G.U. Journal of Science
20(3): 79-85 (2007)

www.gujs.org

Effect of the Voellmy Coefficients on Determining Run-out Distance: A Case Study at Uzungöl, Turkey

Önder KOÇYİĞİT♠, İbrahim GÜRER

Gazi University,Faculty of Engineering and Architecture, Civil Engineering Department, Maltepe, 06570, Ankara

Received: 11.02.2006 Accepted:12.03..2007

ABSTRACT

In this study, the traditional Voellmy model which has been widely applied since 1956 for all types of avalanches was used in defining the path length to compute the run-out distance of avalanches that occurred in Uzungöl. Uzungöl, a village which is located in a valley of North-Eastern Anatolia was chosen as a pilot project area since some fatal snow avalanches occurred in this area in the 1992 winter season. Due to limited data and field observations, dynamic and turbulence friction coefficients were taken as μ= 0.155 and ξ= 500 m/s^2, respectively, for well defined slopes. Although it wasn't possible to check most of the computed values which need to be measured during an avalanche, the run-out distance was found to be determined quite accurately. A number of the Voellmy coefficients were tested to compute the run-out distance, and the effect of those coefficients on the hydraulic parameters of the avalanche, such as discharge, velocity and depth, was investigated.

Key Words: Voellmy coefficients, Run-out distance, Avalanche dynamic, Uzungöl

1. INRODUCTION

The number of avalanche incidents has dramatically increased in recent decades such that 66% of total avalanche events in Turkey occurred in the last 15 years [1]. A number of victims lost their lives in those avalanches especially in Eastern Anatolia, where highly mountainous regions exist. Two main reasons caused this catastrophic result. The first reason was the heavy winter conditions occurred in recent years and the second reason was that Turkey was unprepared to cope with an avalanche problem of that size. After facing a number of big avalanches resulting in loss of lives, collaborative research and international projects were thus undertaken between Turkey and some European Countries such as Switzerland and France within the framework of the International Decade of Natural Disaster Reduction (IDNDR) [1]. The resulting joint research project integrated to prepare hazard zone mapping in Turkey, to forecast avalanches, to educate local people and engineers in this field of avalanche research and finally to arouse the public's interest in avalanche incidents. Among the case study areas considered, Uzungöl village, which is placed in a typical countryside valley in Northeastern Anatolia, was preferred as a pilot project area (Figure 1). The reasons this village was chosen as a case study area were that the place is a winter tourist destination and that a vital avalanche occurred in the 1992 winter season resulting in loss of lives. The altitude of the avalanche track is between 1100 m and 2150 m and the track faces towards the north. There is a dense forest of coniferous trees around Uzungöl. However, very limited avalanche data was available for this area that could be used to forecast and model avalanches and to design avalanche protection structures. During the project [1], besides the existing meteorological station in the area, a special measurement device was used to collect required data regularly in the framework of this collaboration. Snow depths, wind direction and speed, density of snow, temperature of snow and snow-water equivalence were among some of the parameters that were collected. Those parameters were measured daily during the project period. A project team visited the area fortnightly and measured snow profiles and performed Ramsonde tests. However, essential parameters such as the avalanche velocity and density of flow for the path suggested by Buser and Frutiger [2], which enable the computation of the thrust pressure and the run-out distance could not be measured during the 1992 avalanche incident. Nevertheless, the Voellmy [3] approach, which has been widely used since 1956 for

♠Corresponding author, e-mail: konder@*gazi.edu.tr*

all types of avalanches, was applied in defining the track length to compute the run-out distances of avalanches in Uzungöl. In this study, various Voellmy coefficients have been discussed for the first time to analyse avalanches in Turkey and the aim of the paper is to suggest and help in finding appropriate Voellmy coefficients that can be applied to avalanches occurring in Turkey. Discussion of the formulae proposed by Voellmy [3] and Salm [4], [5] is not to objective of this paper.

