Relationships between Volume Concentration and Deposition Range of Typical Debris Flow Material

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ABSTRACT

The motion of a debris flow in longitudinal section of a valley can be broadly divided into three zones: initiation, transit and deposition. The generation of debris flow source material and deposition, characteristics are heavily influenced by terrain gradient. Surface runoff, rainfall intensity and catchment area all affect the scale of the dangers associated with debris flows. In order to estimate debris flow volumes for secfic regions, the concentration of those volumes were also estimated. Concentrations were derived by estimating debris flow material characteristics from an equilibrium theory analysis and also analyzing established databases to identify the influence of climate and local geologic characteristics. By way of numerical simulation, this study also simulated horizontal and vertical flow phenomena of overflow to provide an appropriate basis for estimating length of the debris flow deposition zone. While the field investigation results of debris flow hazards during typhoon Morakot reveal that a debris flow has motion courses of scouring and deposition. In order to be able to accurately forecast the depsition zone and impact strength of debris flow, it is expected future follow-up works can establish more detailed investigational databases and provide a planning basis for varying hydrological conditions.

Keywords: debris flow potential stream; Typhoon Morakot; volume concentration; slope; equilibrium concentration

Ⅰ. Introduction

Since Typhoon Toraji in 2001, terrain has been divideed into three debris flow terrain zones, namely: initiation zone, transit zone and deposition zone. In Taiwan, the composition of debris flow has been described in Article 59 of Soil and Water Conservation Technical Specifications, a debris flow refers to a mixture of substances such as mud, sand, gravel and boulders with water, and is a flow body mainly acted by gravity, and supplemented by the action of water. In 2006 Soil and Water Conservation Manual, it describes that debris flow is caused by heavy rains, making flow volume of river/stream increases sharply, so water flow is capable of scouring soil mass accumulated on both banks of the river or looser soil mass on river bed, and mix with them in the form of slurry-like mass and transformed into debris flows. With respect to debris flow volume, a study proposed to use ground water levels and landslide volume scale as well as marks left by previous river levels on facilities submerged by floods to evaluate velocity and flow rate (Johnson and Rodine, 1984). This study focuses on debris flow potential rivers/streams having debris flow threats, offers numerical analysis method for estimating length and volume concentration of deposition zone, and obtained impact data of overflow in vertical direction and flow direction to provide for planning purposes of disaster prevention databases as well as catchment zones.

Ⅱ. Literature Review

The estimation of debris flow impact range in this study is developed from expert method. Hiroshi Ikeya and Takaku Mizuyama (1982) of Japan used debris flow records occurred in Shodoshima region to propose a relationship equation of flow distance, slope below overflow and debris flow volume, deposition length can be estimated from debris flow volume. In 2002, Soil And Water Conservation Bureau had once estimated debris flow volume and applied to Hiroshi Ikeya's formula, used catchment zone and earth volume statistics of Taiwan region debris flow events and drew relation maps, at present Taiwan region earth volume is estimated by adopting Map V90 or V95 (Tsai Yuan-Fang, 1999).

The field investigations and phenomena after debris flow occurred, reveal the following five points: (1) For debris flow in river valley area, the overflow position is at material source occurrence place or lower edge of water gathering basin.Assuming material source is not provided by both sides of the river valley, debris flow volume and scale can be estimated from deposition on the river valley (Cannon, 1993); (2) In downstream flat area or sector-shaped area, the distribution characteristics of debris flow deposits are not well paned, coarse particles are deposited on the sector edge, while fine particle size is deposited on the inside of the flow channel, the geometrical shape of sector-shaped area can be estimated from debris flow volume (Huang Hsin-Rong, 1997); (3) In the meandering river channels, also have observed continuous overflows - deposition phenomena and deposition zone overlapping characteristics, debris flow has a wave band and intermittent characteristics (Johnson, & Rodine, 1984); (4) On the terrace platform, relationships between debris flow deposition length and stage height difference, longitudinal length, material particle size, as well as volume concentration, and mutually corroborated from experimental data (Katsuo Sasahara and Hideki Tanaka, 2006) to estimate the relationships between slope, volume concentration and deposition length; (5) If persistent rainfall occurs in the source catchment zone, gentle slope flood will diffuse over immature deposits of debris flow, then transit into immature debris flow (mudflow-like) type, and then further transit into general sediment (Tseng Wen-Xiao, 2002), motion pattern along the path is gradually close to general sediment situation, also known as transient debris flow phenomenon.

