Natural Hazards **32:** 395–412, 2004.

Reliability-Based Delineation of Debris-Flow Deposition Areas

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(First received: 26 July 2002; accepted: 27 August 2003)

Abstract. In this paper, a methodology is proposed for the delineation of debris-flow deposition areas. First, based on the theory of reliability, the delineated hazardous area is defined. Then, uncertainty analyses of all the uncertain parameters affecting the probable maximum length, width and thickness are performed. Finally, the proposed methodology is applied to an actual site susceptible to debris flow. It is found that the maximum deposition length is much more uncertain than the maximum deposition width. The delineated hazardous areas for various reliability are obtained using the inverse first-order second moment method. The proposed methodology is recommended for the delineation of debris-flow hazardous areas, because the influence of all the uncertain parameters is considered.

Key words: debris flow, deposition area, hazardous area, uncertainty analysis, reliability.

1. Introduction

Debris flows occur in many areas in Taiwan due to intense storms and steep slopes. Improper land use, such as deforestation and excavation of slopes for roads or buildings, deteriorates the situation. Many canyons in Taiwan are susceptible to debris flows. When the debris flow travels through the steep canyon and reaches the canyon mouth, the debris spreads over a broad area where developed areas are often found. An effective means to reduce the debris-flow hazards is the delineation of the threatened area, also referred to as deposition area or hazardous area herein, in advance. One can then control the development of the hazardous area or provide adequate warning devices.

Regarding the delineation of debris-flow hazardous areas, one needs to know how far and how wide the debris flows can deposit. Takahashi (1991) proposed empirical formulas for the probable maximum length and thickness of the debris-flow deposits. Major and Pierson (1992) made experimental analysis of fine-grained slurries. Shieh and Tsai (1997) constructed relationships among the maximum length, width and thickness based on experimental data. So far, the delineation of the debris-flow deposition area is limited to a deterministic approach. That is, the existing methods ignore the influence of the uncertain parameters on the probable

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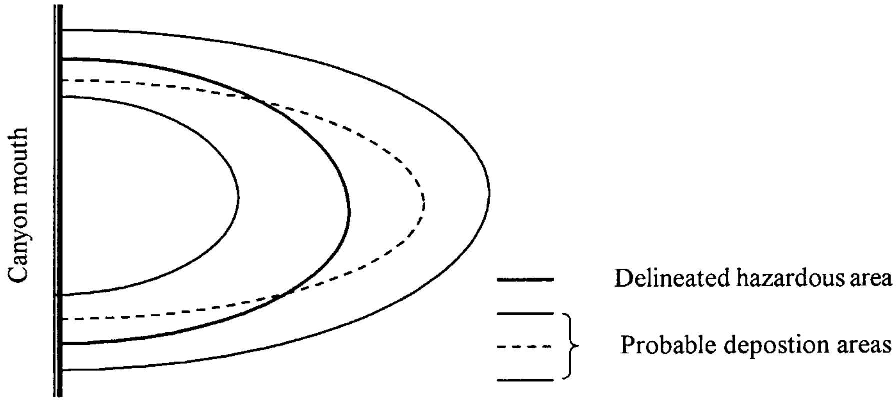

Figure 1. A schematic diagram showing the delineated hazard area and hypothetical probable deposition areas of debris flows.

maximum length, width and thickness. Hence, efforts on the search for a reliability-based methodology (Ang and Tang, 1984; Yen *et al.*, 1986; Mays and Tung, 1992) are justified.

The objective of this paper is to develop a reliability-based methodology for the delineation of debris-flow deposition areas. First, the delineated hazardous area is defined using the concept of reliability. Furthermore, uncertain parameters affecting the probable maximum length, width and thickness are identified and their corresponding means and standard deviations are derived. Finally, an actual application of the proposed methodology is performed. The delineated hazardous areas for various values of reliability are obtained.

2. Basic Theory

A common measure for reducing the damages of debris flows is the management of areas susceptible to debris flows. For such a purpose, one has to delineate an area for the site of interest first and declare it as a hazard-warning area. However, the actual deposition area may fall inside or outside the delineated area as shown in Figure 1. The probability that the actual deposition area falls within the delineated area is called reliability herein. The reliability r can be mathematically expressed as $r = \text{Prob}[R \geq L]$, where R is the delineated hazardous area, and L is the actual deposition area. It should be noted that only the area starting from the canyon mouth is concerned in this paper. Variables R and L can be referred to as resistance and loading, respectively, of a system according to the terminology of reliability analysis theory. Using the safety margin $\text{SM} = R - L$ as the performance function (Mays and Tung, 1992), then the reliability can be further expressed as

$$r = \text{Prob}[R \geq L] = \text{Prob}[\text{SM} \geq 0] = \text{Prob}\left[W \geq \frac{\mu_{\text{SM}}}{\sigma_{\text{SM}}}\right], \tag{1}$$

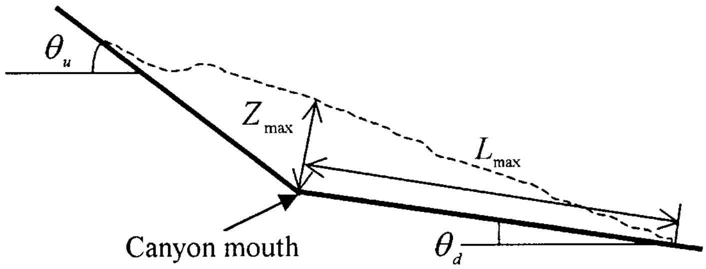

Figure 2. A sketch of the debris-flow longitudinal profile.

where $W = (\mathrm{SM} - \mu_{\mathrm{SM}})/\sigma_{\mathrm{SM}}$, and μ_{SM} and σ_{SM} are the mean and the standard deviation of SM, respectively. Assuming that the random variable W is normally distributed, one can obtain the reliability r as

$$r = 1 - \Phi(-\beta) = \Phi(\beta) \tag{2}$$

where $\beta = \mu_{\mathrm{SM}}/\sigma_{\mathrm{SM}}$ is the reliability index, and $\Phi(\beta)$ is the cumulative distribution function of the standardized random variable W.

