IMPACT ACTIONS ON ROCKFALL PROTECTION BARRIER

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ABSTRACT: *Rockfall hazards have always been an issue in mountainous areas. To mitigate these hazards, efforts have been put in to building rockfall protection barriers. The erection of barriers in mountainous areas can often be difficult and costly when piling is required. This research explores the viability of building barriers without foundation. This type of barrier will experience rocking when subject to impact. A rocking barrier relies solely on inertial resistance to resist impact. An advantage of a rocking barrier is that the barrier itself experiences significantly less stress compared to a cantilever wall. Closed-form expressions have been developed and validated by the use of Finite Element Method (FEM) analysis and experimentations. Closed-form expressions enable users to predict the horizontal displacement of the wall by hand calculations.*

KEYWORDS: impact action, mass reduction factor, coefficient of restitution, LS-DYNA, rocking wall

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1 INTRODUCTION

Rockfall is a very common natural disaster that often occurs in mountainous regions, for example Switzerland, Japan and Hong Kong. It can be caused by landslides, earthquakes [1], chemical degradation and weathering of rocks [2], freeze and thaw processes due to cold climates [3, 4], etc. Over the years, a lot of efforts have been taken by the governments for rockfall prevention and protection. For instance, Hong Kong has spent about US$2.3billion to address landslide and rockfall hazards in the past 20 years [5]. Although the impact area of a rockfall event is usually small, it can severely damage structures that are struck. More importantly, rockfall poses a significant threat to human lives.

In order to prevent rockfalls from reaching the public, passive rockfall protection barriers need to be erected in mountainous regions. The design of structures exposed to rockfall hazard would need to take into considerations impact actions. A traditional approach in codes of practice is to represent impact actions by equivalent quasi-static forces [6, 7]. However, this approach has not been supported by research, and cannot be applied with confidence.

The equal energy method is more transparent as it is based on fundamental laws of physics. It involves equating the kinetic energy of the impactor and the target's strain energy at maximum deflection, and takes the form as shown by Equation (1) [8]:

$$\Delta = \frac{mv_0}{\sqrt{mk}} \tag{1}$$

This expression is able to estimate the deflection demand of the structure (Δ) when the impactor's mass (m), impact velocity (v_0) and target's stiffness (k) are known. It might seem to be a versatile method, but it assumes that the total amount of the impacting energy is absorbed by the target. In the case where only a small amount of energy has been transferred, this expression will produce highly inaccurate result.

On top of that, Equation (1) has not incorporated the mass of the target as input. In fact, it has been shown that the inertial effects arising from the target's mass can significantly reduce its deflection [9, 10]. Analytical solutions were derived and validated by physical experiment and FEM simulation. However, the validations were done by considering the two extreme cases for the analytical solution: impactor embedded into the target and impactor perfectly rebounded from the target. These two scenarios provide predictions for the range of deflection. Tests were conducted to ensure that the recorded deflection is in between the two limits. This paper goes one step further to validate the analytical solution based on an assumed amount of energy loss as measured by COR.

Analytical solutions discussed above are able to estimate the deflection of the target with some sort of constraints (cantilever, simply supported, etc). This paper explores the viability of designing rockfall barriers without any base restraints. The barrier is expected to resist impact solely by the inertial effects arising from its self-mass. Quantification of the wall's deflection demand based on an analytical model will be the focus of the paper.

2 WALL WITH RESTRAINED BASE

2.1 ANALYTICAL SOLUTION

To take into account the target's inertial effect and energy loss from the system, Equation (1) has been modified. By assuming that the transfer of momentum is immediate (short contact duration), the principle of conservation of momentum can be applied:

$$mv_0 = -mv_1 + \alpha mv_2 \tag{2}$$

where m and v_0 is the mass and incident velocity of the impactor, v_1 and v_2 is the velocity of the impactor and target after the impact, and α is the mass ratio of the target to impactor.