Based on indoor identification and interpretation of aerial photos, it is learned that the overflow point is delineated from the vertex of valley mouth or sector-shaped area, then according to debris flow deposition length formula as well as conditions such as riverbed slope situation and preservation object position, and reference to probable preservation object positions, to initially designate affected range to terrain conditions of deposition zone or sector-shaped area in downstream after conducted field surveys and interviews and recorded field terrain and geomorphology, as debris flow numerical simulation range.

With regard to the critical slope theory and laboratory results, it is a continuation of the theory of equilibrium concentration. It considers that the concentration of upper water should be 0 when riverbed enters into gentle slope from steep slope, and gravel-type debris flow transforms into immature debris flow form debris flow, if the sediment deposition concentration on riverbed is C*, then through assuming equilibrium concentration C = C*/2, derived that the critical slope can be used as a way to distinguish between the occurrence conditions of debris flow and immature debris flow. When the slope θ of slope surface is greater than the critical slope θ_C, it is called as a debris flow; if θ does not reach θ_C, then it is called as a immature debris flow (Tseng Wen Xiao, 2002). As for designating basis of determining the overflow point of a debris flow, is on the critical slope point of the stream, and if the stream catchment area can reach 3 hectares, then the occurrence potential class of a debris flow can be interpreted according to stream deposition material and amount of collapsed material source in catchment area.

Ⅲ. Study Area

3 .1 Basic data collection

This study area collected map information including topographic maps and aerial photos for Kaohsiung City DF006, Kaohsiung City DF066, Kaohsiung City DF067, Kaohsiung City DF068 and Kaohsiung City DF069 in Maya Neighborhood, Namaxia Dist., Kaohsiung City. The study scope is shown as in Figure 1. After conducting field surveys, basic information was confirmed, and learned that that these five debris flow potential streams had once experienced a total of five times of disasters during Typhoon Kalmaegi in 2008 and Morakot in 2009, as shown in Table 4, and described in detail as below.

During Typhoon Kalmaegi on July 18, 2008, the rip rap of Jiasian Farm forest road in upstream of Kaohsiung City DF068 catchment zone damaged and blocked traffic, about 4,000 cubic meters of debris deposited in basketball courts.

During Typhoon Morakot in August 2009, due to upstreams of Kaohsiung City DF006 and Kaohsiung City DF068 catchments collapsed, a lot of debris flowed out of river course, resulting in about 500 meters damaged road in Chiahsien Farm forest road and Taiwan Provincial Highway No.21, and invaded into buildings in San-Ming Middle school and Mayan Visitor Center.

3 .2 Hydrological analysis

In typical debris flow disaster type, it is to consider that flood entrains debris on riverbed or scraps riverbank material, so adopting the context of flooding and stream entraining debris triggered by rainfall, this also becomes an important issue in this study.

This study referenced outdoor investigation results and related GIS map layers, compiled and edited numerical terrain, reviewed hydrologic analysis based on terrain factors, described as below.

1. The coverage of numerical terrain includes catchment zone and maximum affected areas, compiled and edited numerical terrain, and set boundary conditions.

2. The collection of hydrological records includes rainfall alert values published by rainfall stations of the Water Conservation

Bureau, as well as the annual maximum day maximum rainfall records, etc., and conducted data supplement and rain-type analysis.

3. Hydrological frequency analysis of different re-occurrence periods, based on the rainfall pattern analysis and the assumption of equivalent Manning's N value to estimate flood hydrograph of different re-occurrence periods.

