Recent Advances in Debris Mobility Modelling for Assessing Natural Terrain Landslide Hazards in Hong Kong

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ABSTRACT

Debris mobility modelling has made major advances in the past decade in the Geotechnical Engineering Office. The advances are two-fold. Firstly, there are improvements in numerical tools for both two- and three-dimensional debris mobility analyses. Two-dimensional debris mobility modelling has changed its computing engine from Microsoft Excel using the programming language Visual Basic to a stand-alone calculation module using the multi-paradigm programming language C# that coupled with ArcGIS. Three-dimensional debris mobility modelling has gained the benefits of advances in computer technology to couple Smoothed Particle Hydrodynamics, a numerical method used for simulating the dynamics of continuum media, with ArcGIS. Secondly, there are technical developments on the choice of basal resistance models and use of mobility parameters for assessing the mobility of different landslide hazards, such as those within channelised debris catchments with adverse site settings that are prone to the development of sizeable channelised debris flows with high mobility and those within topographic depression catchments. This paper presents the background to the technical advances in debris mobility modelling in the past decade and summarises details of the individual developments.

1 INTRODUCTION

Hong Kong is characterised by its dense population fringing the hilly terrain, which inevitably expose the city to a high risk of landslide hazards, such as natural terrain landslides. Amid the presence of such risk, the Geotechnical Engineering Office (GEO) has been taking a leading role in Hong Kong in advancing the understanding of landslides, and enhancing the techniques, knowledge and expertise in the management of natural terrain landslide risk in the past decades.

In particular, strategic and continuous efforts have been made to enhance the capability of the profession to carry out forward prediction of the mobility and runout distance of natural terrain landslides by means of numerical simulation, with notable progress in the past two decades. A detailed account of the work done in the period from 1997 to 2007 has already been documented in Kwan et al. (2007). As for the past decade, major advances in debris mobility modelling have been achieved in Hong Kong, especially under the impetus of the launch of the Landslip Prevention and Mitigation Programme (LPMitP) in 2010 to systematically mitigate and contain landslide risk from both man-made slopes and natural hillsides.

The advances of this subject area in the past decade are two-fold. Firstly, there are improvements in numerical tools for both two- and three-dimensional debris mobility analyses. Two-dimensional (2D) debris mobility modelling has changed its computing engine from Microsoft Excel using the programming language Visual Basic to a stand-alone calculation module using the multi-paradigm programming language C# that coupled with ArcGIS, a Geographic Information System (GIS) desktop software. Three-dimensional (3D) debris mobility modelling has gained the benefits of advances in computer technology to couple Smoothed Particle Hydrodynamics (SPH), a numerical method used for simulating the dynamics of continuum media, with ArcGIS. A summary of the use of SPH and other numerical modelling techniques in simulating landslide motion is presented in Soga et al. (2016). Both advances have enhanced the computational capability and efficiency of the modelling tools, streamlined the work process of natural terrain hazard studies and improved output visualisation that have, in overall, provided better results and efficiency in the study and mitigation of natural terrain landslide risk. Secondly, there are technical developments to support the selection of appropriate basal resistance models and use of mobility parameters for assessing the mobility of different types of landslide hazards, such as those within channelised debris catchments with adverse site settings that are prone to the development of sizeable channelised debris flows with high mobility and those within topographic depression catchments. This paper presents the background to the technical advances in debris mobility modelling in the past decade and summarises details of the individual developments.