Figure 1. Case study area: lake and settlement area in Uzungöl

2. LITERATURE REVIEW

Avalanche science first started in the former Soviet Union in the 1930s, and since then a vast amount of literature has been published. The earliest important attempt in modelling of avalanches made in the former USSR was not known in the West until recent years. The first avalanche model, developed by Tibilissi [6] in 1935, was documented after Bozhinskiy and Losev's[6] translation paper in 1998. The detail of the model concept can be found in Kozik [7]. As Salm [8] explained in his paper, Tibilissi introduced a model based on dry friction (Coulomb friction) as a frictional force which increases linearly with speed. Then, Voellmy [3] introduced his model, which consists of a velocity-squared term similar to the Chezy resistant for turbulent water flow in open channels (ξ) and Coulomb-like friction (μ). Today, the values of these parameters are still the subject of research [8],[9]. One of these studies is the comprehensive research based on the analysis of friction coefficients carried out by Buser and Frutiger [2], who calculated various μ and ξ values considering data obtained from 20 avalanche events which had very long run-out distances in different regions of Switzerland. In their studies, they found that μ=0.155, ξ=1120 m/s^2 for the Voellmy equation and μ=0.157, ξ=1067 m/s^2 for the Salm equation using the best fitting method. Apart from Voellmy and Salm models, many others have been developed parallel to the development in computer technology. Examples of such models are a model developed by Grigoryan et al. [10], which is based on hydraulic turbulent friction coefficient, Coulomb friction (μ) with an upper limit and PCM (Perla-Cheng-McClung) developed by Perla et al. [11], which depends on Coulomb friction (μ) and M/D (mass/dynamic drag) for terms proportional to squared velocity. Furthermore Brugnot and Pochat [12] proposed a model based on dry friction and dynamic drag coefficients while Maeno and Nishimura [13] suggested a model related to velocity by an exponential function. Norem et al. [14],[15] introduced a theoretical based model, called NIS (Norem-Irgens-Schieldrop) which is based on visco-elasto-plastic material. A detailed literature review about such models can be found in Sovilla [16]. As a statistical model, one early study was performed by Lied and Bakkehoi [17]. They assumed that there is regional homogeneity in avalanche behaviour in a specific mountain range and obtained the relationship between the run-out distances and a number of key parameters of the path profile. This idea has been applied by different researchers to different mountain series throughout the world [18]. In addition, both statistical and hydraulic continuum dense-snow avalanche models were carried out in the same study by Barbolini et al.[9] using five avalanche incidents. They found that Coulomb friction (μ) shows a closer relation to run-out distance than turbulent friction (ξ); and for hydraulic-continuum models, the debris deposition pattern is useful for selecting model coefficients, rather than relying purely on run-out distances. In recent studies, besides numerical models, various methods such as fuzzy approach have been tested to simulate avalanche movement. Some of these studies are Barbolini et al. [9], Turnbull and Bartelt [22], Barpi [21], De Toni and Scotton [20] and Sovilla et al. [19]. The common goal in most of these recent studies is to solve the governing equations of avalanche motion (i.e. mass and momentum conservation equations) with a specific solution procedure and track the motion of the avalanche from initiation to run-out. However, as Barbolini et al. [9] and Salm [8] pointed out, μ is a crucial parameter in terms of calculation of run-out distance or impact pressure. Salm [8] noted in his paper that despite the existence of some suggestions made in the literature about estimation of the μ coefficient for confined avalanches (for example, as done by Voellmy [3], Schaerer [23] and Savage [24]) an unconfined avalanche should also be observed where the development of speed has to be carefully measured with high resolution due to the starting point of the avalanche flow being on a relatively long constant slope angle.

