# Rockfall Field Test at Tung Shan Terrace, Hong Kong

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Abstract: A series of rockfall field tests was carried out at a slope at Tung Shan Terrace, Hong Kong, which locates above the Stubbs Road. The two-fold objectives of the rockfall field test are to demonstrate the effectiveness of the rockfall fence and to provide useful data of coefficient of restitution. Over 50 rockfall tests were conducted. The mass of the cubic and rectangular boulders range from 16 kg to 300 kg. Impact energies of the boulders are from 0.8 kJ to 14.7 kJ. The maximum observed tangential and normal coefficients of restitution were about 0.65 and 0.4. The depth of holes in soil indented by the boulders can be up to 0.2 m. Angular rotations are induced during inclined impacts, and the rotational speed is roughly proportional to the tangential coefficient of restitution. Lateral dispersion of the rebound phase was also reported. This study provides the first well-documented rockfall field test in Hong Kong.

## 1 INTRODUCTION

Rockfall is one of the natural hazards posing problems to mountainous regions in the world. Although the hazard of rockfall is generally underestimated by the general public comparing to landslides, the potential damages caused by rockfall can be enormous. The magnitude of some infrequent events of rockfalls and rockslides can be extremely large. The Elm, Frank, and Hiem rockslides or rockfalls are notable examples (e.g. Whalley 1984, Flageollet & Weber 1996). Rockfall mitigation is extremely important in protecting highways and residents in the mountainous countries. For a comprehensive review of the rockfall problems, we refer to Giani (1990), Richards (1988) and Chau (1997). Analysis for rockfall data in Hong Kong was also done by Chau et al. (1998).

To reduce the rockfall hazard, ditches, cable nets, rockfall shelters, and rockfall fences, have been widely used. The design of these rockfall mitigations requires estimation of the horizontal and vertical travel distances of the probable rockfall events, the bouncing height at various positions along the slope, as well as the impact energy of rockfalls at locations at which these mitigation devices are to be installed. The common practice to acquire such information relies on computer simulations (e.g. Wu 1985, Spang & Sonser 1995, Pfeiffer & Bowen 1989, Hungr & Evans 1988). The main uncertainty in the output of the rockfall simulations comes from our limited knowledge and data on the coefficient of restitution, parameters controlling the amount of rebounding after each boulder impact. It is well-known that the coefficients of restitution are not material parameters (Wu 1985, Richards 1988, Spang & Sonser 1995), but yet no comprehensive effort has been made to quantify the coefficient of restitution in terms of the impact energy level, the shape of the boulder, the roughness of the slope surface, the deformability of both the boulders and slopes, and the angle of impact. The main reason for this drawback may be due to the fact that field testing is quite expensive and time consuming and it is difficult to control the conditions of each in-situ impact. Thus, a series of rockfall experiments done in laboratory were proposed by Chau et at. (1999) and Wong et al. (2000).

However, the validity of the laboratory-based coefficient of restitution must be demonstrated by field observation. Therefore, a rockfall field test was carried out recently at Tung Shan Terrace, Hong Kong. This is the first time that a comprehensive field test was carried out in Hong Kong. It should path the way for the future works of rockfall field tests. In addition, the performance of a rockfall fence system at the site was examined. This is also the first rockfall fence system used in any private project which has been designed using the rational approach, instead of using the conventional safety fence.

Various rockfall field tests have been carried out in the past. The first field test was apparently done by Ritchie (1963). Subsequent field tests include those by Bozzolo et al. (1988), Beggs et al. (1984), Broili (1977), Wu (1975), Bozzolo & Pamini (1986), Azzoni *et al* (1991), Evans & Hungr (1993) and Robotham et al. (1995).

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## 2 ROCKFALL FIELD TEST

### 2.1 *Test location and test conditions*

The tested site is located at No. 21, Tung Shan Terrace, which is just above the Stubbs Road on the Hong Kong Island. Figure 1 shows a photograph of the location of the field test. Figure 2 shows a typical section at the site, showing the platform, slope, wall, rockfall fence, and bamboo scaffolding.

A masonry wall existed along the site boundary with height varying from 10 m at northern boundary to 5 m at western boundary. The proposed rockfall fence was erected along the toe of the masonry wall (see Figures 1-2). The locations for releasing boulder are also shown on Figure 1. The boulders were released by pushing them over the top of the existing platform of the concrete deck (which is to be demolished) at the elevation of about 111.79 mPD. The falling height was from 4.5 m to 5 m, depending on the size of the boulders.