The kinetic energy loss is incorporated into the expression by using the Newton's Coefficient Of Restitution, COR (the target's initial velocity of zero is not included in the expression):

$$COR = \frac{v_1 + v_2}{v_0} \tag{3}$$

By combining Equation (2) and (3):

$$\frac{v_2}{v_0} = \frac{1 + COR}{1 + \alpha} \tag{4}$$

By the use of Equation (4), the kinetic energy ratio can then be expressed as:

$$\frac{KE_2}{KE_0} = \frac{\frac{1}{2}\alpha mv_2^2}{\frac{1}{2}mv_0^2} = \alpha\left(\frac{v_2}{v_0}\right)^2 = \alpha\left(\frac{1 + COR}{1 + \alpha}\right)^2 \tag{5}$$

Also,

$$KE_2 = \frac{1}{2}k\Delta^2 \tag{6}$$

By substituting Equation (6) into Equation (5):

$$\Delta = \frac{mv_0}{\sqrt{mk}} \times \sqrt{\alpha\left(\frac{1 + COR}{1 + \alpha}\right)^2} \tag{7}$$

Equation (7) is similar to Equation (1), except that it includes a factor derived from the kinetic energy ratio, Equation (5).

As explained above, Equation (7) is derived from the fundamental principle of equal momentum. However, it is based on the assumption of a system of spring connected lumped masses. Thus, it is important to carry out physical experimentation and FEM computer numerical simulation to verify the expression along with Equation (5).

2.2 EXPERIMENTAL AND NUMERICAL VERIFICATION

The experimental set up is shown in Figure 1. A pendulum impact test was conducted on a 1m long steel beam with cross section of 0.15m × 0.02m. The steel beam was welded onto another steel beam, which was in turn bolted rigidly onto the ground. Steel plates with total mass of 38kg were attached onto the beam to increase the effective target mass. All the steel beams and plates used here are mild steel with density of 7850kg/m^3, Young's modulus of 200GPa, and yield strength of 300MPa. A cast iron ball weighing 5kg was raised to a height of 1m and then released to strike the beam. The incident velocity of impact was 4.43m/s, which will later be checked with measurements by High Speed Camera (HSC). A laser displacement sensor ILD1700-50 with measurement frequency of 2.5kHz and measurement range of up to 50mm was used to measure the beam's displacement following the impact. At the same time, a HSC with frame rate of 3000fps was used to measure the velocity of the impactor before and after the impact.

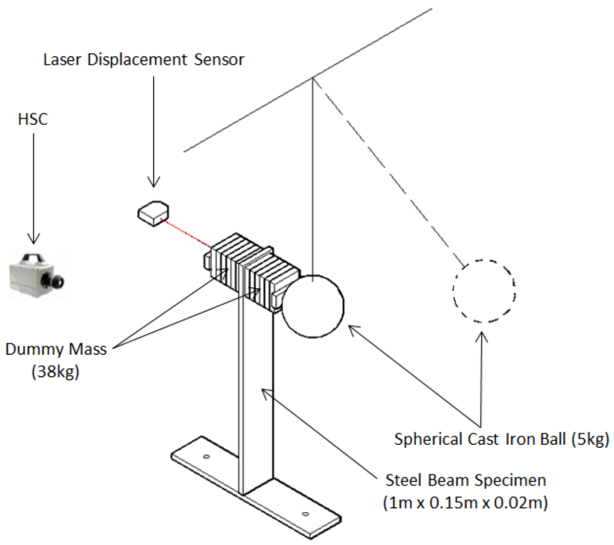

Figure 1: *Cantilever steel beam experimental set up*

Meanwhile, FEM computer simulations were carried out using software LS-DYNA, as shown in Figure 2. Instead of connecting the pole to a beam, the base of the pole was simply fixed by specifying constraint in all six DOF by using the BOUNDARY card. From the LS-DYNA library, MAT_001 was chosen to be the material model for the steel pole and plates, whereas MAT_020 was chosen for the impactor. Since the steel plates were rigidly bolted to the pole in the physical experiment, the contact between them was defined as per the tied surface to surface contact algorithm. In addition, the automatic surface to surface contact algorithm was used to define the contact between the impactor and the steel plate that it comes in contact with. A stiffness based hourglass control type (IHQ = 4) with hourglass coefficient of QM = 0.03 was specified as per recommendation by Ref. [11] in order to prevent zero energy hourglass mode that can lead to model's instability. The input parameters are summarised in Table 1.

