The case study of Badouzih rockfall in northern Taiwan: mechanism, numerical simulation and hazard assessment

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ABSTRACT

The aim of this study is to reconstruct the rockfall movement trajectory and runout distance for understanding the falling dynamics in northern Taiwan. The Badouzih rockfall was triggered by rainfall on August 31st, 2013 in Keelung City in northern Taiwan. A 43 m^3 volume rock was detached from the summit of the hillslope by toppling failure near 68K, Highway Route 2. The rockfall hazard caused road closure and car crush with the giant falling boulder. The field survey showed that the weathering process led to the extension of joint, during the heavy rainfall, the infiltration and the surface runoff washed the weathered material away, lead to the unstable and the fallen of the rock. The process can be divided into roll, fall and bounce, taking about 23 seconds in total. With the video record and the field investigation, a three dimensional numerical model (RAMMS::ROCKFALL) characterized by irregular block shape was adopted and verified in this study.

KEYWORDS

Rockfall; Badouzih; RAMMS; rock shape; trajectory

INTRODUCTION

Rockfall and debris slide are geologic hazard which occur in the costal mountainous area and usually been triggered by intense weathering and heavy rainfall. Rockfall can be categorized as a failure behavior of rock mass at a steep slopeland and weak joint plane (slope >55 [deg.]; Central Geological Survey). The moving type of rockfall is consist of fast free falling, toppling, rolling (with an obvious trajectory), and bouncing based on the landform, fragmentation condition, and strength of rock mass. The literature reveals the number of rockfall events between 82K-139K of Highway Route 2 (or called Northern Coastal Highway) reached 84 during the period between 1994-1996 (total volume: 25,500 m^3). The spatial distribution of historical rockfall (1994-2003) on Highway Route 2 demonstrates it has a highly dependence on the seasonal climate, especially in autumn and winter.

So far, a large number of computer numerical approaches have been developed for quantitative and modelling rockfall behavior based on different mechanical frameworks. The common numerical program for rockfall hazard analysis includes the following four methods: (1) Lumped mass approach (LMA); (2) Rigid body approach (RBA); (3) Discrete element method

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(DEM); (4) Discontinuous deformation analysis (DDA). The approaches mentioned above provide the user the information of energy, trajectory, moving velocity, and jumping height of dangerous rockfalls, so the corresponding analysis of rockfall hazard can be performed for both advanced engineering practice and protective measures (Agliardi et al.,(2009); Cottaz et al.,(2010); Chen et al.,(2013); Leine et al., (2014); Giovanni et al.,(2015). We therefore use the RAMMS (RApid Mass Movement System) for reconstructing the 3D rockfall behavior and runout distance for understanding the characteristic of Badouzih rockfall event on August 31st, 2013 (Figure 1, inset). In the paper, the available video record from dashboard camera (source: YouTube), remote sensing interpretation, geologic parameter collection, and field survey are summarized to reconstruct the failure mechanism of the rockfall. The approach allows us to build an irregular rock shape similar to the one in question instead of the typical spherical particle shape. The result of the 3D numerical simulation was compared with 2D Rocfall studies (Wei et al., (2014)). As a result a rockfall hazard map for this study site is produced and validated.