3. Reliability-Based Delineation

In this section, the maximum length and width of the debris-flow deposition area are discussed. The maximum length and width corresponding to a given value of reliability are to be found. This problem is referred to as the inverse reliability problem.

3.1. THE MAXIMUM DEPOSITION LENGTH

When a debris flow reaches the canyon mouth (end of the flow channel), the debris will spread over flatter ground. The probable maximum deposition length $L_{\max}$ from the end of the flow channel (Figure 2) can be estimated from (Takahashi, 1991)

$$L_{\max} = \frac{\left\{U_u \cdot \cos(\theta_u - \theta_d)\left\{1 + \dfrac{[(s-\rho)\cdot C_{DE}\cdot K_a + \rho]\cdot\cos\theta_u}{2[(s-\rho)\cdot C_{DE} + \rho} \cdot \dfrac{gh_u}{U_u^2}\right\}\right\}^2}{\dfrac{(s-\rho)g\cdot C_{DE}\cdot\cos\theta_d\cdot\tan\alpha}{(s-\rho)\cdot C_{DE}+\rho} - g\cdot\sin\theta_d} \tag{3}$$

where θ_u is the bed slope of the flow channel (degree), θ_d is the bed slope of debris-flow fan downstream of the end of the flow channel (degree), g is the acceleration of gravity (m/s^2), s is the density of gravel (g/cm^3), ρ is the density of water

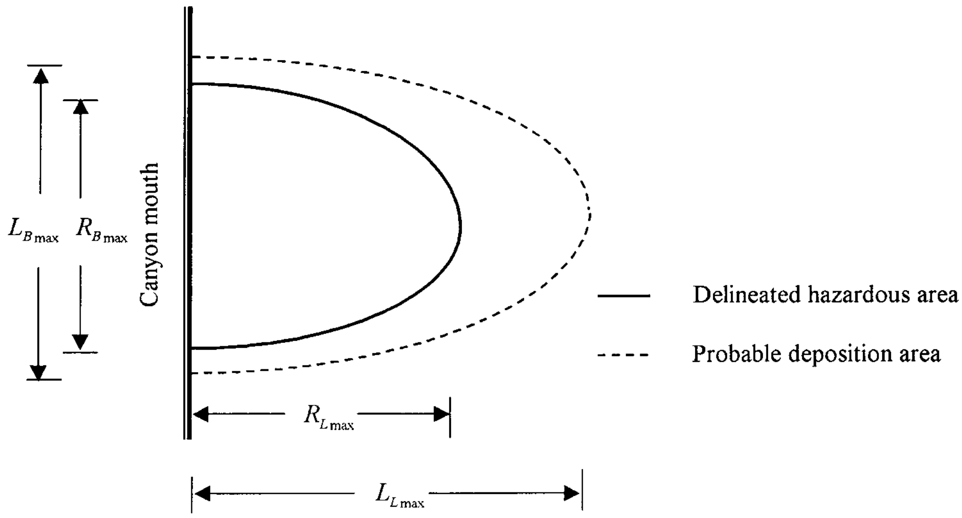

Figure 3. Sketch of $R_{L_{\max}}$, $L_{L_{\max}}$, $R_{B_{\max}}$, $L_{B_{\max}}$.

(g/cm^3), h_u is the average debris-flow depth in the flow channel (m), U_u is the cross-sectional mean velocity of debris flow in the flow channel (m/s), K_a is the coefficient of active earth pressure, α is the angle of dynamic friction (degree), and C_{DE} is the equilibrium debris-flow concentration. The values of parameters θ_u, θ_d, s, h_u, U_u, α and C_{DE} originate from measurement methods, field data, or the expert knowledge of the investigators. These parameters are considered as random variables herein. Hence, the safety margin for the maximum deposition length becomes

$$\mathrm{SM}_{L_{\max}}(\theta_u, \theta_d, s, h_u, U_u, \alpha, C_{DE}) = R_{L_{\max}} - L_{L_{\max}}(\theta_u, \theta_d, s, h_u, U_u, \alpha, C_{DE}) \quad (4)$$

where $R_{L_{\max}}$ is the delineated maximum length and $L_{L_{\max}}$ is the probable maximum length (Figure 3).

3.2. THE MAXIMUM DEPOSITION WIDTH

The probable maximum deposition width (Figure 4) at the canyon mouth (end of the flow channel) can be estimated from (Shieh and Tsai, 1997)

$$B_{\max} = \frac{V}{\kappa \cdot Z_{\max} \cdot L_{\max}} \quad (5)$$

where V is volume of debris flow (m^3), $Z_{\max}$ is the maximum deposition thickness (m), and κ is a coefficient varying from 0.220 to 0.235. V, $Z_{\max}$, $L_{\max}$ and κ are regarded as random variables herein and, hence, the safety margin for the maximum deposition width becomes

$$\mathrm{SM}_{B_{\max}}(V, \kappa, Z_{\max}, L_{\max}) = R_{B_{\max}} - L_{B_{\max}}(V, \kappa, Z_{\max}, L_{\max}) \quad (6)$$

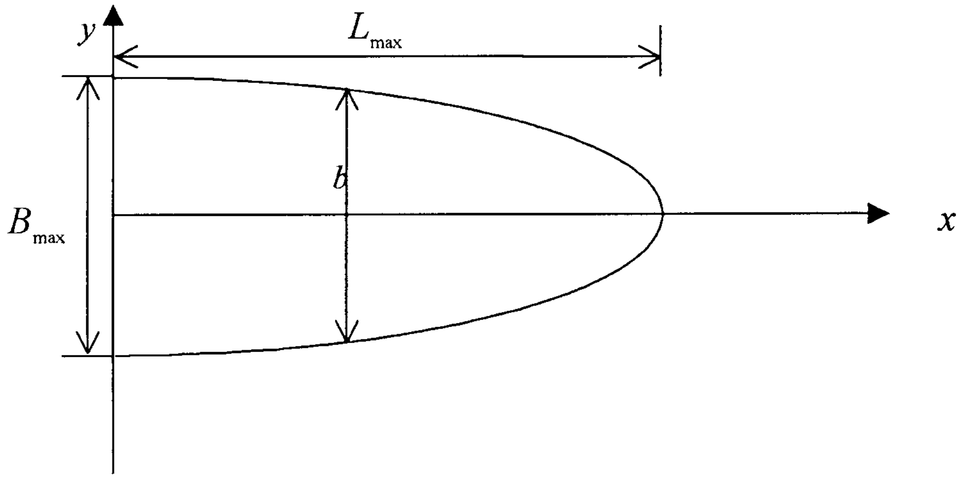

Figure 4. The top view of the deposition area.

where $R_{B_{max}}$ is the delineated maximum width and $L_{B_{max}}$ is the probable maximum width (Figure 3).

