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Comparison between 2D numerical and 3D finite element debris mobility modelling

Comparaison entre la modélisation numérique 2D et la modélisation 3D par éléments finis de la mobilité des débris

A.K.C. Cheung
Ove Arup & Partners Hong Kong Limited, Hong Kong, China

J. Yiu (from same institution)

ABSTRACT: This paper describes the commonly adopted 2D numerical debris mobility modelling technique in Hong Kong and discusses why this has been a preferred modelling approach by practitioners for more than 10 years. This paper then introduces some recent advances made in the development of 3D analysis for debris mobility, and presents a detailed study on the comparison of debris mobility modelling using a conventional 2D numerical software DAN-W and an advanced 3D finite element software LS-DYNA, based on a landslide event occurred in Hong Kong which impacted a building in the University of Hong Kong and damaged a temporary steel footbridge next to the building. The study concludes that using LS-DYNA 3D simulation can produce similar results as compared to the actual scenario or 2D DAN-W. Although both DAN-W and LS-DYNA can model the landslide successfully, LS-DYNA is considered to be more sophisticated and accurate. Its merits over 2D conventional analysis are discussed.

RÉSUMÉ: Cet article décrit la technique de modélisation numérique 2D de la mobilité des débris de glissement de terrain communément adoptée à Hong Kong et explique pourquoi cette méthode de modélisation est préférée par les praticiens depuis plus de 10 ans. L'article présente ensuite quelques avancées récentes dans le développement de l'analyse 3D de la mobilité des débris de glissement de terrain et présente une comparaison détaillée entre la modélisation à l'aide d'un logiciel numérique 2D classique, DAN-W, et d'un logiciel avancé de calcul 3D aux éléments finis, LS-DYNA. Cette comparaison est basée sur un glissement de terrain à Hong Kong qui a touché un bâtiment de l'Université de Hong Kong et endommagé une passerelle temporaire en acier adjacente au bâtiment. L'étude conclut que la simulation 3D avec LS-DYNA est capable de produire des résultats similaires au scénario réel et à ceux du scénario 2D par DAN-W. Bien que DAN-W et LS-DYNA soient tous les deux capables de modéliser le glissement de terrain avec succès, LS-DYNA est considéré plus sophistiqué et plus précis. Ses avantages par rapport à l'analyse conventionnelle 2D sont discutés.

Keywords: Debris mobility; LS-DYNA; finite-element modelling; DAN-W; landslide

1 INTRODUCTION

Hong Kong is situated in the subtropical zone and has a high annual precipitation. This results in the triggering of more than 300 landslides annually within the natural terrain. In recent years, due to the limited land supply for the increasing demand in residential and commercial activities, there has been a substantial increase in developments encroaching the undisturbed natural terrain areas. The accuracy in debris mobility modelling has become one of the most important aspects in respect to public safety.

2 NUMERICAL METHODS FOR DEBRIS MOBILITY MODELLING

2.1 Background

Back in the 1990s, the Geotechnical Engineering Office (GEO) (or the Geotechnical Control Office before 1991) of the Hong Kong Government focused mainly on the failures within man-made features. This is mostly because the accidents or fatality rates due to hazards arising from man-made slopes are far more than those from natural terrain landslides. Between 1983 and 2002, failures arising from any natural terrain caused 3 fatalities while man-made slope failures have caused 18 fatalities (Ng et al., 2003). Therefore, only until the early 2000s when most of the man-made features have been either studied or upgraded, the Government changed their focus to mitigating natural terrain hazards.

In order to better predict landslide motion distance and velocity for hazard risk assessment and for design of mitigation measures, and to better estimate the area that may potentially be affected by the movement of potential landslide, there is an increasing demand for more accurate debris mobility modelling tool.

Due to the advance in computational power in recent years, different numerical techniques and computer-based models now exist and they are capable of simulating large deformation in 3D. It is important to compare the current state-of-the-art program with conventional model.