2 ENHANCEMENTS OF NUMERICAL TECHNIQUES

2.1 Two-dimensional debris mobility modelling

In light of the simplicity of 2D modelling over its 3D counterpart, 2D debris mobility modelling tools have been widely adopted in daily practice for natural terrain hazard studies and detailed design of natural terrain mitigation measures in the last decade. Among the 2D debris mobility modelling tools, "2d-DMM" (which stands for two-dimensional debris mobility modelling) which was developed by the GEO (Kwan & Sun 2006) has been one of the most popular tools in Hong Kong. It was coded initially using Visual Basic for Applications on Microsoft Excel, and thus providing a basic, easily-understandable platform for analysis and plotting of numerical results. Nonetheless, with the increasing demand of both computational and graphical performance of 2D debris modelling by the geotechnical profession in recent years, particular under the context of the LPMitP, the computation architecture of 2d-DMM needs to be upgraded to enhance the analytical capability, visualisation, user friendliness, as well as possible integration of the debris mobility modelling package with the GIS, which is frequently used by the geotechnical profession to carry out assignments ranging from desk study of natural terrain hazards to detailed design of natural terrain hazard mitigation measures.

In 2014, the GEO undertook the initiative to revamp 2d-DMM from a program embedded in a spreadsheet to a stand-alone Microsoft Windows application, by means of the modern multi-paradigm programming language C#. Brought by the change of the programming architecture, the revamped 2d-DMM (Version 2.0) is more extensible to additional features and compatible with third-party programs. With these advantages, new customisations were made on the revamped 2d-DMM (Version 2.0) to suit the need of routine geotechnical study and design, such as to enable specification of any number of "block" (an element which represents landslide debris) to represent the landslide debris, resulting in more precise computation results. Also, new graphical post-processing features such as on-the-run generation of various hydrographs, (i.e. the time history of an attribute, velocity for example, of the landslide debris over stationary reference locations, e.g. the proposed location of structural measures to contain landslide debris) are provided. The user interface of the revamped 2d-DMM (Version 2.0) is given in Figure 1.

The GEO continued its effort to enhance the user experience of 2d-DMM (Version 2.0) by incorporating 2d-DMM (Version 2.0) in ArcGIS Desktop. As GIS technology is becoming more popular in Hong Kong, the geotechnical professionals rely increasingly on the capability of GIS to display and analyse spatial data in relation to the study and design of natural terrain hazards and their mitigation measures. Recently, ArcGIS has been widely adopted in the geotechnical industry to analyse and exchange spatial data for planning, investigation and design purposes. Typically, the topography of a study area of natural terrain based on Light Detection and Ranging (LiDAR) data is stored in the digital elevation model (DEM) on the ArcGIS platform. With the ArcGIS application for 2d-DMM, the vertical profile of the flow path, which is an essential input for the debris mobility analysis, can be generated automatically and more accurately based on the DEM. In addition, a batch of numerical runs along various prescribed flow paths may be

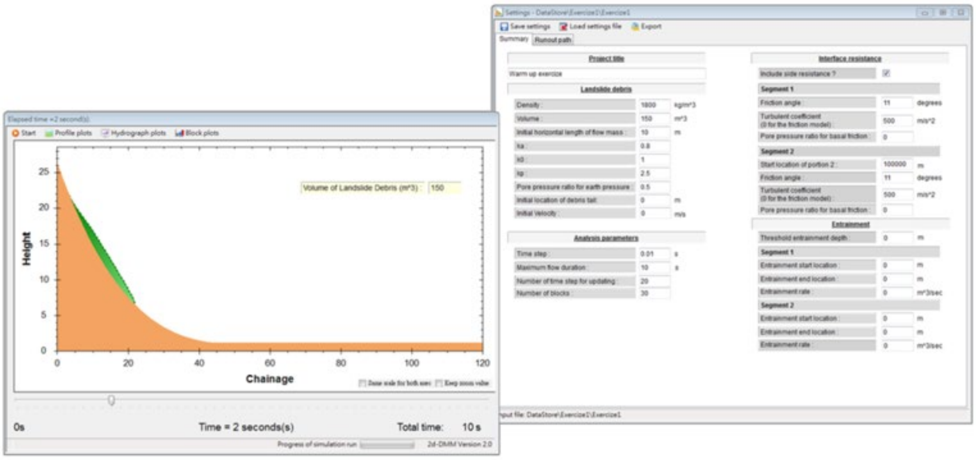

Figure 1: Graphical user interface of 2d-DMM (Version 2.0)