Since debris flow motion characteristics analysis will usually assumeas the debris flow behaves as a non-Newtonian fluid, and the flowing soil mass has plasticity, yield stress and a very high specific gravity, if occurs dehydration, will make debris flow to form a higher concentration, its viscosity coefficient is also several times higher than mud flow, and its flow speed can generate a considerable difference when influenced by steep drop of terrain, and can up to several times of flood's flow speed. However, in field investigation it is more difficult to estimate the characteristics of such as material volume concentration. In summary of the above, it is necessary to study some items in the exploration, including deposition range, deposition depth, major particle sizes of deposits, slope of deposition surface, and debris deposition volume overflowed from river course (debris flow-out volume).

3.3 Debris flow assumptions

In order to estimate flow-out volume and volume concentration (C_V) of debris flow, Takahashi (1991) once conducted a deposition simulation of gravel-type debris flow in a experimental tank for experimental data of slope and volume concentration. The result revealed that, when a debris flow with volume concentration of 0.364 flows into a gentle slope surface (the slope θ of the gentle slope surface must be less than the critical slope θ_C) from a steep slope surface, and when input of debris flow maintained a fixed volume, the deposition length quickly reached maximum, and the following arrived debris flow would gradually increase the thickness and lateral width of the deposition zone.

The defined volume concentration of the debris flow is between 0.45 and 0.55, in general experience, when C_V is within the range between 0.2 and 0.45, it is called as high concentration mud flow like flood (National Park Service, Fish & Wildlife Service, 1998), as shown in Table 1.

Researchers also established a relationship equation of slope and debris flow deposition (Iwao Izumi and Hiroshi Ikeya, 1978; Shi Bang-Zhu and Hsieh Cheng-Lun, 1998), this study is based on the theoretical basis of equilibrium concentration (C) (Takahashi, 1991), as shown in Equation 1. In the equation, C: volume concentration of debris flow in flowing; ρ: water density (Kg/m^3); σ: debris density (Kg/m^3); θ: valley slope (degrees); ϕ_S : internal friction angle of debris (degrees). While the specific gravity the debris flow mixture (mud body) is γ_m , as shown in Equation 2. In the equation, γ_S : specific gravity of fine gravel is about 26.5(KN/m^3), γ_W : specific gravity of water is about 9.81 (KN/m^3).

$$C = \frac{\rho \tan\theta}{(\sigma - \rho)(\tan\phi_S - \tan\theta)} \qquad \text{Equation 1}$$

$$\gamma_m = \gamma_W + C_V(\gamma_S - \gamma_W) \qquad \text{Equation 2}$$

In the equation, the debris internal friction angle composed by the test area soil mass can adopt saturated state of soil mass internal friction angle as the wave band relation of flow state of debris flow and deposition zone (Zhou Bi-Fan, et al., 1991), C_V is affected by specific gravity γ_{DF} of debris flow , the flowing soil mass material will directly affect the ϕ_S , if the major particle size is bigger, the internal friction angle will become greater, and the slope of riverbed deposition formed on slope surface is steeper, in the initial exploration, on gravel soil the slope of riverbed deposition derived from equilibrium concentration formula is about 7.6 to 11.1 degrees.

In the vicinity area close to Maya Middle School (formerly San-Ming Middle School), its terrain is located in the river terrace and historical debris flow alluvial sector terrace, consists of a total of three layers; besides, boulders in forest road and culverts of provincial highway formed obstacles as well as transient overflow. The longitudinal profile of elevation changes of streams are shown in detail as in Figures 2, 3. The average riverbed slope of Kaohsiung City DF006 is about 13%, about 7.7 degrees, and the average riverbed slope of Kaohsiung City DF068 is about 19%, about 10.3 degrees. In addition, this study queried the recommended valuesof debris flow volume concentration based on occurred debris flow facts (Flow evident), their volume concentrations are from 0.48 to 0.55, see Table 1 about details.

For rocks surface particle size about 30 cm of debris flow deposits, and there is a high proportion of fine sand in the central location of the deposits, refer to deposition material and concentration diagram in Figure 4, the volume concentration is roughly 0.45 to 0.55, therefore, selected 0.5 as volume concentration.