2.2 2D-numerical method - DAN by Hungr (1995)

In 1995, Professor Oldrich Hungr developed a numerical model (Hungr, 1995) which is a continuum model based on Lagrangian finite difference scheme with the ability of selection of a variety of material rheologies. In his model, run-out parameters including maximum distance reached, debris velocity, thickness, as well as distribution of debris deposits, behaviour in bends and at obstacles along debris runout can be modelled.

After the publication of his paper and model, GEO has commissioned a pilot study where 20 selected notable natural terrain landslides were back-analysed using the DAN developed by Hungr (1995). The results shown that, with the proper selection of parameters including base friction angle and turbulence coefficient, the DAN can model the 20 natural terrain landslides satisfactorily under Frictional or Voellmy Rheology (Ayotte & Hungr, 1998). The DAN model was further improved with a pseudo three-dimensional platform. It gives users the flexibility of modifying the channel cross section geometry. Users can also pre-define the change in the width and depth of the run-out path by using polynomials. This revised DAN was named as DAN-W. Due to its user-friendly interface and accurate prediction of debris-mobility in pseudo-3D environment, it has been a commonly adopted debris mobility program for more than 10 years.

2.3 3D-finite element method – LS-DYNA

With the need of more precise debris mobility modelling for natural terrain hazard study, Chen & Lee (1998) first proposed a 3D modelling software to model landslide. In addition, another widely used 3D model called 3D-DMM has also been proposed to study landslide.

Recently, the GEO has been looking into even more sophisticated and advanced numerical software to understand debris flow characteristics as well as flexible barrier – debris interaction. LS-DYNA was introduced by Arup and was accepted as an approved debris mobiltiy assessment software by GEO by 2017, after the completion of the pilot numerical investigation of the interactions between landslide debris and flexible debris-resisting barriers study.

LS-DYNA is a multi-purpose finite element program capable of simulating highly dynamic and large deformation problems. Its fully automated contact analysis and wide range of material models enable users worldwide to solve complex real world problems in various engineering disciplines. LS-DYNA was proven as an advanced numerical modelling technique for debris mobility modelling.

3 THE COMPARISON

3.1 Overview

The following commercially available computer programs, which are both accepted by GEO as a verified debris mobility modelling software, were employed for the comparison work:

i) 2D Numerical – DAN-W
ii) 3D Finite Element – LS-DYNA

A well-documented landslide was chosen for the study and debris mobility modelling has been carried out in DAN-W and LS-DYNA. Results such as runout distance, runout extent, thickness of debris and frontal velocity at selected observation point were compared.

It should be noted that whilst the required inputs for each program are slightly different from each other, best effort have been made to ensure all input parameters were consistent, such that their influence on the comparison result were kept to minimal.

3.2 The Sample Case

The natural terrain landslide behind Chow Yei Ching (CYC) Building of the University of Hong Kong (HKU) (hereinafter refers as "the landslide") was adopted. The details of the landslide incident are available in the Landslide Study Report LSR 3/2009 (GEO, 2009). The landslide was located at approximately 100m above CYC Building of HKU. Figure 1 shows the aerial photograph of the landslide after the landslide incident. The landslide comprises two source area, viz. the primary source area and the secondary source area. The primary source area involved a detachment of approximately 1,750m³ of debris of which about 220m³ remained within the source area. Therefore, about 1,530m³ of materials was completely detached from the source area. The crown of the primary source area was situated at around +192mPD. The secondary source area involved a detachment of approximately 210m³ of debris. The crown of the secondary source area was situated at around +145mPD. With the additional entrained debris along the run-out trail, over 2,000m³ of debris ran down the hillside and flowed down to CYC Building. The landslide travelled a total distance of over 210m at an apparent travel angle of 29°.