3.3. THE DEPOSITION AREA

In the common practices of reliability analysis, one wants to find the reliability. But here $R_{L_{max}}$ and $R_{B_{max}}$ for a given value of reliability r are to be found. The inverse first-order second moment method (Armen *et al.*, 1994) is used herein to obtain $R_{L_{max}}$ and $R_{B_{max}}$. According to the experimental results of Shieh and Tsai (1997), the shape of the deposition area (Figure 4) can be described by

$$\left(\frac{x}{L_{max}}\right)^2 + \left(\frac{b}{B_{max}}\right)^2 = 1, \quad x \geq 0 \tag{7}$$

where x is the distance from the end of the flow channel (m), and b is the deposition width at x (m). Once a set of $R_{L_{max}}$ and $R_{B_{max}}$ is obtained using the inverse first-order second moment method, replacing L_{max} and B_{max} by $R_{L_{max}}$ and $R_{B_{max}}$ in Equation (7) gives the delineated area corresponding to a known value of reliability:

$$\left(\frac{x}{R_{L_{max}}}\right)^2 + \left(\frac{b}{R_{B_{max}}}\right)^2 = 1, \quad x \geq 0 \tag{8}$$

4. Uncertainty Analysis of Maximum Length

To perform the reliability analysis, one has to estimate the means and standard deviations of the probable maximum length and width first. As Equations (4) and

(6) show, $R_{L_{\max}}$ and $R_{B_{\max}}$ are functions of random variables. Most of these random variables are in turn functions of other fundamental random variables.

As Equation (3) shows, the maximum deposition length $L_{\max}$ is a function of θ_u, θ_u, s, h_u, U_u, α and C_{DE}. Keeping only the first two terms in the Taylor-series expansion of $L_{\max}$ and taking the expectation, one can obtain the approximate mean of $L_{\max}$ as

$$\bar{L}_{\max} = \frac{\left\{\bar{U}_u \cdot \cos(\bar{\theta}_u - \bar{\theta}_d)\left\{1 + \frac{[(\bar{s}-\rho)\cdot \bar{C}_{DE}\cdot K_a + \rho]\cdot \cos\bar{\theta}_u}{2[(\bar{s}-\rho)\cdot \bar{C}_{DE} + \rho} \cdot \frac{g\bar{h}_u}{\bar{U}_u^2}\right\}\right\}^2}{\frac{(\bar{s}-\rho)g\cdot \bar{C}_{DE}\cdot \cos\bar{\theta}_d \cdot \tan\bar{\alpha}}{(\bar{s}-\rho)\cdot \bar{C}_{DE}+\rho} = g\cdot \sin\bar{\theta}_d} \tag{9}$$

where $\bar{\theta}_u$, $\bar{\theta}_d$, $\bar{s}$, $\bar{h}_u$, $\bar{U}_u$, $\bar{\alpha}$ and $\bar{C}_{DE}$ are means of θ_u, θ_d, s, h_u, U_u, α and C_{DE}, respectively. Similarly, keeping the same terms and finding the standard deviation, the approximate variance of $L_{\max}$ can be written as

$$\begin{aligned} S^2_{L_{\max}} = {} & \left[\frac{\partial L_{\max}}{\partial \theta_u}\right]^2_{(\bar{\theta}_d,\bar{s},\bar{h}_u,\bar{U}_u,\bar{\alpha},\bar{C}_{DE})} s^2_{\theta_u} + \left[\frac{\partial L_{\max}}{\partial \theta_d}\right]^2_{(\bar{\theta}_u,\bar{s},\bar{h}_u,\bar{U}_u,\bar{\alpha},\bar{C}_{DE})} s^2_{\theta_d} \\ & + \left[\frac{\partial L_{\max}}{\partial s}\right]^2_{(\bar{\theta}_u,\bar{\theta}_d,\bar{h}_u,\bar{U}_u,\bar{\alpha},\bar{C}_{DE})} s^2_s + \left[\frac{\partial L_{\max}}{\partial h_u}\right]^2_{(\bar{\theta}_u,\bar{\theta}_d,\bar{s},\bar{U}_u,\bar{\alpha},\bar{C}_{DE})} s^2_{h_u} \\ & + \left[\frac{\partial L_{\max}}{\partial U_u}\right]^2_{(\bar{\theta}_u,\bar{\theta}_d,\bar{s},\bar{h}_u,\bar{\alpha},\bar{C}_{DE})} s^2_{U_u} + \left[\frac{\partial L_{\max}}{\partial \alpha}\right]^2_{(\bar{\theta}_u,\bar{\theta}_d,\bar{s},\bar{h}_u,\bar{U}_u,\bar{C}_{DE})} s^2_{\alpha} \\ & + \left[\frac{\partial L_{\max}}{\partial C_{DE}}\right]^2_{(\bar{\theta}_u,\bar{\theta}_d,\bar{s},\bar{h}_u,\bar{U}_u,\bar{\alpha})} s^2_{C_{DE}}. \end{aligned} \tag{10}$$

As shown in Equations (9) and (10), the means and variances of θ_u, θ_d, s, h_u, U_u, α and C_{DE} are needed. Reading the topographic map by different persons can form a set of observed data of θ_u. Then the mean and variance of θ_u can be estimated from this data set. The mean and variance of θ_d can be obtained in a like manner. The means and variances of s, h_u and α can be estimated from field data. As to U_u and C_{DE}, their means and variances are derived as follows.