3. GOVERNING EQUATIONS

Voellmy [3] described the primary mathematical model of snow avalanche motion. He established his model using a fundamental hydraulic theory with two resistive force contributions, one of Coulomb type, in which the shear force is proportional to the normal force, and the other of viscous type, in which the drag is assumed proportional to the velocity squared [25]. Voellmy's model is given as:

$$\frac{dv}{dt} = \frac{g}{\gamma \cdot h'}\left[h' \cdot (\gamma - \gamma_a) \cdot (\sin\psi - \mu\cos\psi) - \frac{\gamma}{\xi} v^2\right] \quad (1)$$

where v is the avalanche velocity, g is the gravitational acceleration, γ and γ_a=1.25 kg/m^3 are the densities of snow and air respectively, h' is the snow layer of vertically measured thickness, ψ is the angle of avalanche track slope, μ is the friction coefficient and ξ is the slip coefficient (turbulence). Of solving Equation (1), the maximum velocity can be expressed as;

$$v_{\max} = \left[h' \cdot \xi \cdot (1 - \frac{\gamma_a}{\gamma}) \cdot (\sin\psi - \mu\cos\psi)\right]^{1/2} \quad (2)$$

Velocity at starting zone (v_0) can be calculated using Equation (2), by taking h' as the snow depth at the starting zone (h_0) and neglecting the $\frac{\gamma_a}{\gamma}$ term, resulting in :

$$v_0 = \left[h_0 \cdot \xi(\sin\psi_0 - \mu\cos\psi_0)\right]^{1/2} \quad (3)$$

where ψ_0 is the angle of track slope at starting zone. Q, discharge of the avalanche, can be expressed in terms of open channel principles using the following relationship;

$$Q = B_0 \cdot h_0 \cdot v_0 \quad (4)$$

where B_0 is the channel width at starting zone. Run-out distance S was described by Salm [5] with a very similar form of Voellmy's run-out distance formula and was used to determine distances from the point P where the gradient of the track diminishes to about 9º or 10º [2]:

$$S = \frac{h_s \cdot \xi}{2g} \ln\left[1 + \frac{v_p^2}{v^2}\right] \quad (5)$$

where v_p is the velocity at point P and can be computed using the following equation for unconfined avalanches:

$$v_p = \left[\frac{Q}{B_p} \cdot \xi(\sin\psi_p - \mu\cos\psi_p)\right]^{1/3} \quad (6)$$

where B_p is the channel width of the path. For laterally confined or canalised avalanches, this relationship becomes [4],

$$v_p = \left[R \cdot \xi(\sin\psi_p - \mu\cos\psi_p)\right]^{1/2} \quad (7)$$

where ψ_p is the slope angle at point P, R is the hydraulic radius which is a ratio of the channel crosssectional area and channel "wetted perimeter". h_s is the deposit height and can be expressed as:

$$h_s = h_p + \frac{v_p^{\,2}}{10g} \tag{8}$$

where h_p is the snow depth at point P and can be calculated as:

$$h_p = \frac{Q}{B_p . v_p} \tag{9}$$

In Equation (5), v velocity can be determined as follows:

$$v = \left[h_s \xi (\mu \cos\psi - \sin\psi)\right]^{1/2}$$

Control section length (x) is a short distance in which flow is assumed to reach constant velocity and is located at the bottom of the avalanche track [4]:

$$x = \frac{0.7 \cdot \xi \cdot h_p}{g} \tag{10}$$

4.RESULTS AND DISCUSSIONS

Voellmy's modified model by Salm was applied to Uzungöl avalanche track. Results are summarized in Figure 2. As noted by Buser and Frutiger [2], two friction coefficients μ (dynamic friction coefficient) and ξ (turbulence coefficient) may be set to quite different values depending on the size, type and ground condition or track shape of the avalanche. For this reason, in this study different scenarios were considered and a number of different friction coefficients were tested to compute the run-out distance and the effect of those coefficients on the hydraulic parameters of the avalanche, such as velocity and depth of avalanches and observed run-out distance, was investigated. Following the avalanche incident in Uzungöl in 1992, field observations were carried out. Field observations proved that the coefficients used in this study assist to compute accurate run-out distance. Calculated hydraulic parameters such as velocity at starting zone (v_0) and in track (v), flow height (h), deposited height (h_s) and discharge (Q) are shown in Figure 2. Herein it should be noted that the avalanche discharge was assumed as constant along the path. Variation of the starting velocity, velocity along the path and the deposited snow depth against friction coefficients μ and ξ are listed in Table 1. The avalanche data in Table 1 was generated using Equations from 3 to 9 considering different scenarios for the Uzungöl case. As expected from the equations, higher ξ values produce higher velocities and deposited snow depths, whereas higher μ values retard the velocities and deposited snow depth. Conversely, variation of those coefficients has a pronounced effect on run-out distance as shown in Figure 3.

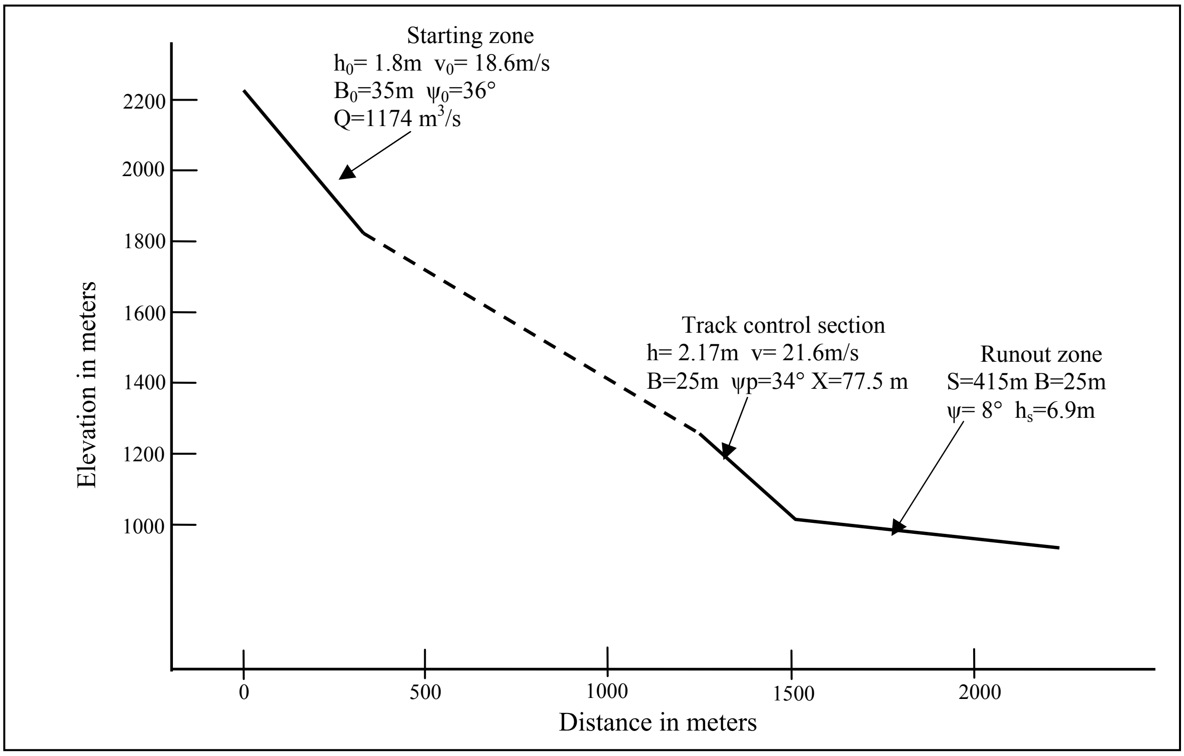

Figure 2. Voellmy-Salm model results for Uzungöl track (inspired from [26])