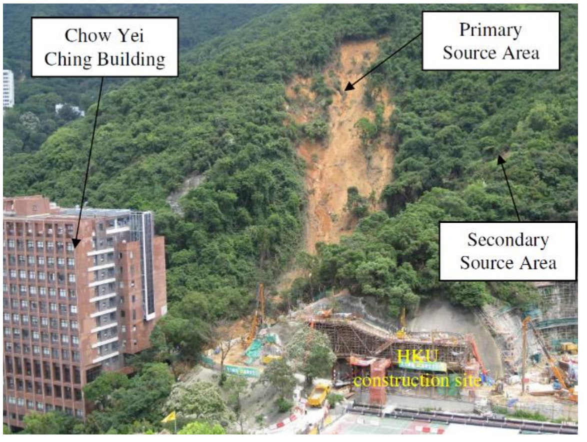


Figure 1. An aerial photograph of the site after the landslide incident (extracted from LSR 3/2009)

3.3 Mechanisms of Failure

In order to model the landslide correctly, i.e. with the correct choice of parameters, it is necessary to understand the mechanisms of failures. According to the LSR 3/2009, the mode of failure of the primary source area was predominantly open hillslope failure until the debris reached the confluence point of the secondary source debris trail. The debris then became channelised until it reached the CYC building. As a result, this landslide theoretically can be seen as a combination of open hillslope and channelised landslide. Careful selection of different parameters and rheologies is considered crucial.

3.4 Reasons for choosing this landslide for simulation

1. This landslide was well-documented in GEO Landslide Study Report. Site observation, photographs and detailed digital survey records are available for the Study.

2. This landslide comprises two source areas and has affected a building structure. Therefore, the landslide can provide a more complicated yet interesting research subject of significance.

3. The landslide comprised two source volumes of 1530m³ and 210m³ respectively, which are comparable to the source volume of the natural terrain landslide commonly occurred in Hong Kong.

3.5 The model setup

Figure 2 and 3 show the model setup in DAN-W and LS-DYNA for the landslide respectively.

In DAN-W, the runout profile characteristics and potential debris flow trajectory were based on GIS assessment using the available topographical data. Debris was modelled as a continuum mass based on Lagrangian finite difference scheme. The primary and secondary landslides have to be modelled separately.

In LS-DYNA, the topography was made up of quadrilateral rigid shell elements. The debris mass was modelled in LS-DYNA as Arbitrary Lagrangian-Eulerian (ALE) material, which adopted an adaptive meshing technique such that the large deformation and movement of the debris mass during the landslide can be properly simulated. The primary and secondary landslides are modelled in one single model, to allow mixing of debris at the drainage convergence point.