specified using the ArcGIS application for 2d-DMM calculations, thus eliminating the manual effort in carrying out 2D simulation for each flow path one-by-one. In addition, numerical results, such as the runout distance and the hydrographs, may be shown on the ArcGIS platform directly. With such integration, 2D debris mobility modelling may now be carried out directly on ArcGIS in a more accurate and efficient manner, bringing values at different design stages of natural terrain hazard mitigation measures.

In order to ascertain that the revamped 2d-DMM (Version 2.0) is capable of producing reliable numerical results, the program was validated against the field observations of historical natural terrain landslides in Hong Kong, as well as against the previous version of 2d-DMM which has already been well-validated before. The validation work indicated that the revamped 2d-DMM (Version 2.0) is consistently capable of producing results that match closely the field observations and results produced by the previous version of 2d-DMM. The 2d-DMM (Version 2.0) is now one of the standard software packages for geotechnical study of natural terrain hazards and design of mitigation measures in Hong Kong.

2.2 Three-dimensional debris mobility modelling

While 2D simulation strikes a good balance between computation efficiency and modelling capacity, it has its own limitations. For example, 2D simulation cannot explicitly calculate the change of landslide motion due to the presence of transverse bends, nor be able to model the splitting of landslide debris passing through a bifurcation of drainage lines. In these cases, 3D debris mobility modelling is preferred. In 2004, the GEO has pioneered the development of 3D debris mobility modelling by adopting the concept of Particle in Cell (PIC). Details of the PIC numerical model is documented in Kwan & Sun (2007). An extra step was made in 2009 to develop a new debris mobility modelling module which made use of the numerical scheme of SPH to simulate the motion of landslide debris in a more computationally cost-effective manner. The SPH model is one of the rapidly evolving, well-recognised by the literature and popular tools to calculate the motion of deformable materials. The formulation principle of the SPH module, in general, followed McDougall & Hungr (2004). The fundamental concept of SPH is to split the landslide debris into smoothed particles which, by means of spatial interpolation, enables a meshless particulate numerical scheme to solve continuum governing equations. The SPH simulation is undertaken in a time-stepping finite difference framework with an initial condition that all the particles are at rest. Formulation of the underlying governing equations of the 3D debris mobility modelling is given in Law et al. (2016).

The SPH module was coded as a stand-alone Microsoft Windows application, and designed to be computationally efficient and extensible in order to allow for easy integration with third-party applications. Nonetheless, labour-intensive pre- and post-processing are the major drawbacks of any 3D analysis. Some tedious steps involved are conversion of the DEM to the coordinates of the topography, calculation of the geometry of the landslide source, import and export of data for simulations and post-processing, as well as generation of engineering plots based on the raw textual outputs. These procedures may be error-prone and time-consuming, requiring experience to diagnose problems encountered and thus creating a major hurdle to the practical use of the SPH module for day-to-day applications.

In order to tackle such a bottleneck, a one-stop GIS solution has been developed which integrates the SPH module with ArcGIS, through an ArcGIS application that comprises three modules, viz. input module, SPH module and post-processing module. The modules are connected seamlessly such that there is no need to export data from one module to another manually. The input module is responsible for guiding the user to set up the SPH model on the ArcGIS platform in a step-by-step manner. In particular, the module converts raw topography data (e.g. LiDAR point clouds) to the grid-based topography input data for SPH analysis. The module offers an option to trim the topography at the source location considering the detachment of debris material at its basal sliding surface. After the user has entered all the input data, the SPH module is turned on which is capable of running on multiple processors. Based on the computed attributes of the SPH points (e.g. debris thickness, location, velocity), the SPH module prepares the data files for the post-processing module to display the results on the ArcGIS platform. Important engineering plots such as the velocity profile of landslide debris along the flow path, and the time history of the velocity and thickness of the landslide debris passing through a user-specified location in the flow path are available. Export of data to Microsoft Excel format for other analysis is also enabled. Furthermore, landslide animation in three dimensions can be generated in order to facilitate a review of the simulated flow process (Figure 2). The ArcGIS application, bundled with the input module, SPH module and post-processing module, is called the 3d-DMM (Version 2.0). Similar to the 2d-DMM (Version 2.0), validation work was undertaken to confirm that the computer program is capable of producing reliable numerical results. Historical landslides in Hong Kong were back-analysed in the validation work which showed that the 3d-DMM is consistently capable of producing results that match closely the field observations. Details of the validation exercise are given in Law et al. (2016).