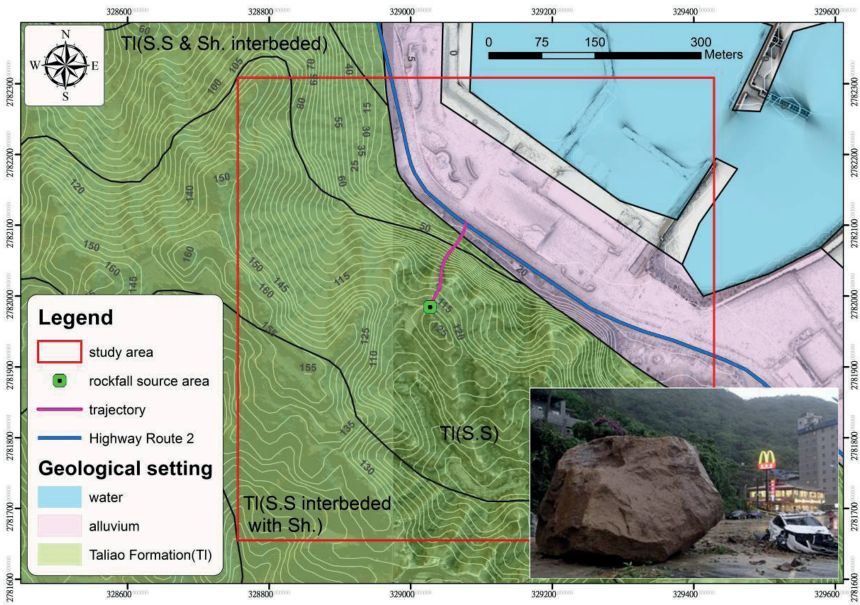

Figure 1: Study area and geological setting of Badouzih, Keelung (Central Geological Survey, 1988, scale: 1/50,000).

STUDY AREA AND METHODOLOGY

The study area is located near Badouzih Harbor, about 10 km northeast of downtown Keelung City, northern Taiwan. The annual mean rainfall and averaged rainy days are 3,772 mm and 197.6 days, respectively (Central Weather Bureau, from 1981-2010). The toe of the hillslope is encircled by Highway Route 2 (Figures 1, red rectangular area). The study area consists mainly of calcareous massive sandstone belonging to the Taliao Formation which features ridges and escarpments along the northern rocky coast. Apparently, as shown in Figure 1, the Taliao formation of rockfall area includes two types: one is sandstone (S.S), and another one is sandstone and shale interbedded (S.S & Sh. Interbedded). The attitude of the bedding plane is approximately N81°E/8°S and the attitude of the slope surface at the source area is approximately N70°W/35°N, forming an anaclinal slope. Regarding to the regional landforms, both intense erosion and weathering processes along the northern coastline forms a landform which characterized by steep cliffs (slope: 35°-80°). In addition, the environmental geological map published by the Central Geology Survey also indicated that the study area is situated in a high rockfall susceptibility zone. The highest rainfall intensity of 94.5 mm/h (August 31, 2013 15:00-16:00) occurred in the Keelung area during the influencing period of the Typhoon Kongrey. The rockfall disaster was triggered at 16:19 after orographically rainfall. The intensity-duration-frequency analysis demonstrated that the short-term rainfall of approximately a 100-yr recurrence period plays a dominant role for triggering the rockfall event.

To analysis the Badouzih rockfall event, aerial image interpretation (produced in 2004), digital terrain model (resolution: 5 m), field investigation, and rainfall data in the region were prepared and analyzed to understand the triggering mechanism and dynamic process firstly. Secondly, the parameter of environmental geology and dimension of rockfall were extracted to input in the numerical simulation. Three dimensional numerical simulation RAMMS was employed to study the dynamic characteristics of the rockfall event. RAMMS is a numerical modelling tool which developed by the WSL Institute for Snow and Avalanche Research SLF, and is used to predict and assess the natural hazard such as snow avalanche, debris flow, and rockfall. The RAMMS:: ROCKFALL module suggests a hard rigid-body approach and involves many types of contact drag force on complex terrain (for detailed theoretical background please see Leine et al., (2014) and Glover et al., (2015)). RAMMS can compute runout trajectory over terrain, including jump heights, velocity, rotational velocity, total kinetic energy and contact-impact force with 3D visualization. We defined a similar rock by using rock builder while measuring the size of the rock deposited on the highway (Table 1). To ensure the appropriate simulation for Badouzih rockfall event, the different geological setting and forest roughness were considered to describe the rockfall dynamic characteristics (Table 2). The initial condition of release rock was set by trial and error method to trigger the rock sliding based on the interpretation of video record. Furthermore, the batch of numerical runs for rockfall simulation was performed for the purpose of assessing the influence area in this study.

Table 1: Parameter used for reconstructing the rockfall shape in the study.