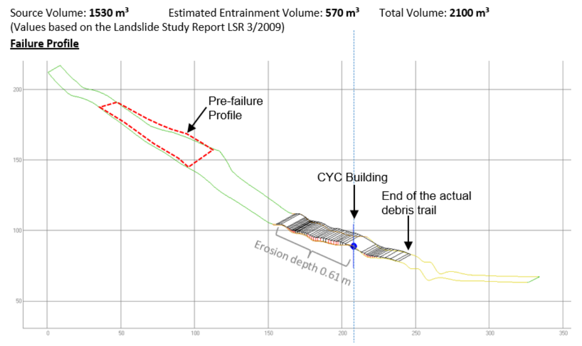


Figure 2. Model Setup in DAN-W

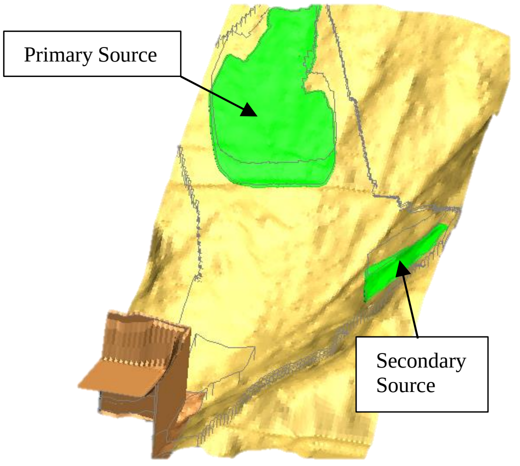


Figure 3. Model Setup in LS-DYNA

3.6 The Input Parameters

Debris source volume and unit weight generally followed what have been described in LSR 3/2009 (GEO, 2009). The most sensitive input parameters in debris mobility modelling are the rheology used (Voellmy or frictional rheology), basal friction angle (ϕ_a), turbulence coefficient (ξ) and internal friction angle (ϕ_i). In general, both DAN-W and LS-DYNA are sensitive to basal friction angle and turbulence coefficient but DAN-W is less sensitive to internal friction angle.

A number of back-analysis were carried out in both DAN-W and LS-DYNA in order to obtain the best-fit set of parameters. They are summarised in Table 1 below.

Table 1. Summary of the best fit parameters adopted in the DAN-W and LS-DYNA Model

Model Type	Basal Friction Angle	Int. Friction Angle	Turbulence Coefficient
DAN-W	19° (Pri. Source) 11° (Sec. Source)	32	500 m/s²
LS-DYNA	19°	25	500 m/s²

Note: In LS-DYNA, other material properties such as density, shear modulus, bulk modulus are required for input. They are assumed value and are not sensitive to the analysis

3.7 Results

3.7.1 DAN-W

The DAN-W results for both primary landslide and secondary landslide are given in Table 2 below.

Table 2. Summary of DAN-W results

	Primary Landslide	Secondary Landslide	Total
Travel distance downslope of CYC	30m	35m	35m
Maximum debris thickness at CYC	1.11m	0.34m	1.45m
Debris velocity at CYC	6.81m/s	3.79m/s	6.81m/s
Volume passing CYC	540.2m³	131.2m³	671.4m³

As the models were simulated using the best fit parameters from back-analysis using DAN-W, the predicted run-out distance matched very well with the actual debris trail runout. The sum of the thickness of deposits of the two landslides in Case 3 Model is 1.45m, which is slightly lower than the recorded thickness of 2-3m.

The results suggested that the DAN-W model using best fit parameters can simulate the debris flow with very high degree of accuracy. However, the best fit paramters must be obtained through a number of trial-and-error processes and involved enginering judgement. If the natural terrain catchments overlooking a study area have insufficient amount of past landslides, back-analysis cannot be carried out.

3.7.2 DAN-W limitations

For DAN-W analysis, the major deficiency is that landslide can only be modelled in 2-dimension. The extent of the final deposition of debris cannot be modelled. The “blockage effect” of the CYC Building cannot be simulated. Debris thickness cannot be obtained in 3D space.

In addition, the debris run-out paths are based on the critical flow-paths generated using LiDAR data. In some circumstances, like when there is a bifurcation along a flow-path, all the debris can only be modelled in one single direction.

3.7.3 LS-DYNA

The LS-DYNA results are given in Table 3 below.

Table 3. Summary of DAN-W results

	Both Primary and Secondary Landslide
Travel distance downslope of CYC	28m
Maximum debris thickness at CYC	3.8m
Debris velocity at CYC	6.24m/s
Volume passing CYC	N/A

Again, the predicted runout distance matched very well with the actual debris trail runout. Graphical output (plan view) of the LS-DYNA simulation at 70.0s (top) compared to the actual debris trail (left) are shown in Figure 4. The maximum debris thickness when the debris came to rest was 3.8 m as recorded in LS-DYNA. At the corner of the CYC building, the modelled debris thickness was 3.4 m (Figure 5). As compared to the recorded debris thickness 2-3 m in LSR3/2009, the modelled debris thickness appeared to be slightly thicker than the actual scenario. The velocity results suggested that the resultant velocity of both primary landslide and secondary landslide from LS-DYNA results resembled closely to the DAN-W results.