Figure 2: Simulated landslide motion in three-dimension using 3d-DMM (Version 2.0)

3 ENHANCED GUIDELINES ON ASSESSMENT OF DEBRIS MOBILITY

3.1 Channelised debris flows

Lo (2000) summarised the findings of back analyses and gave recommendations on the basal resistance model and the associated model parameters for natural terrain landslide simulations in Hong Kong. Lo (2000) suggested to adopt an apparent basal friction angle (ϕ) of 20° when the friction model is used, whereas ϕ = 11° and a turbulence coefficient (ξ) = 500m/s^2 (which have been found to be appropriate by Hungr (1998) and Ayotte & Hungr (1998)), were recommended when the Voellmy model is used to assess the mobility of channelised debris flows. Since the publication of Lo (2000), additional data on natural terrain landslides in Hong Kong have become available and more cases have been back analysed by the GEO.

A systematic back analysis of the known long-runout (i.e. >200 m) historical channelised debris flows in Hong Kong was completed in 2011 using 2d-DMM (Version 1.1). Based on the results, the Voellmy model would provide a better prediction of the spatial distribution of debris deposition along the runout path, as well as velocity profile where the velocity might be cross-checked against that deduced from the available information, as compared with the friction model. Also, the friction model tends to give a higher predicted velocity profile along the runout path of a channelised debris flow. Similar observations were made by Ayotte & Hungr (1998). In fact, the friction model suffers the defect of being unable to raise the basal resistance under high debris travelling velocity, which does not make physical sense in view of the presence of increased dissipative interactions such as particle collision and turbulence drag anticipated during rapid debris motion. As such, it was concluded that the Voellmy model is a better rheological model for channelised debris flows and that the recommendations of Lo (2000) on the use of friction model for channelised debris flows are no longer applicable (GEO 2011).

In addition to the choice of basal resistance model, the recommended value of input parameters for the Voellmy model for forward prediction of the mobility of channelised debris flows were reviewed with reference to the newly available field records. In particular, back analyses of selected June 2008 channelised debris flows of high mobility were carried out using 2d-DMM (Version 1.1). Based on the results of the back analyses, it is projected that approximately 99% of the June 2008 channelised debris flows were less mobile than that predicted using the recommended Voellmy parameters given in Lo (2000). Thus the recommendations given in Lo (2000) were considered to be robust for forward prediction purposes. As for the approximately 1% of the June 2008 channelised debris flows that were more mobile than that predicted using the recommended Voellmy parameters given in Lo (2000), most of these landslides involved adverse site settings and watery debris (i.e. debris mass with a very high water content) of high mobility. Adverse site settings that are prone to the development of sizeable channelised debris flows with watery debris of high mobility have been diagnosed by Wong (2009). These include the following:

- Sizeable debris flow at a major drainage line (e.g. site with a large catchment and a long flow path where a large amount of storm water and entrainable materials may be available for mixing with the landslide debris).
- Sizeable debris flow along a major drainage line into which many tributaries are feeding (i.e. possible sudden increase in the water content of the moving debris whenever the debris passes through a confluence point).
- Discharge of debris onto a pool of water on the drainage line or debris from a small drainage line onto a major drainage line, where there is a potential for a large amount of running storm water.