Parameter	value	reference
size of rockfall [m]	4.54 * 4.09 * 3.84 m	in-situ measuring
elevation of source area [m]	119	in-situ measuring
density [kg/m^3]	2,650	experimental result
release point (x, y)	(329028, 2781980)	aerial image(TWD97)
initial rotational velocity (X, Y, Z) (rad/s)	(0.3, 0.5, 0)	video record
rock type	Equant_1.3	calculated by RAMMS
rock mass [ton]	115.44	
rock volume [m^3]	42.75	

Table 2: Geologic parameters used in the RAMMS simulation

No.	terrain material		friction	reference
1	TI (S.S)	colluvium	0.25 (soft)	in-situ measuring
2	TI(S.S and Sh. interbedded)	colluvium	0.25 (soft)	in-situ measuring
3	Road and Fishery Harbor	concrete	0.40	in-situ measuring
4	Forest type	Height [m]	Drug [kg/s]	
	medium	1.5-3.0	1500	in-situ measuring

RESULTS AND DISCUSSIONS

With respect to the failure mechanism of rockfall, field investigation shows the event is composed of four successive movement behavior from source area to the toe, including rolling, falling, bouncing, and rolling (Figure 2). Evidently, one can observe the collapsed rock leaves a long trace on the gentle slope, and falls at the breakpoint on the cross-sectional profile (point **a** in Figure 2(a)). A falling vertical height of 40 m impacted and made a deep pit in the soft talus material (point **b** in Figure 2(b)). The following bouncing down the slope

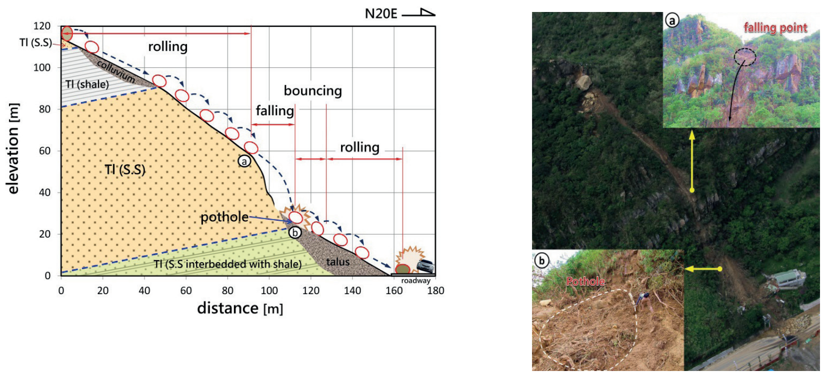

Figure 2: (a) Analysis of rockfall trajectoryon the cross-sectionalprofile (revised form Wei et al., (2014)) and (b) field survey verification displayed on aerial image taken by UAV (source: GIS Center, FCU, Taiwan).

crashed into the houses situated along the rockfall path. The rock was rolling in the lower part of the talus before it stopped on the highway.

Figure 3(a) shows 3D rockfall trajectory, contact points, and velocity as a function of horizontal distance. In comparison with the observed rockfall path (erosion marks) on the aerial image, both rockfall trajectory and stopping point in RAMMS simulation is much similar to the mapping result (Figure 3(c), (d)). The post-disaster mapping form the aerial image confirmed the exactly trajectory of rockfall and was compared with the simulation. The simulated result indicates the rolling motions of rock occurs on the upper part of the the gentle slope (H=55 to 120 m), then it increases the moving velocity at the steep slope with bouncing until it impact the talus (H=25 to 55 m). As shown in Figure 3(b), the RAMMS::ROCKFALL model predicts a maximum rockfall speed of 20.5 m/s at the breakpoint of the slope during the bouncing stage of the rockfall trajectory. The contact points and movement patterns predicted by the model match with field observations and preliminarily demonstrate that the RAMMS::ROCKFALL model accurately depicts the rockfall disasters.