4.1. CROSS-SECTIONAL MEAN VELOCITY

The cross-sectional mean velocity U_u can be estimated from (Takahashi, 1991)

$$U_u = \frac{2}{5d}\left\{\frac{g\sin\theta_u}{a\sin\alpha}\left[C_{DE} + (1-C_{DE})\frac{\rho}{s}\right]\right\}^{1/2}\left[\left(\frac{C_*}{C_{DE}}\right)^{1/3} - 1\right] \times h_u^{3/2} \tag{11}$$

where C_* is the concentration of debris-flow deposits, d is the mean diameter (mm), and a is a coefficient ($a = 0.042$ for $C_{DE}/C_* < 0.813$ and $a = 0.24$ for $0.813 < C_{DE}/C_* < 0.842$). Variables C_{DE}, g, a, and h_u are as defined in Equation (3). Assuming that θ_u, C_* and C_{DE} are random variables, one can obtain the mean and the variance of U_u as

$$\bar{U}_u = \frac{2}{5d}\left\{\frac{g\sin\bar{\theta}_u}{a\sin\alpha}\left[\bar{C}_{DE} + (1-\bar{C}_{DE})\frac{\rho}{s}\right]\right\}^{1/2}\left[\left(\frac{\bar{C}_*}{\bar{C}_{DE}}\right)^{1/3} - 1\right] \times h_u^{3/2} \quad (12)$$

$$\begin{aligned} s_{U_u}^2 = {} & \left\{\frac{1}{5d}\left\{\frac{g\sin\bar{\theta}_u}{a\sin\alpha}\left[\bar{C}_{DE} + \left(1-\bar{C}_{DE}\right)\frac{\rho}{s}\right]\right\}\right. \\ & \times \left\{\frac{g\sin\bar{\theta}_u}{a\sin\alpha}\left[\bar{C}_{DE} + \left(1-\bar{C}_{DE}\right)\frac{\rho}{s}\right]\right\}^{-1/2}\left[\left(\frac{\bar{C}_*}{\bar{C}_{DE}}\right)^{1/3} - 1\right]h^{3/2}\Bigg\}^2 s_{\theta_u}^2 \\ & + \left\{\frac{1}{5d}\left\{\frac{g\cos\bar{\theta}_u}{a\sin\alpha}\left[\bar{C}_{DE} + \left(1-\bar{C}_{DE}\right)\frac{\rho}{s}\right]\right\}^{-1/2}\left[\frac{g\sin\bar{\theta}_u}{a\sin\alpha}\left(1-\frac{\rho}{s}\right)\right]\right. \\ & \times \left[\left(\frac{\bar{C}_*}{\bar{C}_{DE}}\right)^{1/3} - 1\right]h^{3/2}\left\{\frac{g\cos\bar{\theta}_u}{a\sin\alpha}\left[\bar{C}_{DE} + \left(1-\bar{C}_{DE}\right)\right)\right\}^{1/2} \\ & \times \left[-\frac{1}{3}\frac{\bar{C}_*^{1/3}}{\bar{C}_{DE}^{4/3}}\right]h^{3/2}\Bigg\}^2 s_{C_{DE}}^2 + \left\{\frac{2}{5d}\left\{\frac{g\cos\bar{\theta}_u}{a\sin\alpha}\left[\bar{C}_{DE} + \left(1-\bar{C}_{DE}\right)\right)\right\}^{1/2}\right. \\ & \times \left[\frac{1}{3}\frac{1}{\bar{C}_*^{2/3}\bar{C}_{DE}^{1/3}}\right]h^{3/2}\Bigg\}^2 s_{C_*}^2 \end{aligned} \quad (13)$$

In general, C_* ranges from 0.6 to 0.7 (Takahashi, 1991). It is reasonable to assume that C_* is equally likely to take on any value over that range. Hence, one can refer to any general textbook of statistics to find the mean and variance of the uniformly distributed random variable C_*.

4.2. EQUILIBRIUM DEBRIS-FLOW CONCENTRATION

Equilibrium debris-flow concentration C_{DE} can be estimated from (Takahashi, 1991)

$$C_{DE} = \frac{\rho\tan\theta_u}{(s-\rho)(\tan\phi - \tan\theta_u)} \quad (14)$$

where ϕ is the internal friction angle (degree). The mean and the variance of C_{DE} can be written as

$$\bar{C}_{DE} = \frac{\rho\tan\bar{\theta}_u}{(s-\rho)(\tan\phi - \tan\bar{\theta}_u)} \quad (15)$$

$$s_{C_{DE}}^2 = \left[\frac{\rho \sec^2 \bar{\theta}_u}{(s-\rho)(\tan\phi - \tan\bar{\theta}_u)} + \frac{\rho \tan\bar{\theta}_u \sec^2 \bar{\theta}_u}{(s-\rho)(\tan\phi - \tan\bar{\theta}_u)^2}\right]^2 s_{\theta_u}^2 \tag{16}$$

5. Uncertainty Analysis of Maximum Width

Equation (5) gives the maximum deposition width $B_{\max}$ as a function of random variables V, $Z_{\max}$, $L_{\max}$ and κ. In a like manner, one can write the mean and variance of $B_{\max}$ as

$$\bar{B}_{\max} = \frac{\bar{V}}{\bar{\kappa}\bar{Z}_{\max}\bar{L}_{\max}} \tag{17}$$

$$S_{B_{\max}}^2 = \left[\frac{1}{\bar{\kappa}\bar{Z}_{\max}\bar{L}_{\max}}\right]^2 s_V^2 + \left[\frac{\bar{V}}{\bar{Z}_{\max}\bar{L}_{\max}}\right]^2 s_\kappa^2 + \left[\frac{\bar{V}}{\bar{\kappa}\bar{Z}_{\max}^2 \cdot \bar{L}_{\max}}\right]^2 s_{Z_{\max}}^2 + \left[\frac{\bar{V}}{\bar{\kappa}\bar{Z}_{\max}^1 \cdot \bar{L}_{\max}}\right]^2 s_{L_{\max}}^2 \tag{18}$$

The variable κ is in the interval 0.220 to 0.235 (Shieh and Tsai, 1997) and is considered to be uniformly distributed in this interval. In addition to the means and variances of κ and $L_{\max}$, those of V and $Z_{\max}$ have to be found as shown in Equations (17) and (18). Their derivations are presented below.