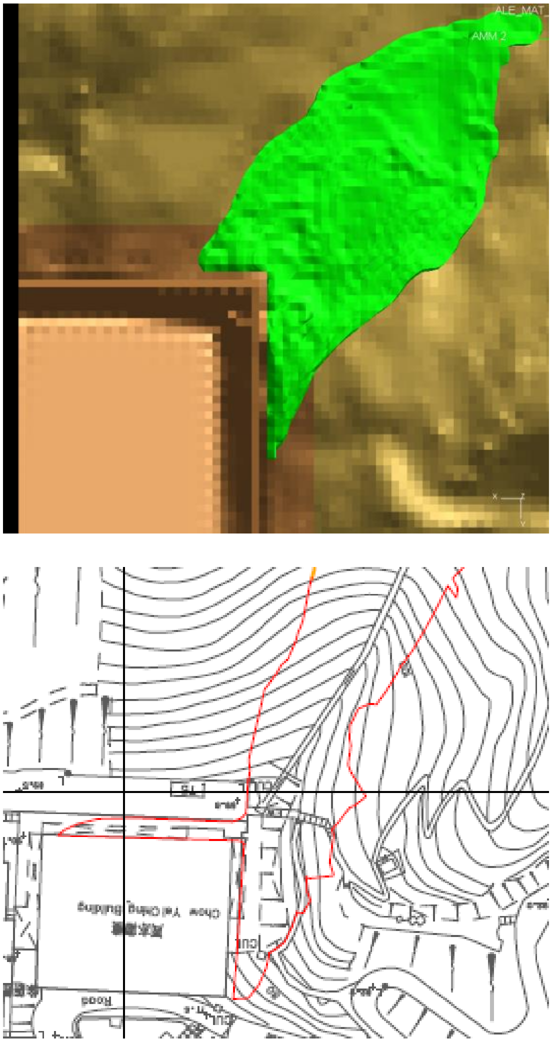


Figure 4. Graphical output (plan view) of the LS-DYNA simulation at 70.0s (top) compared to the actual debris trail (extracted from LSR3/2009) (bottom).

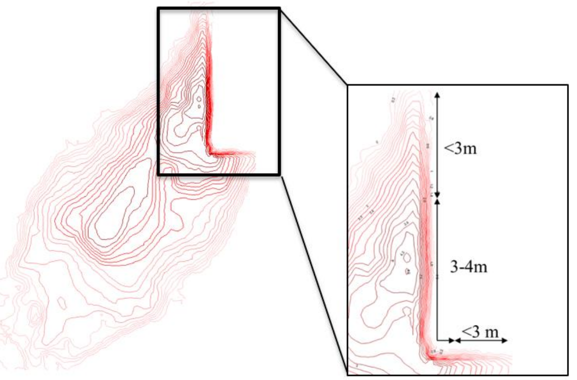


Figure 5. Debris thickness contours at 70s of the debris at rest in the LS-DYNA simulation

4 DISCUSSION

4.1 LS-DYNA strength over DAN-W

LS-DYNA was able to capture the landslide simulation of every 0.01s, or even smaller, which was controlled by the computational power of the machine. Results can be displayed in timesteps set by user. In this landslide model, the results were displayed in each 0.1s interval. In each 0.1 second, all information including displacement, velocity, rotation and acceleration in x,y,z directions were recorded. With such detailed information, variation of these output versus time can be obtained for every nodes. Researchers will be able to focus on part(s) of the landslide that they are specifically interested in. This is not possible to do in 2D software such as DAN-W or 3D software such as 3d-DMM.

LS-DYNA is also able to simulate soil-structure interaction. Unlike DAN-W or 3d-DMM, barrier structure, like rigid barrier or flexible barriers can be explicitly modelled within a single interface. The effect acting on the soil by the barriers can be simulated. An experienced user can also make changes to programme code to tailor made the programme based on user's need.