IV. Result Analysis

4. 1 Analysis of debris flow deposition slope and concentration

This study adopted equilibrium concentration formula to carry out the estimation of debris flow volume concentration for six kinds of debris materials commonly classified in civil engineering works, including: pebble soil, gravel sand soil, medium sand soil, fine sand soil, powder sand soil, and sand soil containing clay, the relationships of their volume concentration Cd and siltation slope are roughly in linear relationship.

Exploring the deposition slopes estimated from equilibrium concentration formula, most of them are less than 10 degrees (only when pebble soil, gravel sand and medium sand at Cd = 0.8, are equivalent to the motion pattern of landslides, their deposition slopes are greater than 10 degrees), if only consider the flow state of debris flow (Cd ranged from 0.45 to 0.55), describe the results of regression analysis for the siltation slopes of commonly classified debris materials as follows:

Take gravel soil as an example, its siltation slope is about 5.55 to 11.09 degrees, as shown in Equation 3 (R^2 =0.9968)。

$$\theta = 19.493C - 3.0592 \qquad \text{Equation 3}$$

where θ is deposition slope (degrees), Cd is volume concentration.

Take gravel sand as an example, its siltation slope is approximately 5.12 to 10.24 degrees, as shown in Equation 4 (R^2 = 0.9967).

$$\theta = 17.998C - 2.8326 \qquad \text{Equation 4}$$

Take medium sand as an example, its siltation slope is approximately 4.70~9.40 degrees, as shown in Equation 5 (R^2 =0.9966).

$$\theta = 16.548C - 2.6108 \qquad \text{Equation 5}$$

Take fine sand as an example, its siltation slope is approximately 3.89~7.81 degrees, as shown in Equation 6 (R^2 =0.9964).

$$\theta = 13.761C - 2.1802 \qquad \text{Equation 6}$$

Take powder sand as an example, its siltation slope is approximately 2.95~5.93 degrees, as shown in Equation 7 (R^2 = 0.9963).

$$\theta = 10.451C - 1.6622 \qquad \text{Equation 7}$$

Take sand containing clay as an example, its siltation slope is approximately 2.40~4.84 degrees, as shown in Equation 8 (R^2 =0.9962).

$$\theta = 8.5365C - 1.3602 \qquad \text{Equation 8}$$

In summary of the above analysis, showed that, the deposition slopes of six commonly classified kinds of debris materials are about below 6 degrees, if it contains higher clay, its deposition slope is about below 2 degrees.

4.2 Numerical simulation result analysis

The deposition range of 2008 simulated re-occurrence period 200 years of Kaohsiung City DF006 is very close to that of Typhoon Morakot, as shown in Figure 5. From the fact that in deposition graph the submerged area is slightly gourd-shaped, it can be learned that terrace terrain exists on its debris flow path, while referenced to the experimental result of Katsuo Sasahara and Hideki Tanaka, showed that after artificial reclamation the ancient sector terrace is easy to result in deposition effect after flowed over flat terrain and decreased slope, and if the deposits entrains coarse granular materials, may cause an increase in impact strength, the debris flow will deposit toward both sides of deposition zone and submerge crops, buildings or roads in both sides of the deposition zone.

Figure 6 shows the re-simulated (after Typhoon Morakot) deposition range of Kaohsiung City DF006 re-occurrence period of 200 years after reasonably adjusted terrain mesh, it is slightly consistent with the deposition range of debris flow occurred in Typhoon Morakot. After experienced Typhoon Kalmaegi in July 2008 and Typhoon Morakot in 2009, the siltation debris in some buildings suffered by debris flow has been cleared, and only windows, doors and iron items were crashed, other parts can be repaired to restore the normal rhythms of life.

Figure 7 shows the re-simulated (after Typhoon Morakot) deposition range of Kaohsiung City DF068 re-occurrence period of 200 years after reasonably adjusted terrain mesh, it is slightly consistent with the deposition range of debris flow occurred in Typhoon Morakot. After experienced Typhoon Morakot in 2009, the current situation of stream in Kaohsiung City DF068 generally does not change, the buried buildings in both Mayan Community Center and San-Ming Middle school has cleared the debris inside the buildings, after field investigation it is found that the debris deposition depth is largely in line with simulation result.