5.1. VOLUME OF DEBRIS FLOW

The volume of debris flow V is (Shieh and Tsai, 1997)

$$V = 60 Q_D C_{DE} t \tag{19}$$

where Q_D is debris-flow discharge (m^3/s) and t is the rainfall duration (min) which is assumed to be equal to the concentration time. Variables Q_D, C_{DE} and t are regarded as random variables herein. Hence, the mean and variance of V can be written as

$$\bar{V} = 60 \bar{Q}_D \bar{C}_{DE} \bar{t} \tag{20}$$

$$s_V^2 = [60\bar{C}_{DE}\bar{t}]^2 s_{Q_D}^2 + [60\bar{C}_{DE}\bar{t}]^2 s_{C_{DE}}^2 + [60\bar{Q}_D\bar{C}_{DE}]^2 s_t^2 \tag{21}$$

where $\bar{C}_{DE}$ and $s_{C_{DE}}^2$ are given above in Equations (15) and (16). The means and variances of Q_D and t are derived as follows.

5.1.1. *The Debris-Flow Discharge*

According to the local technical manual (CSWCS, 1997), the debris-flow discharge Q_D can be expressed as

$$Q_D = \frac{C_*}{C_* - C_{DE}} Q_w \tag{22}$$

where Q_w is the peak water discharge:

$$Q_w = \frac{1}{360} C_r I_t^T A_d \tag{23}$$

where C_r is the runoff coefficient, I_t^T refers to the rainfall intensity with T-year frequency and t-minute duration (mm/hr), and A_d is the drainage area (ha). According to the local technical manual (CSWCS, 1997), the T-year t-minute rainfall intensity I_t^T can be estimated from

$$\frac{I_t^T}{I_{60}^{25}} = (G + H \log T) \frac{A}{(t + B)^C} \tag{24}$$

where A, B, C, G and H are coefficients, and

$$I_{60}^{25} = \left(\frac{P}{25.29 + 0.094P} \right)^2 \tag{25}$$

where P is the mean annual rainfall (mm).

Variables C_*, C_{DE} and Q_w in Equation (22), C_r, I_t^T and A_d in Equation (23), and t in Equation (24) are regarded as random variables. From Equation (22), one can obtain the mean and variance of Q_D as

$$\bar{Q}_D = \frac{\bar{C}_*}{\bar{C}_* - \bar{C}_{DE}} \bar{Q}_w \tag{26}$$

$$s_{Q_D}^2 = \left[\left(\frac{\bar{Q}_w}{\bar{C}_* - \bar{C}_{DE}} \right) \left(1 - \frac{\bar{C}_*}{\bar{C}_* - \bar{C}_{DE}} \right) \right]^2 s_{C_*}^2 + \left[\frac{\bar{C}_*}{(\bar{C}_* - \bar{C}_{DE})^2} \bar{Q}_w \right]^2 s_{C_{DE}}^2 + \left[\frac{\bar{C}_*}{\bar{C}_* - \bar{C}_{DE}} \right]^2 s_{Q_w}^2 \tag{27}$$

where $\bar{C}_*$, $s_{C_*}^2$, $\bar{C}_{DE}$, and $s_{C_{DE}}^2$ are mentioned in previous section already. $\bar{Q}_w$ and $s_{Q_w}^2$ in turn can be obtained according to Equation (23) as

$$\bar{Q}_w = \frac{1}{360} \bar{C}_r \bar{I}_t^T \bar{A}_d \tag{28}$$

$$s_{Q_w}^2 = \left[\frac{1}{360}\bar{I}_t^T \bar{A}_d\right]^2 s_{C_r}^2 + \left[\frac{1}{360}\bar{C}_r \bar{A}_d\right]^2 s_{I_t^T}^2 + \left[\frac{1}{360}\bar{C}_r \bar{I}_t^T\right]^2 s_{A_d}^2 \tag{29}$$

where $\bar{A}_d$ and $s_{A_d}^2$ can be obtained from the data set formed through reading the topographic map by different persons. The local technical manual (CSWCS, 1997) gives C_r a range for a specified land use condition. It is reasonable to assume that C_r is equally likely to take on any value over that range. As to $\bar{I}_t^T$ and $s_{I_t^T}^2$, they can be obtained from Equation (24) as

$$\bar{I}_t^T = (G + H \log T)\frac{I_{60}^{25} A}{(\bar{t} + B)^C} \tag{30}$$

$$s_{I_t^T}^2 = \left[(G + H \log T)\frac{I_{60}^{25} A}{(\bar{t} + B)^{C+1}}\right]^2 s_t^2 \tag{31}$$

where $\bar{t}$ and σ_t^2 are derived as follows.

5.1.2. *Time of Concentration*

The time of concentration is the sum of the time of overland flow and the travel time in the channel. The time of concentration can be estimated from (Shih *et al.*, 1997)

$$t = \frac{L_1}{0.6 \times 60} + \left(\frac{0.87 \times L_2^3}{H_m}\right)^{0.385} \times 60 \tag{32}$$

where t is in minutes, L_1 is the length of overland flow (m), L_2 is the length of channel (km), and H_m is the elevation difference between the most upstream point and the outlet of the channel (m). Regarding L_1, L_2 and H_m as random variables gives the approximate mean and the variance of t as

$$\bar{t} = \frac{\bar{L}_1}{0.6 \times 60} + \left(\frac{0.87 \times \bar{L}_2^3}{\bar{H}_m}\right)^{0.385} \times 60 \tag{33}$$

$$s_t^2 = \left[\frac{1}{36}\right]^2 s_{L_1}^2 + \left[60.3\frac{\bar{L}_2^2}{\bar{H}_m}\left(\frac{0.87\bar{L}_2^3}{\bar{H}_m}\right)^{-0.615}\right]^2 s_{L_2}^2 + \left[20\frac{\bar{L}_2^3}{\bar{H}_m^2}\left(\frac{0.87\bar{L}_2^3}{\bar{H}_m}\right)^{-0.615}\right]^2 s_{H_m}^2 \tag{34}$$

where the means and variances of L_1, L_2, and H_m can be estimated from the data set formed through reading the topographic map by different persons.

