T_{\text{Plymouth}} = 4 \cdot \delta + 16, \quad R = 0.89, \quad (15)$$

$$v_{\text{Plymouth}} = -13 \cdot \delta + 185, \quad R = 0.97, \quad (16)$$

3.5. Discussion

A series of calculations are produced to estimate characteristic parameters of the propagation of the pyroclastic flow during eruptions of the Soufrière Hills Volcano, Montserrat. In the framework of the solid model key-characteristics of the pyroclastic flow are calculated for likely directions; and these profiles are rather similar in terms of the length and the slope angle, **Figure 6(a)**. The Tuitt's Ghaut and Tar River profiles situated close one to another, are characterized by a steep zone of top near volcano peak, and this characteristic feature influences the propagation of the pyroclastic flow (detailed description of this phenomenon is given in paragraph 3.1). As for the Plymouth and White River profiles oriented to the west, a zone of big slope angle is located near the peak of the volcano that makes the pyroclastic flow descend with acceleration. Another curious point to mention is that all profiles are similar over a distance of 2000 m from the volcano peak.

Critical parameters of the pyroclastic flow with the moderate initial velocity (30 m/s - 40 m/s) calculated for original profiles are specially compared, **Figure 6(b)**. For example, in the Tuitt's Ghaut direction, the pyroclastic flow stops when the friction exceeds $15^\circ - 16^\circ$, such conclusion seems to be closely related with the mean

value of the slope angle in this direction ($\alpha = 15^\circ$). In the Plymouth direction, the pyroclastic flow stops when the friction angle is equal to 13° that exceeds the mean slope angle ($\alpha = 12^\circ$). In general, the critical friction angle differs slightly for various directions being in a range from 12° (Tar River) to 16.5° (Tuitt's Ghaut). The range of critical angles for all profiles is rather wide. In the Tuitt's Ghaut direction (homogeneous with average slope angle $\alpha = 15^\circ$), the pyroclastic flow can propagate farther than in other directions (exactly what happened in October–November 2009).

Principal parameters of the pyroclastic flow are estimated for different profiles (250 m resolution) and moderate initial velocity (30 m/s - 40 m/s), **Figure 6(c)-(d)**. Although linear regressions are rather similar with the deviation of 15 - 20 seconds, the pyroclastic flow reaches the sea faster in case it propagates in the White River direction. It is notable that Heinrich *et al.* [24] who performed 3D simulation of the 1997 avalanche when pyroclastic flows were observed in White River valley, pointed out that the small friction angle ($13^\circ - 15^\circ$) gives the best agreement. It correlates with our results as the solid model approach demonstrates that torrents do not reach the sea in characteristic direction in case friction angle is greater than 16° .

Previously, the travel time of the pyroclastic flow was assumed to be 60 seconds by Heinrich *et al.* [36] who applied homogeneous fluid model to describe the motion of the pyroclastic flow in White River valley in December 1997. Later, Heinrich *et al.* [24] studied the same event considering the model of incompressible homogeneous fluid under the joint action of gravity and Coulomb friction and showed that the travel time attained 3 minutes that is close to our estimations. However, from the point of mitigation view, the time available to spread the alarm, is rather short. Earlier the potential danger of distant tsunami triggered by pyroclastic flow from the Soufrière Hills Volcano was discussed by [37]; recently, Bellotti *et al.* [38] studied the feasibility of Tsunami Early Warning Systems for small volcanic islands, and came to the conclusion that time available for detecting tsunamis and spreading the alarm is of the order of few minutes.

Another important parameter studied for all profiles is the impact velocity fitted by a linear regression, **Figure 6(d)**. The biggest values of the impact velocity are achieved in case of the Tuitt's Ghaut's profile. In general, the impact velocities are rather important in terms of possible tsunami generation. Previously Heinrich *et al.* [36] obtained that the pyroclastic flow reached the sea in a minute with velocities of 80 m/s. That is close to our calculations obtained in the framework of the solid model in case of small friction ($9^\circ - 10^\circ$). Previously, Heinrich *et al.* [7]