Figures 8 and 9 show the characteristic of deposition length and deposition width increased along with the increase of debris flow volume. This concept can be slightly explained in the numerical simulation of Kaohsiung City DF006; but in the course of numerical simulation of Kaohsiung City DF068, it is found that the debris volume on slope surface will have the situation of closing to limit, so results in a nonlinear relationship between debris flow volume and its deposition length and width, however, in overall, when debris flow volume increases, the deposition range continues to increase, only the increase amplitude is not a linear relationship.

Another noteworthy point is that in debris transit zone, motion-stopping or deposition-appearing path, the debris flow exists in a band swarm phenomenon. Therefore, in the judgment of debris flow-out volume and estimation of debris deposition volume, not only should consider the debris sources within the river or the collapse of landslides in upstream of catchment zone, but also should consider other probable material sources including the collapse of road slopes, transient river blockage or large-scale soil mass moving areas.

V. Conclusions and Recommendations

In hopes of preventing future disasters similar to Typhoon Morakot in 2009 and heavy rains, currently Taiwan has completed the designation of 1,660 debris flow potential streams, and in addition to the existing experimental methods and field investigation methods, in recent years has also adopted numerical simulation method to conduct debris flow hazardous range analysis.

At present, in order to estimate the debris flow hazardous range from deposition slope, in field investigation it is required to overcome the issue of giving appropriate volume concentration and debris deposition length relationship equation for deposition material type and terrain slope under investigation.

In the course of this study, it is also found that in streams where debris flow phenomenon frequently occurred, the soil and rock source distribution and the total sediment production in catchment zone decreased as debris flowed out, so it is necessary to reduce estimated values when estimating catchment collapse material sources.

The debris flow theory has had considerable successful results, perhaps researchers can simplify very complicated theoretical formulas into simple relationship equations to provide to engineering units for reference in more practical tests, planning and design.

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Figures and Tables

Table 1 Basic information of the five debris flow potential streams in the study area

Item	Stream number	Stream length (km)	Stream average slope (%)	Catchment area (ha)	Overflow point catchment area (ha)	Old stream number
1	Kaohsiung City DF006	0.942	23	50	41	Kaohsiung A012
2	Kaohsiung City DF066	1.514	19	62		Kaohsiung County DF Newly added 01
3	Kaohsiung City DF067	1.738	22	131		Kaohsiung County DF Newly added 02
4	Kaohsiung City DF068	1.176	24	86	72	Kaohsiung County S98-09
5	Kaohsiung City DF069	4.986	14	1305		Kaohsiung County DF Newly added 05

Table 2 Debris flow disaster information over the years of the five debris flow potential streams in the study area

Item	Stream number	Event Name	Date of disaster	Debris flow volume (m^3)	Siltation buried range (ha)	Collapse rate of catchment (%)
1	Kaohsiung City DF006	Kalmaegi Morakot	2008/7/18	20,000	3.3	1.90%
2	Kaohsiung City DF066	Typhoon Morakot	2009/8/8	40,000	2.6	4.33%
3	Kaohsiung City DF067	Typhoon Morakot	2009/8/8	15,000	1.1	2.74%
4	Kaohsiung City DF068	Typhoon Morakot	2009/8/8	30,000	2.4	<1%
5	Kaohsiung City DF069	Typhoon Morakot	2009/8/8	20,000	0.9	4.43%