5.2. THE MAXIMUM DEPOSITION THICKNESS

The maximum deposition thickness $Z_{\max}$ can be written as (Takahashi, 1991; Shih *et al.*, 1997)

$$Z_{\max} = L_{\max} \tan(\theta - \theta_d) \tag{35}$$

where θ is the longitudinal slope of debris-flow deposits (degree) and is also regarded as a random variable. Hence, the mean and the approximate variance of $Z_{\max}$ are written as

$$\bar{Z}_{\max} = \bar{L}_{\max} \tan(\bar{\theta} - \bar{\theta}_d) \tag{36}$$

$$s^2_{Z_{\max}} = [\tan(\theta - \theta_d)]^2 s^2_{L_{\max}} + [L_{\max} \sec^2(\theta - \theta_d)]^2 s^2_\theta + [L_{\max} \sec^2(\theta - \theta_d)]^2 s^2_{\theta_d} \tag{37}$$

where the means and variances of $L_{\max}$ and θ_d have been mentioned before. As to θ, in general it is between 6 and 10 degree according to field investigation and is considered herein to be uniformly distributed over that range.

6. Uncertainty Analysis of Deposition Area

The shape of the deposition area is described by Equation (7). According to Equation (7), the width at any distance x from the canyon mouth (end of the flow channel) is

$$b = B_{\max} \left[1 - \left(\frac{x}{L_{\max}} \right)^2 \right]^{0.5}. \tag{38}$$

Since $B_{\max}$ and $L_{\max}$ are random variables, b is a random variable too. Its mean and variance are written as

$$\bar{b} = \bar{B}_{\max} \left[1 - \left(\frac{x}{\bar{L}_{\max}} \right)^2 \right]^{0.5} \tag{39}$$

$$s^2_b = \left\{ \left[1 - \left(\frac{x}{\bar{L}_{\max}} \right)^2 \right]^{0.5} \right\}^2 s^2_{B_{\max}} + \left\{ \bar{B}_{\max} \left[1 - \left(\frac{x}{\bar{L}_{\max}} \right)^2 \right]^{0.5} (x^2 \bar{L}^2_{\max}) \right\}^2 s^2_{L_{\max}} \tag{40}$$

where $\bar{L}_{\max}$, $s^2_{L_{\max}}$, $\bar{B}_{\max}$ and $s^2_{B_{\max}}$ are given in Equations (9), (10), (17) and (18), respectively.

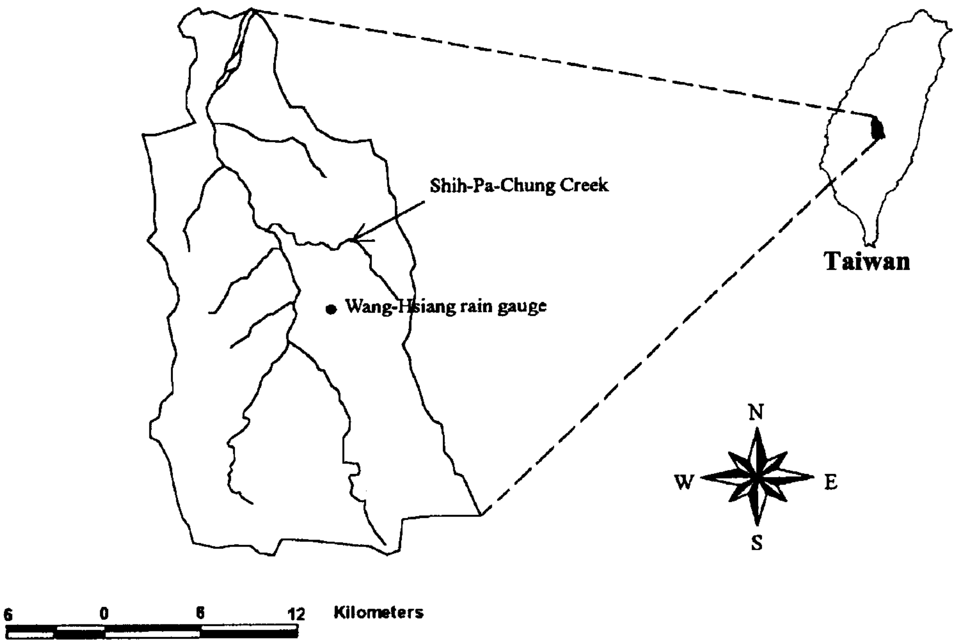

Figure 5. The Chen-Yu-Lan Creek Watershed in central Taiwan.

7. Application and Discussions

The methodology proposed herein is applied to an actual site susceptible to debris-flows. The site, Shih-Pa-Chung Creek, is located in central Taiwan (Figure 5). This creek is a tributary of the Chen-Yu-Lan Creek that flows into the Chou-Shui River, the longest river in Taiwan. The Shih-Pa-Chung Creek is on the Ti-Li Fault and close to the Chen-Yu-Lan Fault.