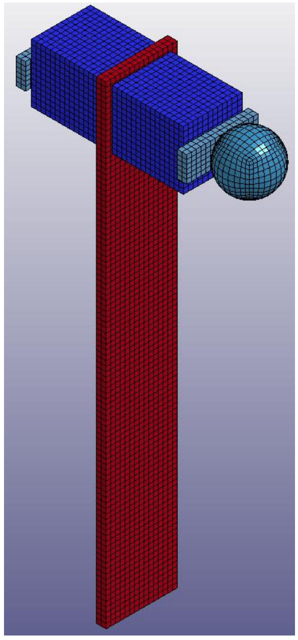

Figure 2: *FEM for the cantilever beam experiment*

Table 1: *Main parameters used in FEM for cantilever beam in LS-DYNA*

Parameters	Input
Impactor material	MAT_20 Rigid
Target material	MAT_001 Elastic
Contact algorithm between impactor and dummy mass	automatic surface to surface
Contact algorithm between dummy mass and target beam	tied surface to surface
Hourglass control type	4
Hourglass coefficient	0.03
Boundary condition	Base fixed in all 6 DOF

Importantly, hand calculation check of the results was carried out by the use of Equation (7). As recommended in [12], for a cantilever beam, the generalised stiffness (k) is $3EI/L^3$, and the generalised mass (αm) is a quarter of the total mass of the beam. The full dummy mass needs to be added to the generalised mass as all the dummy mass effectively resist the impact. COR was calculated by the use of Equation (3), with the HSC measurements as shown in Table 2. The calculated/measured input parameters for Equation (7) are shown in Table 3.

Table 2: *Velocities of the impactor and target for cantilever beam test*

	Impactor	Target
Velocities prior to impact	4.43 m/s	0 m/s
Velocities on rebounce	0.73 m/s	1.05 m/s

Table 3: *Calculated/measured input parameters for Equation (7)*

Parameters	Values
m	5 kg
v_0	4.43 m/s
k	60 kN/m
α	8.38
COR	0.4

The results from the experiment, LS-DYNA simulation and hand calculation are summarised in Figure 3.

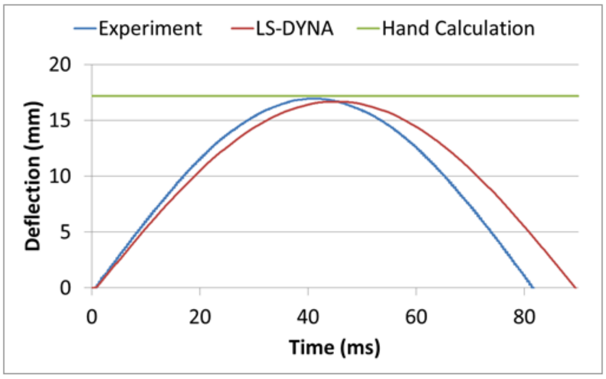

Figure 3: *Deflection values of cantilever beam from experiment, LS-DYNA and hand calculation*

As shown in Figure 3, results from both the experiment and LS-DYNA match closely with the hand calculation estimate. The maximum deflection from experiment and LS-DYNA were 16.9 mm and 16.7mm respectively, as compared to the hand calculation value of 17.2 mm. Hence, Equation (7) is valid. Importantly, the use of energy ratio as defined by Equation (5) has also been validated.

3 WALL WITH UNRESTRAINED BASE

3.1 ANALYTICAL SOLUTION

A sketch of a typical rectangular block with unrestrained base under impact is shown in Figure 4. It will undergo rocking and may overturn depending on the amount of displacement experienced during rocking.

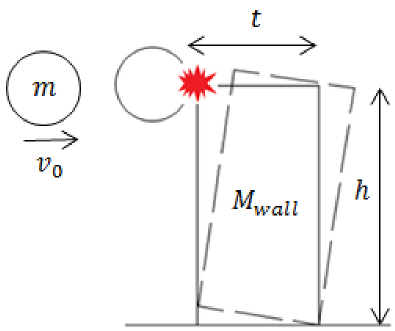

Figure 4: *Rectangular wall experiencing rocking effect under impact*

In Section 2.1, the principle of conservation of momentum was employed to derive the analytical solution. Similarly, the principle of conservation of angular momentum has been employed:

$$m v_0 h = -m v_1 h + I_\theta \dot{\theta} \tag{8a}$$

$$I_\theta = M_{wall} \times \frac{h^2 + t^2}{3} \tag{8b}$$

$$\dot{\theta} = \frac{v_2}{h} \tag{8c}$$

where I_θ is the rotational inertia of the wall and $\dot{\theta}$ is the angular velocity of the wall, about bottom left corner.