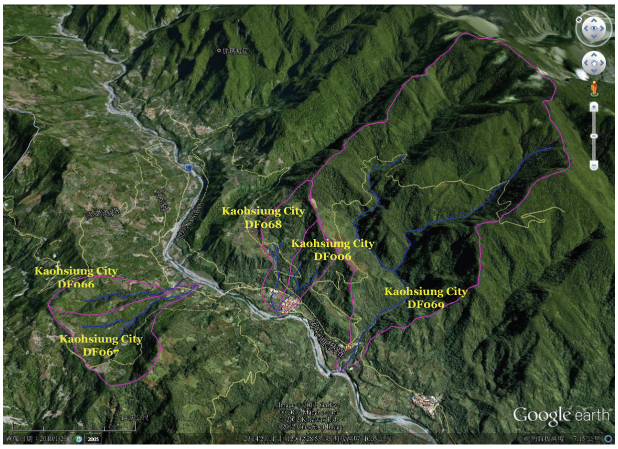

Figure 1 Aerial view of the five debris flow potential streams in the study area

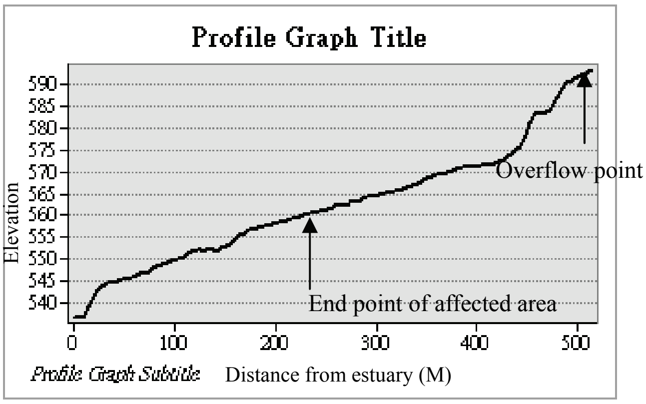

Figure 2 Kaohsiung City DF006 stream longitudinal section elevation change diagram

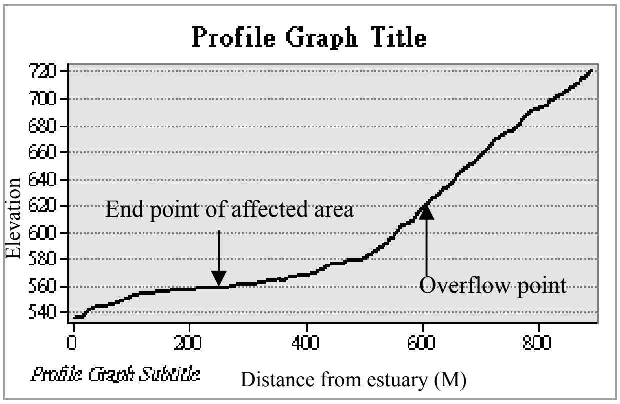

Figure 3 Kaohsiung City DF068 stream longitudinal section elevation change diagram

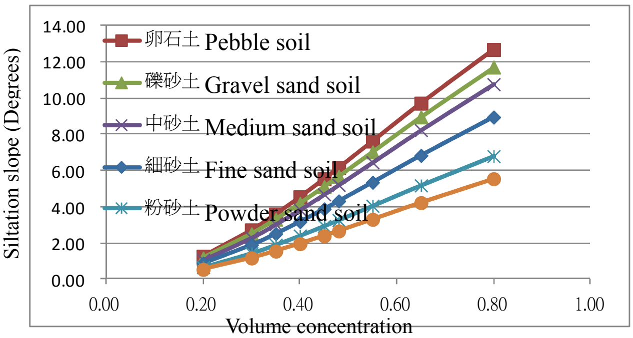

Figure 4 Relationship of siltation slope and volume concentration of six kinds of classified debris

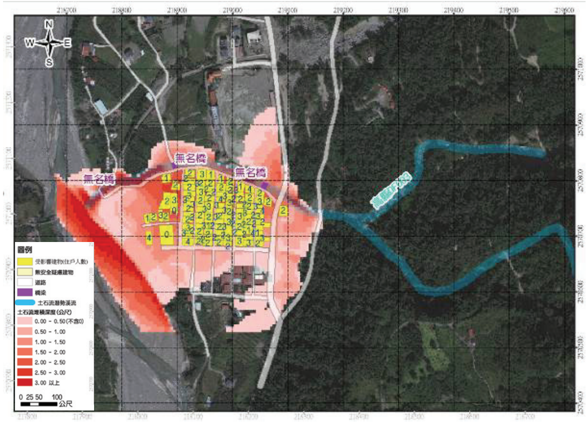

Figure 5 200 years Kaohsiung City DF006 deposition depth diagram completed in 2008