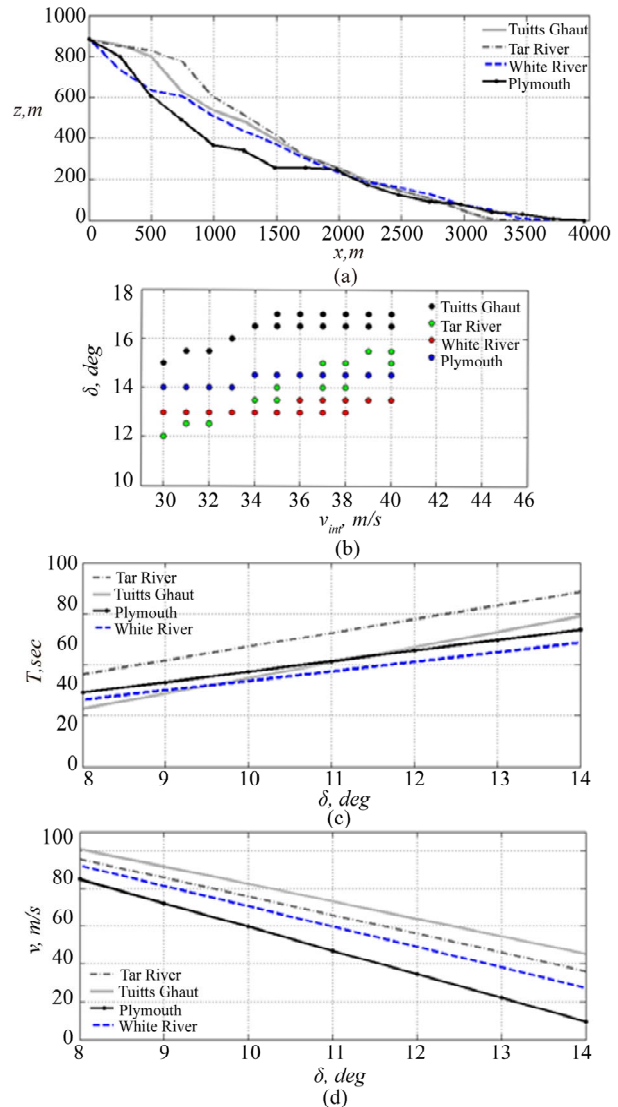


Figure 6. Calculated parameters of the pyroclastic flow in the likely directions: original profiles (a); the critical friction angle of the propagation (b); travel time (c); impact velocity (d).

studied tsunami simulation from Montserrat, and considered impact velocities from 25 m/s to 55 m/s. The same values are obtained in the framework of our approach for large initial velocity of the dome collapse (35 m/s - 40 m/s) and moderate values of the friction angle ($13^\circ - 15^\circ$).

Thus, main characteristic parameters of the pyroclastic flow associated with possible tsunami, are quite similar for different likely directions, except the critical basal friction angle that differs significantly from 12° to 16.5° . This permits to give rough estimations of main characteristics required to analyze not only the propagation of the pyroclastic flow, but also tsunami generation.

In fact, the pyroclastic flow events associated with the small collapse of lava dome have been reported since

October 2009, but only few of them reached the sea; and no tsunami warning was issued [33]. No data about the volume of pyroclastic flows is available but according to our calculations, the pyroclastic flow does not reach the sea when its initial velocity is less than 20 m/s that correspond to collapse of dome 30 m height. So, theoretical predictions for small events are in agreement with observed data. At the present time due to continuous eruption of the Soufrière Hills Volcano, dome grows and thus the tsunami danger rises.

4. Conclusions

The application of the avalanche model, based on the solid block approach, is discussed here to describe the motion of the pyroclastic flow from the Soufrière Hills Volcano, Montserrat. Two parameters are determined to study the propagation of the pyroclastic flow: Coulomb friction and the initial velocity of the pyroclastic flow. The analysis of average characteristics of the pyroclastic flow is performed for different friction angles (8° - 17°), and moderate initial velocity of 30 m/s - 40 m/s. The theoretical model is applied to calculate parameters of the pyroclastic flow in the likely directions (Tar River, White River, Tuitt's Ghaut and Plymouth). Several resolutions of mountain profiles are used, and it is shown that results are sensitive to spline approximation and the use of the average slope angle leads to improper conclusions. At the same time, the original and slightly modified resolution (250 m - 500 m) make possible to describe the observed descend of the pyroclastic flow. The spatial and temporal variations of the velocity in case of the large initial velocity are specially discussed for the Tar River profile. It is shown that the propagation of the pyroclastic flow is described rather fairly in the framework of the applied theoretical model when small profiles are used (250 m and 500 m), and the effect of topography (the steep zone) that decelerates the pyroclastic flow, is observed. For all likely directions, the critical friction angle is evaluated empirically from performed calculations for the small resolution; it varies significantly from 12° to 16.5° for different profiles. Two parameters of the pyroclastic flow are particularly discussed: the travel time and the impact velocity, these characteristics are important from the point of view of tsunami generation. It is shown that both parameters are approximated by similar linear regressions for all studied directions. Generally, the impact velocity hardly exceeds 100 m/s. What is more, the insignificant variation of the friction acts very much on the impact velocity of the pyroclastic flow. The travel time does not exceed 2 minutes; and time available to spread the alarm is rather short; furthermore, volcano eruptions can represent a potential danger of distant tsu-

nami for coastal regions far from Montserrat Island that should be taken into consideration. Proposed estimations of the parameters of the pyroclastic flow in the framework of the solid model are useful for the rough and express evaluation of the characteristics of the debris avalanche.

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