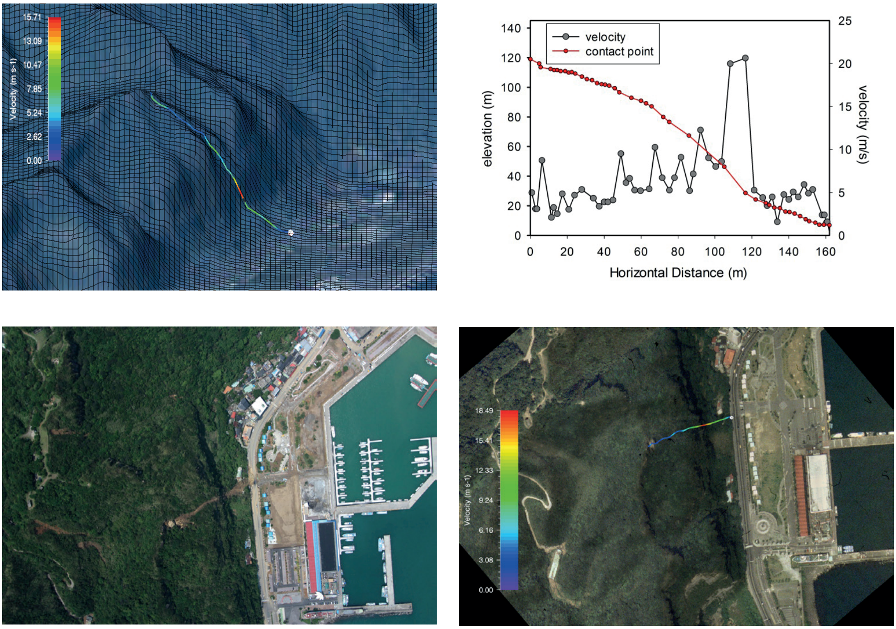

Figure 3: The results of numerical simulation RAMMS-Rockfall: (a) 3D rockfalltrajectory and (b) velocity and contact points for Badouzih rockfall event; (c) the real rockfalltrajectory on the aerial image and (d) simulation trajectory in RAMMS.

Figure 4 shows rockfall speed and trajectory predicted by RAMMS compared to 2D model results reported by Wei et al. (2014). In general, both speed and trajectory predicted by the 3D model are less than 2D model predictions. However the distribution of speed and kinetic energy is similar. Differences between the models may be due to (1) Rock shape: in the 2D rockfall model, rocks are represented as particles and have few contact points with the slope; therefore the resistance to movement is lower. (2) Topographic model accuracy: a DTM of the actual landslide terrain is used in the RAMMS model and rockfall is affected by the three dimensional characteristics of the terrain. Consequently, the travel path of the particles in the three dimensional model differ from the travel path affected by a single two dimensional profile and resistance to movement resulting from topography is more evident. (3) Forest drag: using parameters that describe the vegetative cover of the terrain, RAMMS applies a corresponding drag and rock fall is subjected to an additional energy dissipation effect.

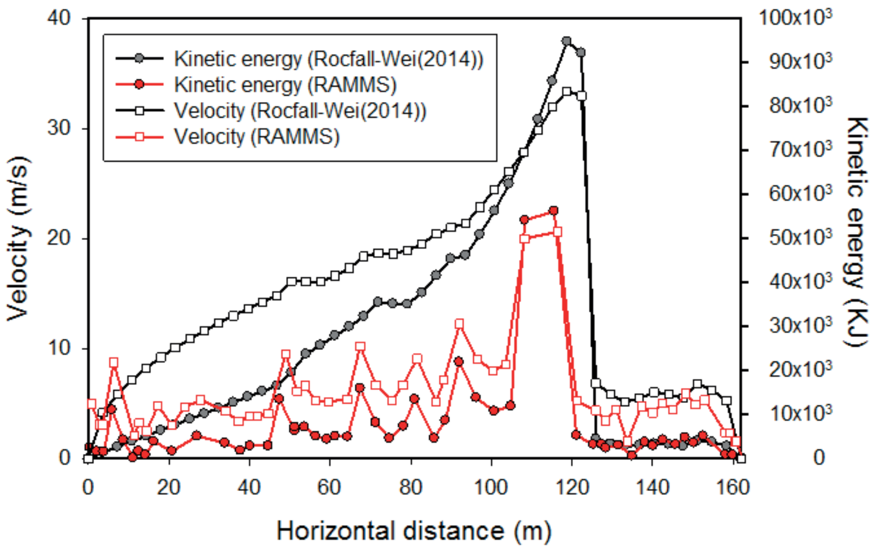

Figure 4: Comparison of velocity and kinetic energy for the simulation results between 3D RAMMS and 2D Rockfall.