As mentioned above, one needs to estimate the means and variances of the upstream and downstream bed slopes of the debris-flow path, the density of gravel, the average debris-flow depth in the flow channel, the angle of dynamic friction, drainage area, the length of overland flow, the length of channel, and the elevation difference between the inlet and outlet of the main channel. In this application, the available field data of s, h_u and α are inadequate for uncertainty analysis, and hence s, h_u and α are considered to be deterministic without uncertainty. Once enough field data of s, h_u and α are available, the corresponding means and variances can be found accordingly. Based on the topographic map with a scale of 1:10000, well-trained persons are asked to measure these variables. For each random variable, a set of readings from different persons is then formed from which the mean and variance can be estimated. Table I summarizes the means and standard deviations of the aforementioned geometric variables. Also included in Table I is the mean and standard deviation of the runoff coefficient. Table II presents the means and standard deviations of the hydrologic variables including the time of concentration

Table I. Means and standard deviations of geometric variables

Variable	Mean	Standard deviation
Bed slope of canyon θ_u (degree)	14.0	3.5
Bed slope of fan θ_d (degree)	6.0	1.5
Overland flow length L_1 (m)	375.0	93.8
Channel length L_2 (km)	2.8	0.7
Elevation difference of channel H_m (m)	1,600	16
Drainage area A_d (ha)	210.0	10.5
Runoff coefficient C_r	0.825	0.060

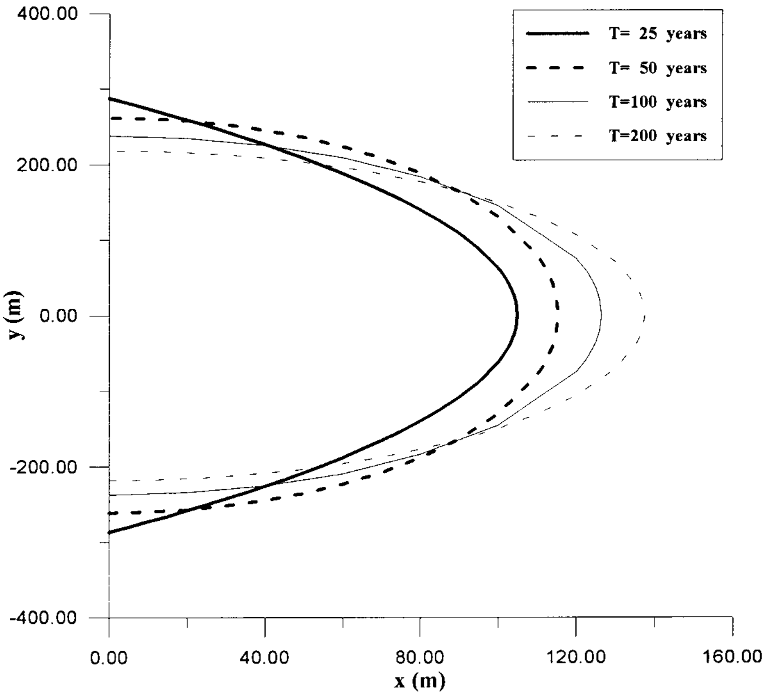

Figure 6. Deposition areas with a reliability of 70% for different return periods.

(rainfall duration), rainfall intensity and peak water discharge under four conditions of return period. Table III summarizes the means and standard deviations of the other variables (named debris-flow variables herein) under four conditions of return period. Parameters values for Equations (24) and (25) are given in Table IV. The values are obtained using the rainfall data of the nearby Wan-Hsiang rainfall station.

Figure 6 shows the delineated deposition areas corresponding to a reliability of 70% for four return periods, namely, 25, 50, 100, and 200 years. In a like

Table II. Means and standard deviations of hydrologic variables

Variable	Return period T (years)							
	25		50		100		200	
	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.
Time of concentration t (min)	21.4	4.1	21.4	4.1	21.4	4.1	21.4	4.1
Rainfall intensity I_t^T (mm/hr)	118.9	29.1	130.7	29.1	142.5	29.5	154.4	30.2
Peak water discharge Q_w (m^3/s)	55.5	14.4	61.0	14.6	66.5	14.9	72.0	15.4

Table III. Means and standard deviations of debris-flow variables

Variable	Return period T (years)							
	25		50		100		200	
	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.
Concentration of debris-flow deposits C_*	0.65	0.03	0.65	0.03	0.65	0.03	0.65	0.03
Longitudinal slope of debris-flow deposits θ (degree)	8.0	0.8	8.0	0.8	8.0	0.8	8.0	0.8
Equilibrium debris-flow concentration C_{DE}	0.3	0.2	0.3	0.2	0.3	0.2	0.3	0.2
Debris-flow discharge Q_D (m^3)	114.5	33.3	125.9	35.4	137.3	37.7	148.7	40.1
Mean upstream debris-flow velocity U_u (m/s)	8.7	6.1	9.2	6.5	9.7	6.8	10.1	7.2
Debris-flow volume V (m^3)	35,970	26,808	39,548	29,198	43,127	31,644	46,705	34,123
Maximum deposition length $L_{\max}$ (m)	88.9	48.9	97.9	53.9	107.1	58.9	116.3	64.0
Maximum deposition thickness $Z_{\max}$ (m)	3.1	1.1	3.4	1.2	3.7	1.3	4.1	1.4
Maximum deposition width $B_{\max}$ (m)	566.3	243.5	513.3	220.7	468.3	201.4	429.8	184.8

Table IV. Parameter values for Equations (24) and (25)

Parameter	Value
Mean annual rainfall P (mm)	2427
Coefficient A	14.05812
Coefficient B	55
Coefficient C	0.54659
Coefficient G	0.53095
Coefficient H	0.32608

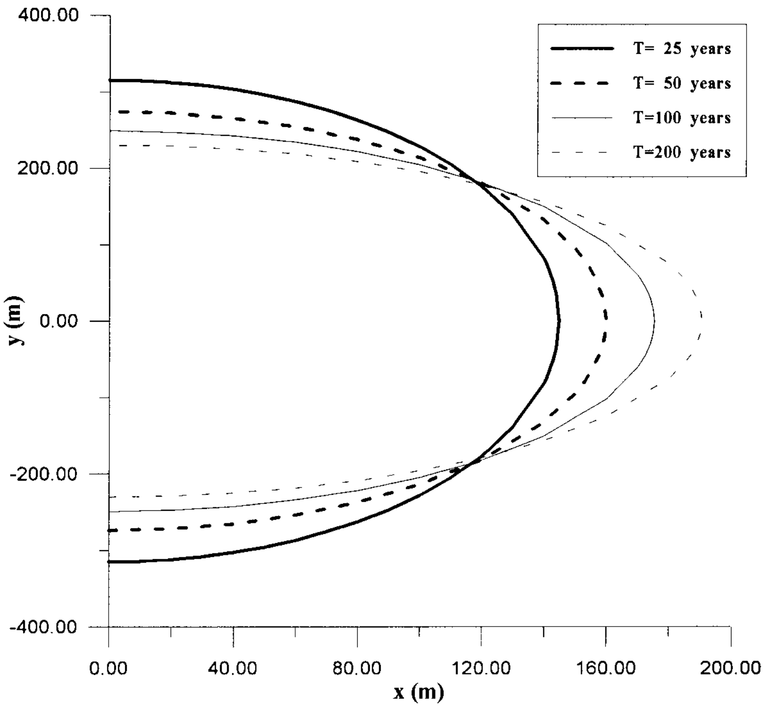

Figure 7. Deposition areas with a reliability of 80% for different return periods.