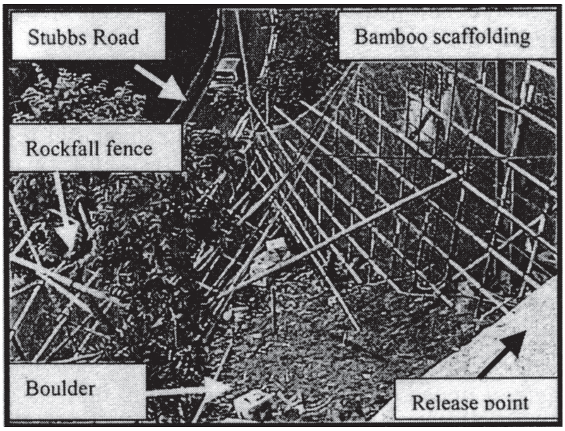


Figure 1. A photograph of the test site at Tung Shan Terrace

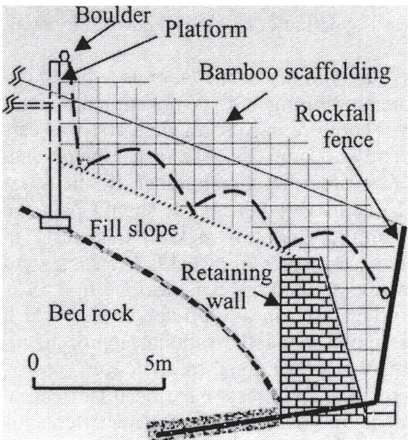


Figure 2. A typical section for Figure 1 at Tung Shan Terrace

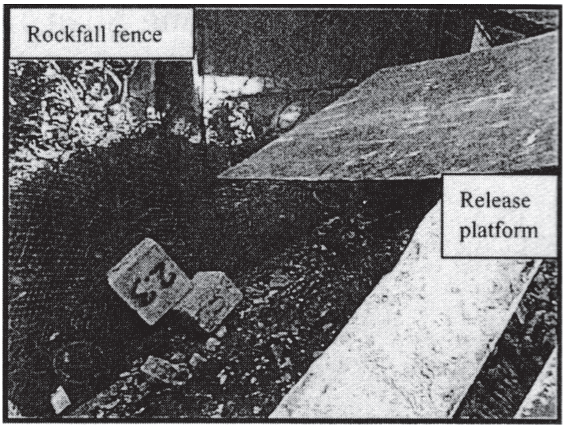


Figure 3. A photograph showing the release platform and the rockfall fence tested at Tung Shan Terrace

The Stage I field tests aimed to determine the coefficient of restitution for boulders of varying sizes falling onto the soil slope surface at Tung Shan Terrace. The Stage II field tests were to assess the performance of the Geobrugg rockfall fence. Figure 3 shows a photo for the rockfall fence test.

### 2.2 *Boulder sizes and number of tests*

There were 6 main groups of boulders. Each group was of different sizes, and the corresponding masses varied from 16 kg to about 300 kg. All boulders were cast from a concrete of density of about 2400 kg/m$^3$. Therefore, the concrete boulders should resemble the deck material closely. The sizes of the boulders were 0.3 x 0.3 x 0.3 m, 0.5 x 0.5 x 0.5 m, 0.3 x 0.3 x 0.45 m, 0.3 x 0.3 x 0.6 m, 0.15 x 0.15 x 0.3 m, 0.45 x 0.45 x 0.3 m; these sizes were labeled as Groups 1-6 respectively. The volume of these boulders ranged from 0.007 m$^3$ to 0.125 m$^3$ . The shapes of the boulders were cubic and rectangular. The energy level of the boulder impacts (KEi) ranged from 0.8 kJ to 14.7 kJ.

In order to make the results statistically sound, 5 boulder specimens were cast for each set of field simulations. Totally, there were 30 (= 5 x 6) rockfall tests conducted for the coefficient of restitution and 20 for the rockfall fence performance, tally to a grand total of 50 field tests.

Before the test, all boulder samples had been marked with a distinct number on each face of boulder for easy recognition.

### 2.3 *Physical properties of soil and concrete*

The density, uniaxial compressive strength, Young's modulus and Poisson ratio of the concrete are about 2.4 Mg/m$^3$, 55 MPa, 36 GPa and 0.19 respectively. The soil composes of 42% of gravel and 58% of sand in the block sample of 0.5 x 0.5 x 0.5 m, while the Mazier soil sample composes 35% gravel, 51% sand and 4% silt. The bulk density, dry density and water content of the block sample are 2.685 kg/m$^3$, 2.334 kg/m$^3$, and 15% respectively. Those for the Mazier sample are 1.8435 kg/m$^3$, 1.508 kg/m$^3$, and 22%. The 50% secant Young's moduli for the block and Mazier samples are 3.7 MPa and 3 MPa respectively. The corresponding Poisson ratios are 0.19 and 0.25. The shear strength parameters for the soils are $c = 0$ and $\phi = 38°$. The concrete and soil samples are supplied by the contractor Cinpek Engineering Limited (CEL), and all tests were carried at the Hong Kong Polytechnic University.