In Section 2.1, α was taken as the mass ratio. For the rocking block, α is defined by Equation (9).

$$\alpha = \frac{I_\theta}{mh^2} \tag{9}$$

By combining Equation (8a), (8c) and (9):

$$v_0 + v_1 = \alpha v_2 \tag{10}$$

Then, by combining Equation (9) with the COR expression of Equation (3):

$$\frac{v_2}{v_0} = \frac{1 + COR}{1 + \alpha} \tag{11}$$

The kinetic energy in the wall immediately following the impact is:

$$KE = \frac{1}{2} I_\theta \dot{\theta}^2 = \frac{1}{2} I_\theta \left(\frac{v_2}{h}\right) = \frac{1}{2} \alpha m v_2^2 \tag{12}$$

Hence, the kinetic energy ratio can be expressed as:

$$\frac{KE}{KE_0} = \frac{\frac{1}{2}\alpha m v_2^2}{\frac{1}{2} m v_0^2} = \alpha \left(\frac{1 + COR}{1 + \alpha}\right)^2 \tag{13}$$

Note that Equation (13) is identical to Equation (5), except that the expression for α is defined differently due to difference in the nature of the motion (linear/rotational). Thus, the validation of Equation (5) in Section 2.2 does validate the use of Equation (13), i.e.

the use of kinetic energy ratio to represent the energy loss from the system. This expression can further be used to derive the analytical solution for estimating deflection Δ.

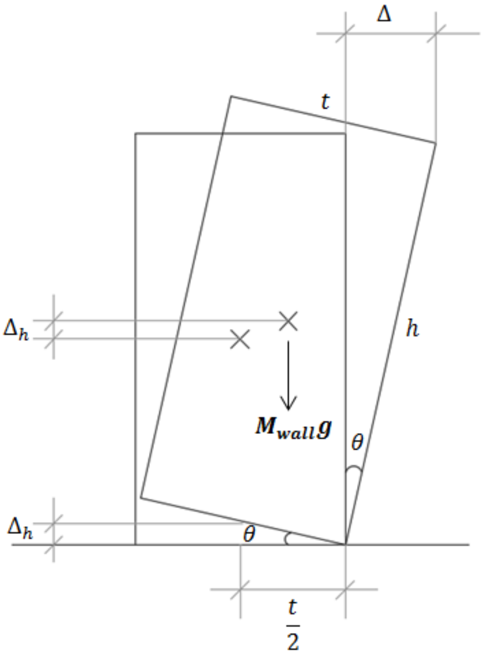

Figure 5: *Sketch of rocking wall showing geometry*

As shown in Figure 5, the wall is expected to be lifted by Δ_h when it is at its maximum deflection Δ. Thus, the total amount of energy gained by the wall can be expressed by its potential energy gained:

$$PE = M_{wall} g \Delta_h \tag{14}$$

This potential energy gained can be equated to the kinetic energy in the wall right after the impact, i.e. $PE = KE$. By using this relationship and combining Equation (13) and (14):

$$M_{wall} g \Delta_h = \alpha \left(\frac{1 + COR}{1 + \alpha}\right)^2 \times \frac{1}{2} m v_0^2 \tag{15}$$

Rearranging Equation (15) gives:

$$\Delta_h = \frac{m v_0^2}{2 M_{wall} g} \alpha \left(\frac{1 + COR}{1 + \alpha}\right)^2 \tag{16}$$

Up to this point, Equation (16) is already able to relate the measureable input parameters to the wall's movement, in terms of Δ_h. A step further will be taken to relate Δ_h to the interest of the context, Δ. This will be done solely based on the geometry of the wall.

From the wall's geometry as shown in Figure 5:

$$\sin\theta = \frac{\Delta}{h} \tag{17a}$$

$$\tan\theta = \frac{\Delta_h}{\frac{t}{2}} = \frac{2\Delta_h}{t} \tag{17b}$$

By using small angle approximation (assuming θ is small), $\sin\theta \approx \tan\theta \approx \theta$. Combining this relationship with Equation (17a) and (17b) gives:

$$\Delta = \frac{2h}{t} \times \Delta_h \tag{18}$$

Combining Equation (16) and (18) gives:

$$\Delta = \frac{m v_0^2}{M_{wall} \frac{gt}{h}} \alpha \left(\frac{1 + COR}{1 + \alpha}\right)^2 \tag{19}$$

With Equation (19), the wall's deflection can simply be calculated by hand. However, Equation (18) has limitations as it is only valid with a small angle of rotation of the rocking wall.