For forward prediction of channelised debris flow catchments that are deemed to be prone to watery debris (e.g. with any of the above adverse site settings), the following Voellmy parameters are recommended: $\phi = 8°$ and $\xi = 500\ m/s^2$. Further details of the review of the mobility modelling of channelised debris flows are given in GEO (2011).

3.2 Failures within topographic depressions

Ho & Roberts (2016) described two main types of natural terrain landslide hazards in Hong Kong, viz. channelised debris flows and open hillslope landslides. However, there are occasions where a natural terrain landslide does not fit in neither the classification of channelised debris flow nor open hillslope landslide. With continuous and focused effort in landslide study, Wong et at. (2006) introduced an additional hazard type to deal with the intermediate situation between channelised debris flow and open hillslope landslide. The new hazard type is associated with failures occurring within topographic depression catchments (TDF). Following the identification of TDF, systematic back analyses were carried out to study the runout characteristics of TDF in order to identify the suitable set of model parameters for forward prediction of TDF in Hong Kong. Historical landslides in Hong Kong were selectively reviewed, with emphasis on mobile landslides (runout distance exceeding 100 m) that occurred within topographic depressions. The site settings of these cases were reviewed using the 1:1000-scale topographic maps and aerial photographs to ensure that they are genuine TDF. The actual runout distances of the selected TDF were critically examined based on site-specific aerial photograph interpretation to discard uncertain runout measurement, such as debris runout due to secondary washout.

The turbulent action involved in the debris motion of TDF is expected to be present, though less than that of CDF. The basal resistance may, therefore, be modelled using the Voellmy model. As discussed above, when using the Voellmy model to assess the mobility of CDF, a turbulence coefficient = 500 m/s^2, is considered appropriate. Based on the numerical formulation of the Voellmy model (Hungr 1995), mobility analyses using a high turbulence coefficient, e.g. 5000 m/s^2 or more, would render the turbulence effect negligible and thus produce results comparable to those derived from the friction model with the use of the same apparent friction angle. Based on the above argument, the back analyses adopted the Voellmy model as the basal resistance model, with the turbulence coefficient within the range of 500 m/s^2 to 5000 m/s^2, by using the computer program 2d-DMM (Version 1.2).

A matrix of probable Voellmy runout parameters (Figure 3) was considered in order to identify the most appropriate set of rheological parameters for forward prediction of the debris mobility of TDF in Hong Kong. Among the rheological parameters considered, the one with apparent basal friction angle (ϕ) = 18°, turbulence coefficient (ξ) = 1000 m/s^2, give runout distances larger than the actual distances analysed for majority of the cases. Having regard to the nature of the dataset, results of the above sensitivity analyses, uncertainties involved and dependence of runout distance on the severity of rainfall, the rheological parameters, ϕ = 18°, ξ = 1000 m/s^2, are recommended for forward prediction of the debris mobility of TDF in general. Nonetheless, case-by-case assessments of the suitable input parameters are still necessary when more mobile historical landslides in the TD catchments are identified.