### 2.4 *Field observation*

Two high-speed video cameras capable of capturing 220 frames per second were used to film the impact and bouncing phases of the rockfall. More specifically, the trajectory of rockfall would be captured and used to back calculate the velocities before and after each impact. It is essential that the point and time of the impact be captured accurately. As shown in Figure 1, bamboo scaffolding was constructed for marking. The bamboo scaffolding had a grid of 0.5 m x 0.5 m. The position of the boulder during the flying mode could be estimated with higher confidence. In addition, a handy digital video camera had also been used to capture the whole trajectory of the boulder fall. When the boulder was ready for releasing, CEL had arranged workers to stop the traffic downslope at the Stubbs Road to prevent any unnecessary accident during the field test. This safety measure was essential.

## 3 RESULTS

### 3.1 *Coefficients of restitution*

For the coefficient of restitution, the normal and tangential coefficients of restitution ($R_n$ and $R_t$) have been calculated based on the rockfall velocities ($v$) after reviewing the images captured by the high speed video camera frame-by-frame. The following formulas were used to calculate $R_n$ and $R_t$:

$$R_n = \frac{v_{nr}}{v_{ni}},\ R_t = \frac{v_{tr}}{v_{ti}} \qquad (1)$$

where the first subscripts "$n$" and "$t$" denote the normal and tangential components of the velocity, while the second subscripts "$r$" and "$i$" denote the rebounding velocity after each impact and the incoming velocity right before each impact respectively.

Figures 4 and 5 show $R_t$ and $R_n$ versus the impact energy respectively. The maximum $R_t$ is about 0.65 and its value decays exponentially with the impact energy as shown in Figure 4. Similarly, Figure 5 shows similar decay in $R_n$. The maximum for $R_n$ is about 0.4. In general, all coefficients of restitution, independent of the definition adopted, decay with the impact

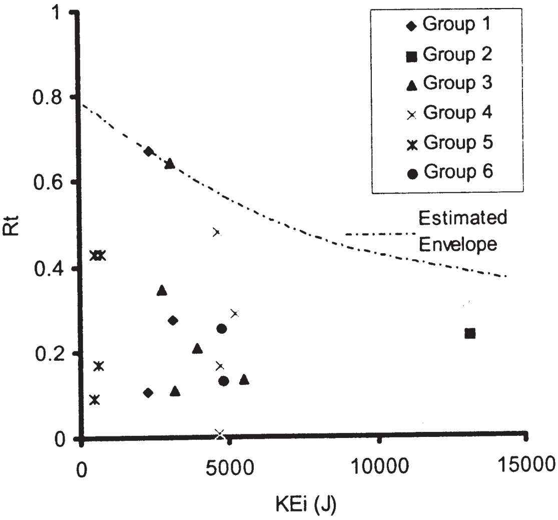


Figure 4. Tangential coefficient of restitution defined in (1) versus the impact energy. The group numbers were defined in Section 2.2

energy. This indicates that nonlinear deformation of soil occurs under impacts with high energy level. Figure 6 shows a typical indented hole in the soil after an impact.

Figure 7 shows data in that $R_t$ - $R_n$ space. As shown, most of the data fall within the range of $R_t < 0.6$ and $R_n < 0.4$. Such diagram is very useful for choosing appropriate set of coefficients of restitution for running rockfall simulation program, such as the CRSP of the Colorado Highway Department (Pfeiffer & Bowen 1986).

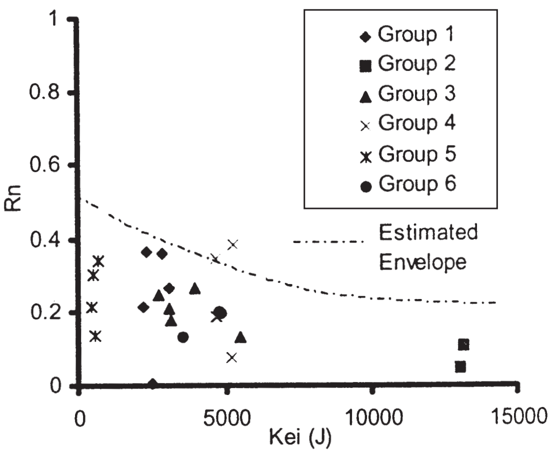


Figure 5. Normal coefficient of restitution defined in (1) versus the impact energy. The group numbers were defined in Section 2.2

As noted, rotational motions were also induced after each impact. The rotational speed $\omega_r$ can be up

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Figure 6. An indented hole caused by an impact of a massive boulder. Boundary of the hole is highlighted by a dotted line

to 20 rad/s corresponding to a tangential coefficient of restitution of 0.6. In general, the rotational speed was observed to increase with the tangential coefficient of restitution. Because of the frictional force being induced at the contact during an inclined impact, rotation is induced in the boulder.