The accuracy of the DTM affects the surface roughness applied to the rockfall. As the accuracy of the DTM is increased to levels typical of LiDAR measurements, the detailed representation of the topography causes surface roughness to increase. Crosta et al., (2015) modeled rockfall using a 2, 6 and 20 m resolution DTM. The high resolution DTM caused dispersion of the particle trajectories. To better understand the distribution and "hotspot" of rockfall predicted by RAMMS::ROCKFALL model, applying the same initial conditions, the calculations were repeated 100 times. Results are shown in Figure 5 for a 5 meter resolution DTM. Within the study area, there are two zones which have a high potential for rock fall. The gully at the left of the source area has a 55% probability of rockfall and is near the travel path of rockfall that has historically caused rock fall disasters. Additionally, 30% of the rockfall travels along the right gully and the last 15% of the rockfall volume remains suspended on the slope. In this study, the rockfall energy classification methodology described in Wei et al., (2014) was applied to categorize the hazard level of the modeled rockfall trajectories. Results demonstrate that Highway Route 2 and parts of the fishing port are within the rockfall hazard area. Mean velocity and kinetic rockfall energy are predicted to be 6.9 m/s and 5,968 KJ and deposition occurs 40 to 80 m (52%) from the actual rockfall location associated with the rockfall disaster. These results demonstrate that the RAMMS::ROCKFALL model is more effective than the 2D model for identifying rockfall disaster extent. Therefore, RAMMS may be suitable for warning and evacuation planning analysis.

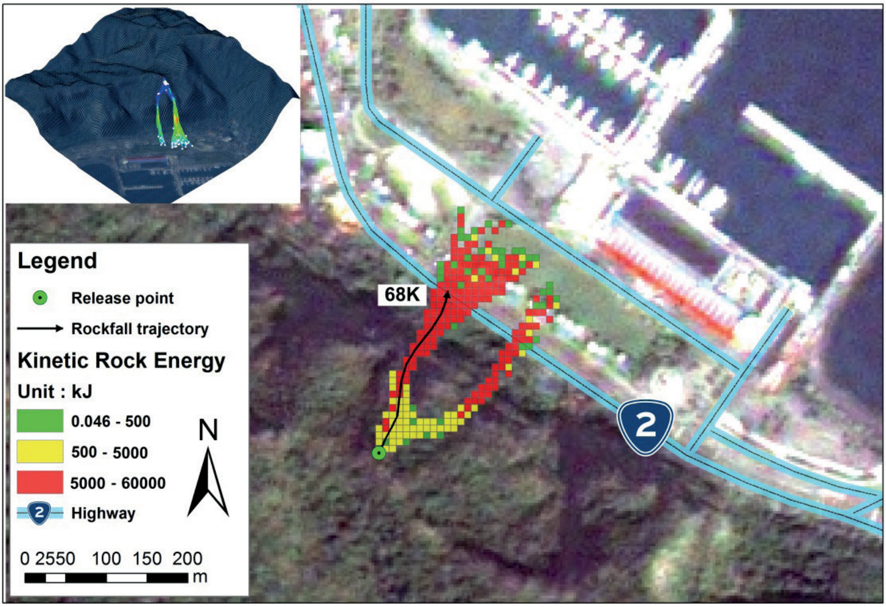

Figure 5: The kinetic rock energy map generated from batch runs in RAMMS: Rockfall (grid cell: 5x5 m).

CONCLUSIONS

The well-known Badouzih rockfall hazard triggered by rainfall on August 31st, 2013 in Taiwan was explored by 3D numerical approach in the study. RAMMS::ROCKFALL is able to integrate the detailed block shape, terrain material, and initial condition to modelling three-dimensional rockfall event. With comparing to the 2D numerical simulation in Badouzih rockfall event, the 3D simulation reveals the resolution of input DTM (surface roughness) and rock shape are main influenced factors to control the moving trajectory under the same initial and boundary conditions. However, the rolling, slipping and bouncing trajectory in Badouzih rockfall simulation presents a similar result in comparison with field survey. For the demand of reducing disaster consequences, the hazard map which associated with rock mass strength assessment (frequency) and numerical simulation (intensity) around alpine region can help predicting future rockfall occurrence.

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