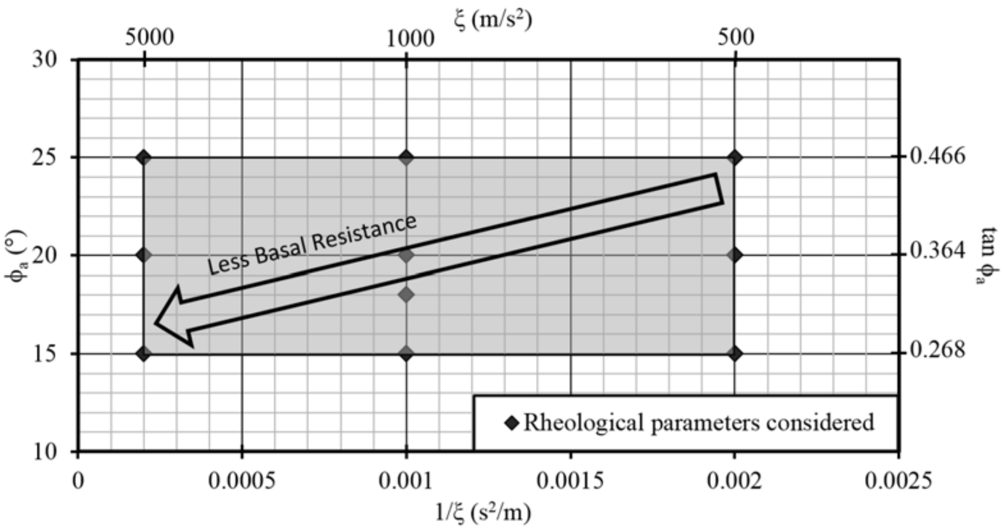

Figure 3: Range of Voellmy parameters considered (GEO 2013)

The recommended Voellmy parameters (ϕ = 18°, ξ = 1000 m/s^2) was tested against a TDF in Kau Lung Hang Shan, Tai Po, which was mapped in detail and super-elevation data were available (GEO 2006). Debris velocity at different points along the runout path were deduced from the super-elevation data, which were compared with the predicted debris velocity profile. Figure 4 shows that the suggested rheological parameters provide a reasonably good fit to both the velocity data and runout distance (within about 10%). Further details of the review of the mobility modelling of TDF are given in GEO (2013).

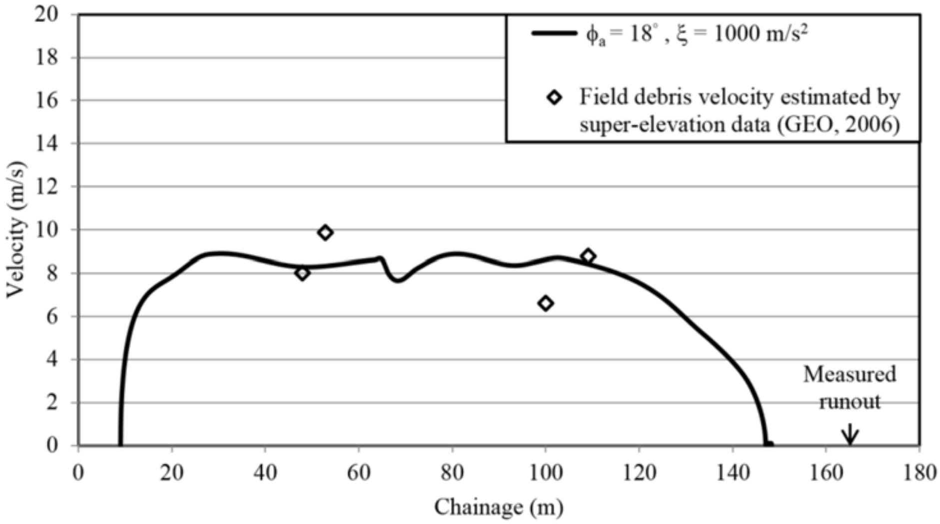

Figure 4: Comparison of predicted debris velocity profile using ϕ_a = 18°, ξ = 1000 m/s^2 and field debris velocity (GEO 2013)

4 DISCUSSIONS

GEO (2011) recommended to consider 3D debris mobility models to simulate debris flows over irregular and complex terrain profiles (e.g. without a well-defined channel alignment, drainage lines with abrupt bends, splitting of debris at bifurcation of drainage lines etc.), and estimate the lateral spread of debris at the outlets of drainage lines. With the launch of 3d-DMM (Version 2.0), the practical deployment of 3D debris mobility modelling in geotechnical study and design becomes more convenient, and thus practitioners are encouraged to use more frequently 3d-DMM (Version 2.0) or subsequent updates in their geotechnical studies and designs.