manner, those corresponding to a reliability of 80% are given in Figure 7. The delineated maximum deposition length increases with increasing return period of rainfall intensity when the reliability is fixed, whereas the maximum deposition width decreases with increasing return period. Figures 8 and 9 give the delineated deposition areas of different reliability for return periods of 25 and 50 years, respectively. When the return period is fixed, the maximum deposition area increases as the reliability increases. The influence of reliability on the maximum deposition length is more significant than that on the maximum deposition width. That is due

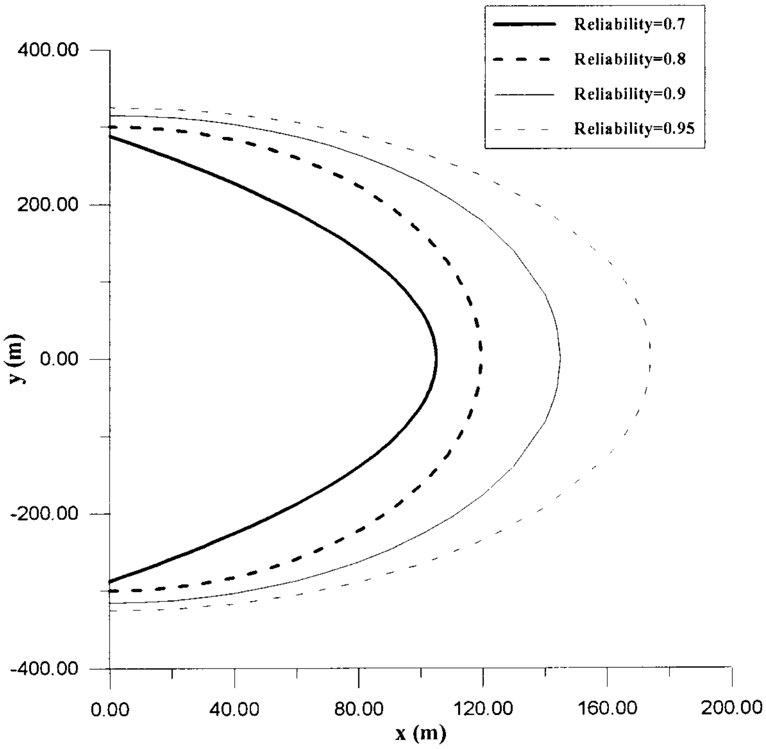

Figure 8. Deposition areas of different reliability with a return period of 25 years.

to the fact that the variables affecting the maximum deposition length are much more uncertain than those affecting the maximum deposition width.

8. Summary and Conclusions

In this paper, a methodology is proposed for the delineation of debris-flow deposition areas. The methodology is based on the theory of reliability. Actual application of the proposed methodology is performed. The delineated maximum deposition length and width are obtained using the inverse first-order second moment method. For a fixed value of reliability, the delineated maximum deposition length increases with increasing return period of rainfall intensity, whereas the maximum deposition width decreases with increasing return period. When the return period is fixed, the maximum deposition area increases with increasing reliability. Because the variables affecting the maximum deposition length are much more uncertain than those affecting the maximum deposition width, the influence of reliability value on the maximum deposition length is more significant than that on the maximum deposition width. The proposed methodology has advantages over existing methods for the delineation of debris-flow hazardous areas, because it considers the influence of all the uncertain parameters.

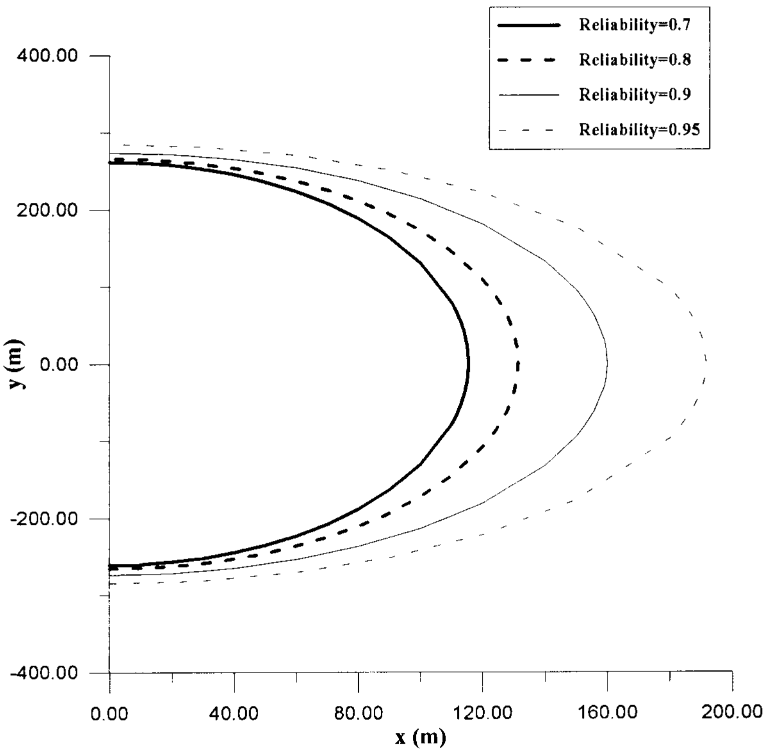

Figure 9. Deposition areas of different reliability with a return period of 50 years.

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