3.2 EXPERIMENTAL AND NUMERICAL VERIFICATION

Experimental and numerical studies have been carried out to verify the use of the hand calculation analytical solution presented in this paper.

A pendulum test using the same impactor from Section 2 was conducted on a 0.2m × 0.4m × 0.2m concrete block with mass of 76kg, as shown in Figure 6. A 10mm thick timber piece was placed behind the block to simulate the translationally restrained condition of the block's rear bottom corner. The timber piece was placed rigidly such that there was no translational movement. Again, a 5kg cast iron ball was raised to a height of 1m before it was released to produce an incident velocity of 4.43m/s. The impactor in this experiment was hung by two steel cables (instead of one). This was to ensure that the impactor travels in the desired trajectory in order that it strikes the middle of the block. A laser displacement sensor ILD1402-100 with measurement frequency of 1.5 kHz and measurement range of up to 100mm were used to measure the block's displacement generated by the impact.

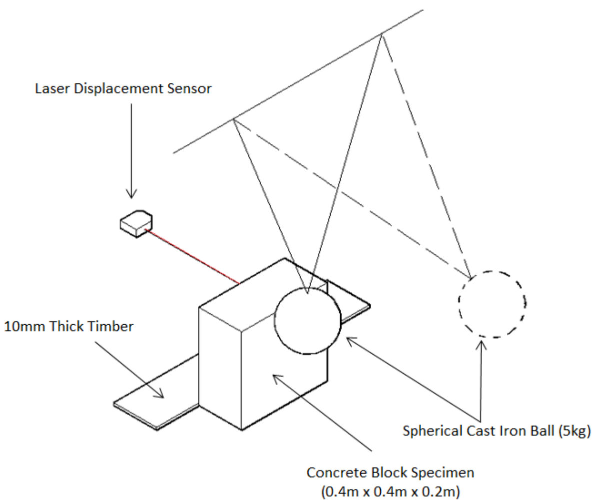

Figure 6: *Rocking wall experimental set up*

Meanwhile, FEM numerical computer simulation was carried out using LS-DYNA, as shown in Figure 7. Instead of having the base fully fixed, only a corner was restrained in the translational direction by adding a plate similar to that in the actual experiment. Since gravitational load is applied, the wall was modelled to sit on a "ground" plate which is constrained in all 6DOF. Gravitational load of $g = 9.81m/s^2$ was applied.

For the concrete block, the continuous surface cap model (CSCM) MAT_159 was chosen from the LS-DYNA library as the material model. The validation application of MAT_159 for concrete under impact actions can be found in Ref. [13, 14]. The same material model was also used to model the floor. MAT_020 was chosen to model the impactor. The automatic surface to surface contact algorithm was used to define both the contact between the impactor and the wall, as well as the contact between the wall and the floor. A stiffness based hourglass control type (IHQ = 4) with hourglass coefficient of QM = 0.03 was specified based recommendations in Ref. [11] in order to prevent zero energy hourglass mode that can result in model's instability. The input parameters are summarised in Table 4.

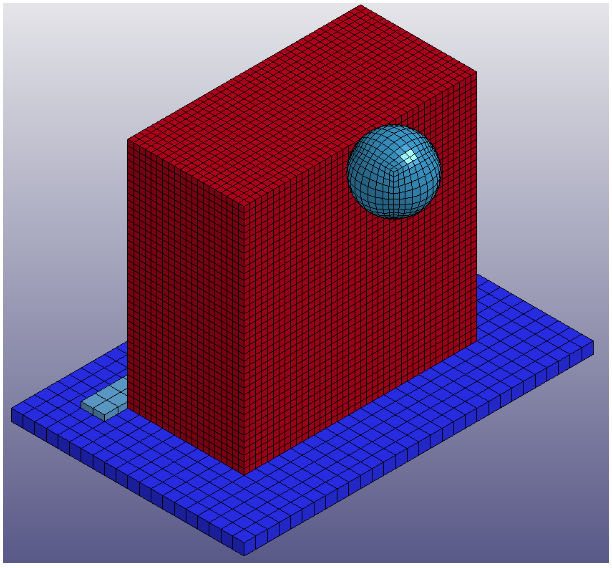

Figure 7: *FEM for the rocking wall experiment*

Finally, hand calculation was carried out. COR was calculated by the use of Equation (3). The velocities of the impactor and the target were taken from LS-DYNA simulation, as shown in Table 5. The calculated/ measured input parameters for the hand calculation procedure are shown in Table 6.