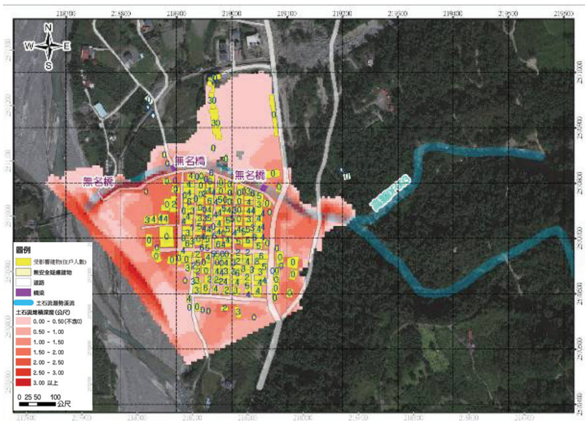

Figure 6 200 years Kaohsiung City DF006 deposition depth diagram completed in 2010

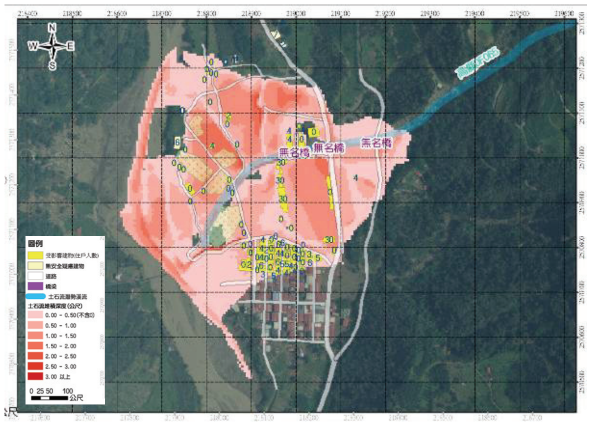

Figure 7 200 years Kaohsiung City DF068 deposition depth diagram completed in 2010

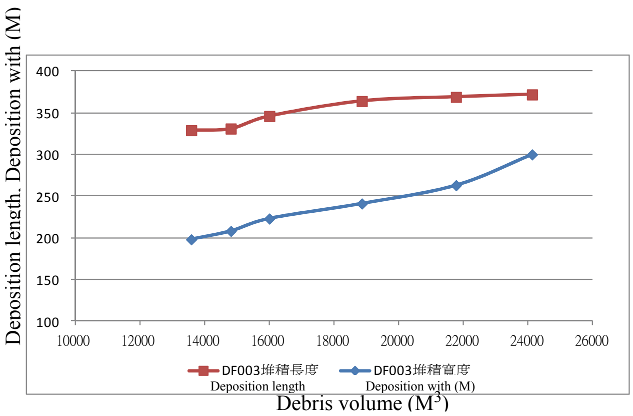

Figure 8 Kaohsiung City DF006 deposition and volume relationship diagram completed in 2010

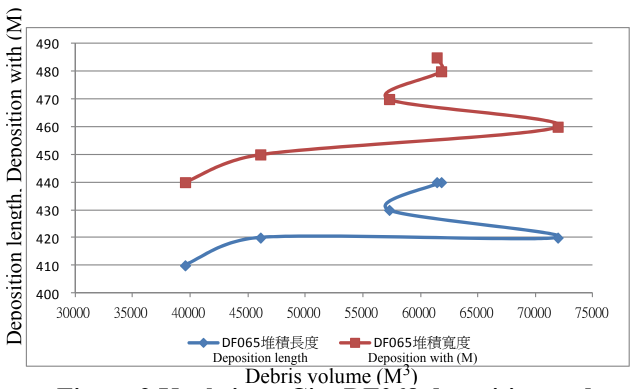

Figure 9 Kaohsiung City DF068 deposition and volume relationship diagram completed in 2010