On the other hand, GEO (2011) recommended to use DEM derived from multi-return air-borne LiDAR to develop debris mobility models. Experience has been gained recently in relation to the choice of appropriate grid size of DEM for 3D debris mobility simulations. For a standard desktop computer with 8 GB of Random-access Memory (RAM), 3d-DMM (Version 2.0) handles in general DEM of about 2,500,000 pixels without encountering computational problems. This is equivalent to the use of a 2 m x 2 m DEM for most of the hillside catchments in Hong Kong. A 2 m x 2 m DEM is considered sufficiently fine to realistically represent the topography of most of the natural terrain and its surrounding features. Figure 5 shows the results of 3D debris mobility modelling in which a 2 m x 2 m DEM was adopted to simulate a number of natural terrain landslides moving along the drainage line and overflowing onto the adjoining man-made features, a dual single-lane road, and a nullah of about 6.5 m wide and 4.5 m deep. The results that the effect of the topography using the 2 m x 2 m DEM to the landslide mobility could have been duly accounted for in the simulations. A 2 m x 2 m DEM seems to provide results that strike a good balance between calculation accuracy and efficiency. Nonetheless, attention shall be paid to certain geometrical characteristics of flow paths (e.g. very narrow flow path) which may demand finer DEM grid than 2 m x 2 m.

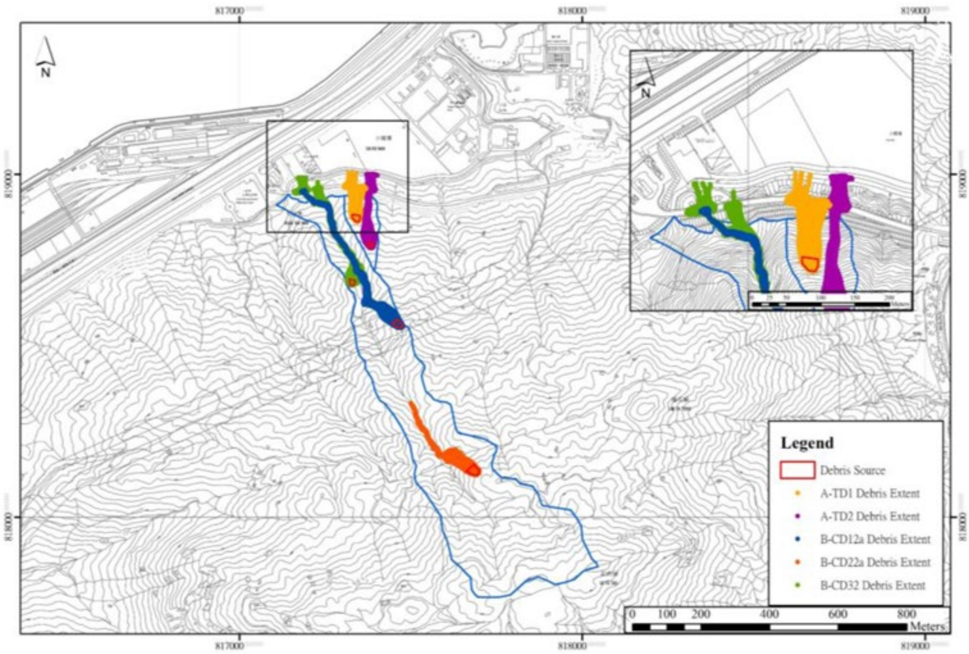

Figure 5: Example of 3d-DMM (Version 2.0) simulations using a 2 m x 2 m DEM

5 CONCLUSIONS

Debris mobility modelling has made major advances in the past decade. With the continuous improvements in computer technology and understanding of behaviour of natural terrain landslides through field observations and physical tests, more major developments in debris mobility modelling and applications are anticipated in the future.

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