Run-out distance changes exponentially with μ values especially in the range of 0.16-0.25, while ξ has a linear effect on the run-out distance. In the Uzungöl case, the run-out distance is a crucial parameter to select accurate friction coefficient pairs. In addition to this, deposited snow depth is to be taken into consideration in choosing the pair of friction coefficients, since the run-out distance alone is not enough to determine precise values of the coefficients. For instance, if the run-out distance S≈400 m, Figure 3 shows that ξ may be in the range of 500-1000 while μ may change between 0.15 and 0.22. Whereas if deposited snow depth h_s is known assume h_s is about 7 m ξ may be set to 500 and μ may be a value in the range of 0.18 - 0.20 according to Table 1. However, as indicated in the extensive work of Buser and Frutiger [2], a number of suggestions exist in the literature to estimate that the friction coefficients and the results are quite different from one to another. For example, Voellmy [3] suggested a relation for the dynamic friction coefficient which is μ=ρ/2000 and here ρ symbolizes density of the snow (kg/m^3). For measured snow density ρ=300 kg/m^3, μ= 0.15 may be selected in the Uzungöl case study. For this application, μ_1=0.25 at starting zone, μ_2=0.155 in the track and ξ=500 m/s^2 along the track have been employed in the model.

Table 1. Variation of v_0(m/s), v_p(m/s), h_s(m) with μ (-) and ξ (m/s^2) for the Uzungöl case study

ξ \ μ		0.16	0.17	0.18	0.19	0.20	0.21	0.22	0.23	0.24	0.25
400	v_0	18.17	18.01	17.85	17.68	17.52	17.35	17.18	17.01	16.84	16.67
	v_p	19.85	19.66	19.47	19.28	19.08	18.89	18.69	18.49	18.29	18.09
	h_s	6.32	6.25	6.17	6.1	6.03	5.95	5.88	5.8	5.73	5.66
500	v_0	20.32	20.14	19.95	19.77	19.59	19.4	19.21	19.02	18.83	18.63
	v_p	22.19	21.98	21.77	21.55	21.34	21.12	20.9	20.67	20.45	20.22
	h_s	7.33	7.23	7.14	7.05	6.95	6.86	6.77	6.68	6.58	6.49
600	v_0	22.25	22.06	21.86	21.66	21.45	21.25	21.04	20.84	20.62	20.41
	v_p	24.31	24.08	23.84	23.61	23.37	23.13	22.89	22.65	22.4	22.15
	h_s	8.33	8.22	8.11	7.99	7.88	7.77	7.66	7.55	7.44	7.32
700	v_0	24.04	23.82	23.61	23.39	23.17	22.95	22.73	22.5	22.28	22.05
	v_p	26.25	26.01	25.75	25.5	25.25	24.99	24.73	24.46	24.2	23.93
	h_s	9.33	9.2	9.07	8.94	8.81	8.68	8.55	8.42	8.29	8.16
800	v_0	25.7	25.47	25.24	25.01	24.77	24.54	24.3	24.06	23.82	23.57
	v_p	28.07	27.8	27.53	27.26	26.99	26.71	26.43	26.15	25.87	25.58
	h_s	10.34	10.19	10.04	9.89	9.74	9.59	9.44	9.29	9.14	8.99
900	v_0	27.26	27.01	26.77	26.52	26.28	26.03	25.77	25.52	25.26	25
	v_p	29.77	29.49	29.2	28.92	28.63	28.33	28.04	27.74	27.44	27.13
	h_s	11.34	11.17	11	10.83	10.67	10.5	10.33	10.16	9.99	9.82
1000	v_0	28.73	28.48	28.22	27.96	27.7	27.43	27.17	26.9	26.63	26.35
	v_p	31.38	31.08	30.78	30.48	30.17	29.87	29.55	29.24	28.92	28.6
	h_s	12.34	12.16	11.97	11.78	11.59	11.41	11.22	11.03	10.85	10.66

5.CONCLUSION

Since this kind of avalanche model study has been performed for the first time in Turkey, the results of this particular case study can not provide sufficient proof for general application of these coefficient values in other avalanche tracks in Turkey. In order to be able to make a general comment on the variation of the friction coefficients in Turkey, it is recommended that this study to be repeated using different sets of avalanche data collected from different events where the data should be sorted out with statistical methods. However, there are some difficulties collecting data throughout avalanche motion and afterwards, since avalanche studies commenced recently (1994) in Turkey.