### 3.2 *Rockfall fence performance*

To examine the performance of the rockfall fence, boulders of various sizes were pushed over a steel platform with an inclined surface extending beyond the existing platform (see Figure 2).

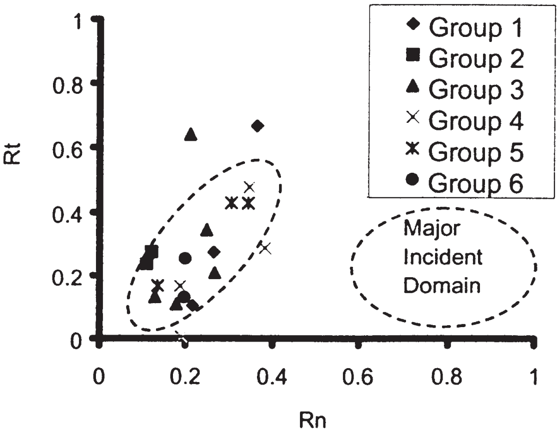



Figure 7. Plot of rockfall data in the parameter space of normal versus tangential coefficient of restitution

Figure 8 shows the deflection of the fence induced by the impact, which is highlighted by dotted lines in the photo. The deflection of the fence is shown clearly by highlighting the position of the boulders at each of the frozen picture, extracted from our video.

Figure 8. A photo showing the deflected shape of the rockfall fence. The boulder is highlighted by dotted lines

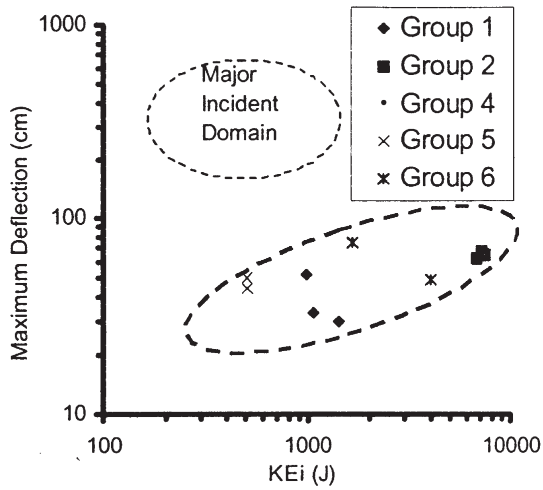



Figure 9. Maximum deflection of the fence versus the impact energy

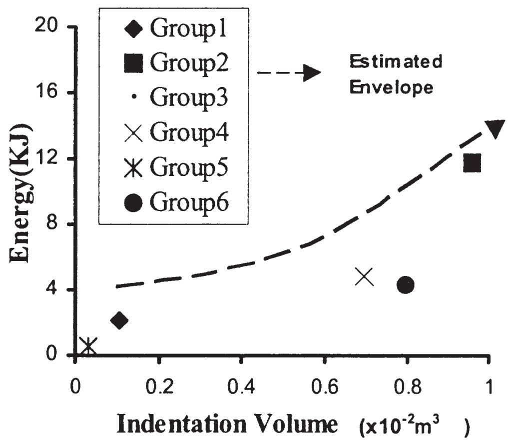
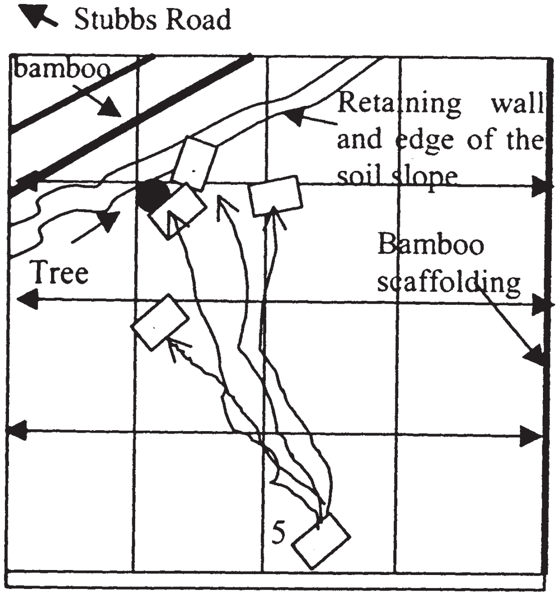