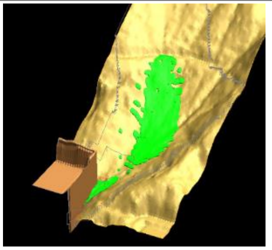
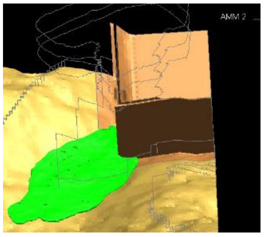
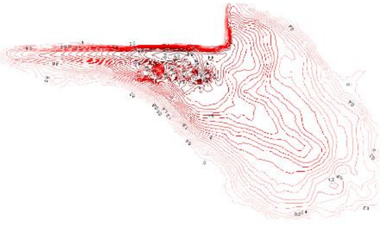
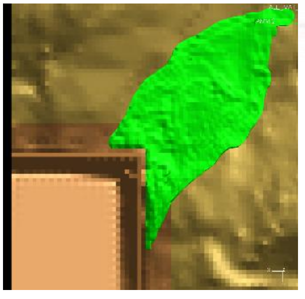
Items	HKU Landslide Case Illustration	LS-DYNA / DAN-W	Graphical Illustration
Interaction between debris from difference sources	Interaction between the debris from the primary and secondary source area	LS-DYNA ✔ DAN-W ✗	
Debris-structure interaction	Blockage effect of the CYC Building	LS-DYNA ✔ DAN-W ✗	
Generation of debris thickness contour	Debris thickness at CYC Building	LS-DYNA ✔ DAN-W ✗	
Areal extent	Areal extent at specific time	LS-DYNA ✔ DAN-W ✗	
Bifurcation of debris trails	Bifurcation of landslide debris at CYC Building	LS-DYNA ✔ DAN-W ✗	

Table 4 Summary of LS-DYNA strength over DAN-W

A summary of LS-DYNA strength over DAN-W, with case illustration, is shown in Table 4 above.

4.2 LS-DYNA Limitation

LS-DYNA required a trained, technically competent user to use. It comprises a sophisticated interface incorporating a large number of functions. It may take some time to explain the modelling process to individual who are not familiar with the software.

In the LS-DYNA simulation of the landslide behind Chow Yei Ching Building of the University of Hong Kong, it takes more than 47 hours to obtain result of the first 60 seconds of the landslide. Here the computational power of the machine will be the crucial factor. Unlike 2D software such as DAN-W, owing to such long computational time, it will be extremely time-consuming to obtain different results by changing certain parameters. For example, in DAN-W, it is a usual practice to use a trial and error method to obtain the best fit parameters when carrying back-analysis of a landslide. However, in LS-DYNA, it may take more than a week to obtain a reasonable set of parameters. In this study, the LS-DYNA simulation is based on the best fit parameters obtained by the DAN-W modelling, which could save some time.

In the most up-to-date development of LS-DYNA technology, there is no direct way to calculate the volume of debris passing through a specific plane or point under the LS-DYNA simulation. In addition, entrainment along debris run-out trail cannot be modelled.

5 CONCLUSIONS

Natural terrain landslide modelling using 2D software DAN-W has been widely used by practitioners in the past 10 years, particularly due to the implementation of Landslip Prevention and Mitigation Programme (LPMitP) initiated by the GEO.

Recently, LS-DYNA has been proven a highly sophisticated software for debris mobility modelling (Cheung et al., 2018). The use of LS-DYNA for debris mobility modelling in all Government and private projects has been approved by the GEO of Hong Kong Government by 2017. Based on a case study on the comparison of natural terrain landslide modelling demostrated in this paper, LS-DYNA demonstrated its strength in modelling natural terrain landslide over DAN-W. Local practitioners are akin to use 2d conventional software such as DAN-W or 2d-DMM for natural terrain landslide. This is reasonable for most cases. However, for some special landslides like the landslide modelled in this study, when debris interaction from different sources, bifurcation of landslide debris and debris-structure interaction are anticipated, 3D numerical software LS-DYNA could be used to model these scenarios.

6 ACKNOWLEDGEMENTS

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