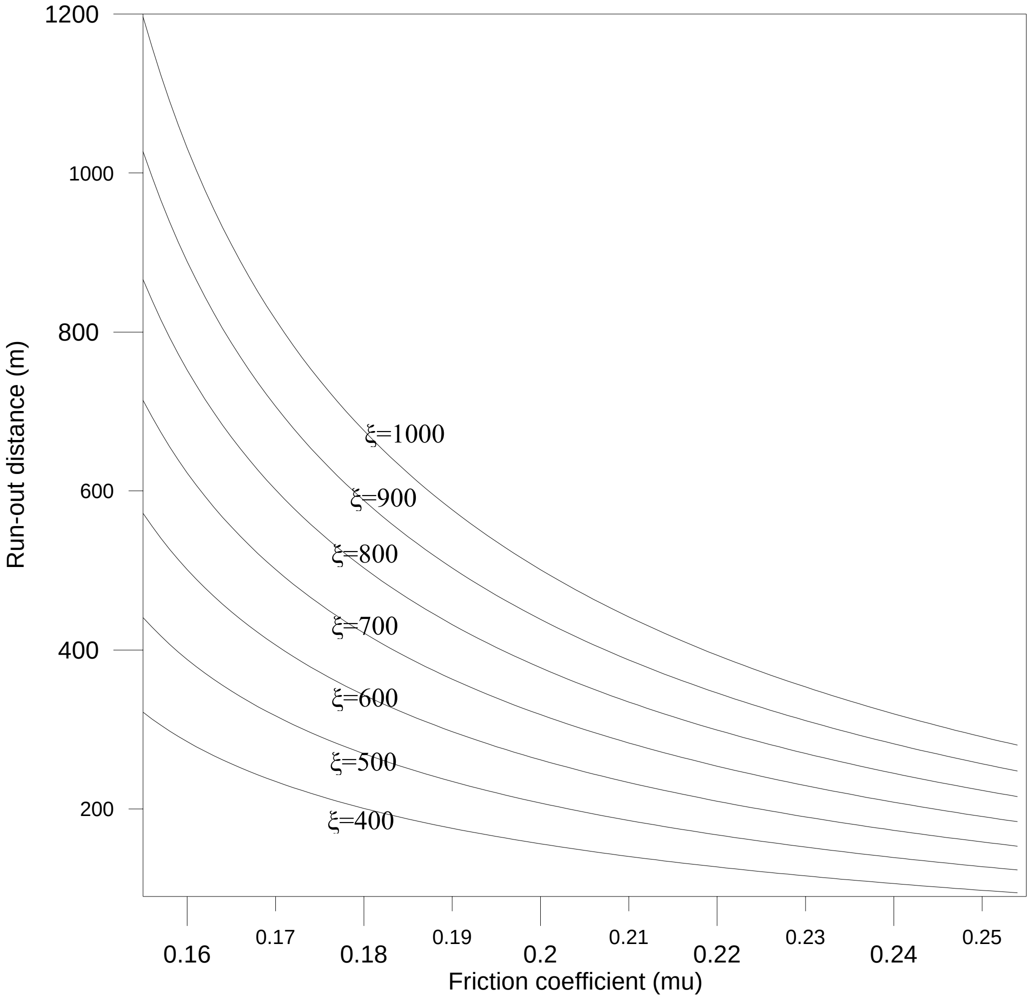

Figure 3. Variation of the run-out distance with (ξ ,m/s^2) and (μ, -) for the Uzungöl case study

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