Figure 10. The indentation volume of the impact crater versus the impact energy




The platform of the existing deck which is 5 m above the soil slope

Figure 11. The lateral deflection and plan view of the falling path of group 4 boulders (300 x 300 x 600). Note that the fifth boulder stopped without any bouncing motion. This is the plane view of the slope shown in Figure 1

Figure 9 shows the maximum deflection of the fence versus the kinetic energy. The maximum deflection of the fence can be up to 100 cm for the largest boulders. For impacts of kinetic energy up to 14 kJ, the fence appeared to perform quite adequately, and there was no observable damages and breakage of the fence after 20 impacts. However, there was a permanent deformation at the fence after the field test.

### 3.3 *Size of impact crater on soil*

Figure 10 shows indentation volume in the soil slope versus the impact energy. The volume was estimated as the product of the size and the depth of the hole. The size of the impact indentations is found to increase with the impact energy. The overall trend is that the volume increases quickly as the impact energy increase. However, for larger impact energy level the increase in crater size becomes less significant when the impact energy level is close to 14.7 kJ.

### 3.4 *Lateral dispersion of the rockfall path*

We observed that nearly none of the 50 rockfall paths are identical (including the bouncing as well as the rolling modes). Inevitably, slight change in the initial soil profile at the point of impact may subsequently lead to a different final position of the boulder. Figure 11 illustrates the case of group 4 boulders. The initial position of impact and the final positions of the boulders are shown together their path of motions. The maximum angle of lateral dispersion can be up to 30 degrees.

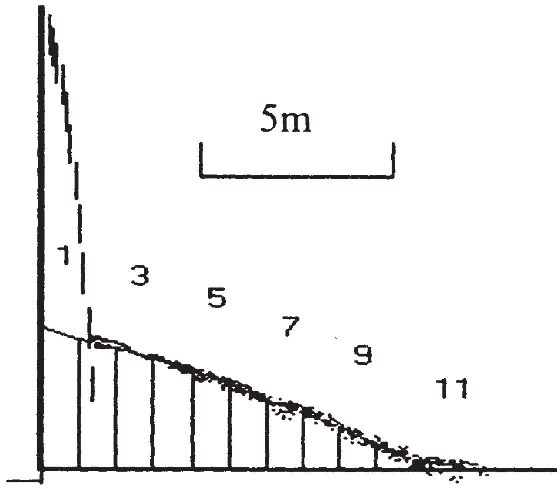



Figure 12. Trajectories of rockfall at Tung Shan Terrace predicted by CRSP, using the obtained coefficient of restitution (compared with Figure 1)

## 4. ROCKFALL HAZARD ANALYSIS

To apply the obtained results on the coefficient of restitution, a rockfall hazard analysis for Tung Shan Terrance was done using the Colorado Rockfall Simulation Program (CRSP). Full details of the capabilities and limitations of the program were given by Pfeiffer & Bowen (1989). Figure 12 shows some typical rockfall simulations for Tung Shan Terrace which was modeled by 11 sub-sections. The dotted lines indicate the trajectories of rockfall simulation. For this particular output, 200 boulder falls were simulated. The sizes of boulders were assumed as 0.3 m, the initial down slope and horizontal velocities are prescribed as 0.6 m/s, and the tangential and normal coefficient of restitution were assumed as 0.35 and 0.239. The maximum surface roughness is set as 0.05 m. About 90% of the boulders stopped on the soil slope, and 10% fell off the soil slope. Among them, 33% stopped within 1 m, 50% stopped between 1 m to 2 m, and the remaining 7% spreads from 2 to 6 m. For those fell off the soil, the maximum bouncing height was 0.1 m which was below the top of the installed rockfall fence. Therefore, the designed rockfall fence was considered as effective.

## 5 CONCLUSION

This field test is a pioneering rockfall field test in Hong Kong, in which the coefficients of restitution were measured accurately using high speed video cameras. This field test should also path the way for future rockfall field test in Hong Kong, and hopefully set the standard for further studies. It also provides the first database for the coefficients of restitution observed in the field. The purposely-built rockfall fence was found to meet the design intent, capable of catching all probable boulders predicted by the CRSP. Its deflection was shown to be within allowable limit of 2 m, subject to the rockfall of a maximum impact energy of 14 kJ.

Similar field tests to be carried in the future are essential to the successful, safe and economic design of rockfall fence.

## ACKNOWLEDGEMENT

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