Table 4: *Main parameters used in FEM for cantilever beam in LS-DYNA*

Parameters	Input
Impactor material	MAT_20 Rigid
Target material	MAT_159 CSCM Concrete
Ground material	MAT_159 CSCM Concrete
Contact algorithm between impactor and target	automatic surface to surface
Contact algorithm between target and base	automatic surface to surface
Hourglass control type	4
Hourglass coefficient	0.03
Boundary condition	Both ground and restraining plate fixed in all 6 DOF

Table 5: *Velocities of the impactor and target for rocking wall test*

	Impactor	Target
Velocities prior to impact	4.43 m/s	0 m/s
Velocities on rebounce	0.99 m/s	0.64 m/s

Table 6: *Calculated/measured input parameters for rocking wall hand calculation procedure*

Parameters	Values
m	5 kg
v_0	4.43 m/s
COR	0.37
M_{wall}	76 kg
t	0.2 m
h	0.4 m

The details of the hand calculation process are shown in below to show that it is feasible to be done without the aid of any computer program.

The rotational inertia of the wall is first calculated in order to calculate α:

$$I_\theta = M_{wall} \times \frac{h^2 + t^2}{3}$$

$$= 76 \times \frac{0.4^2 + 0.2^2}{3}$$

$$= 5.1\ kgm^2$$

$$\alpha = \frac{I_\theta}{mh^2} = \frac{5.1}{5(0.4)^2} = 6.33$$

From Equation (19):

$$\Delta = \frac{mv_0^2}{M_{wall}\frac{gt}{h}}\alpha\left(\frac{1 + COR}{1 + \alpha}\right)^2$$

$$= \frac{5(4.43)^2}{76\left(\frac{(9.81)(0.2)}{0.4}\right)}(6.33)\left(\frac{1 + 0.37}{1 + 6.33}\right)^2$$

$$= 0.058m$$

$$= \mathbf{58mm}$$

A more accurate estimate of Δ is 71mm when the geometry of the rotating block is factored into the calculation. Details of the refined calculation are not shown herein.

This hand calculation method gives the maximum value of the deflection, which is critical from a design perspective. In order to better compare with the experimental and computer simulation results, a deflection-time history curve (instead of just one maximum point) has been generated for the hand calculation method. This was done based on varying the kinetic energy to potential energy ratio at different point of time (maximum kinetic energy and zero potential energy right after the impact, and vice versa when the deflection reaches Δ). The peak of the curve is the maximum deflection, i.e. 71mm.

The results from the experiment, LS-DYNA simulation and hand calculation are summarised in Figure 8.

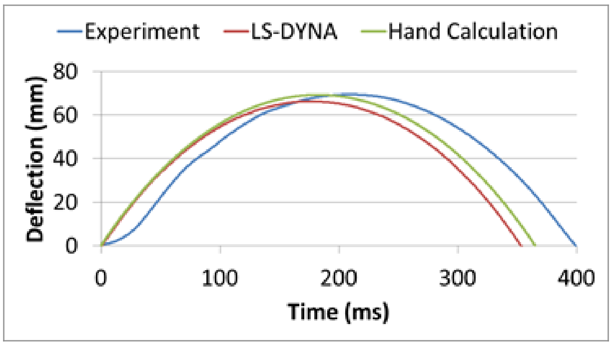

Figure 8: *Deflection values of rocking wall from experiment, LS-DYNA and hand calculation*

As seen from Figure 8, the deflection value calculated from the expressions from Section 3.1 matches with those from the FEM simulation as well as the experimental measurement. Hence, the hand calculation methodology is verified.

4 CONCLUSIONS

The use of kinetic energy ratio expression was first verified by conducting pendulum impact tests on a cantilever steel pole, followed by FEM simulations. This serves to verify the simplified expression developed in [9] by the use of an expression which includes COR, which can be measured by HSC.

The second part of the paper explores a new innovative type of rockfall barrier, which is without a foundation at the base. It is called the rocking wall, as it relies rocking and inertia to resist the impact action. A methodology was derived to estimate the displacement of a rocking wall for given impact condition. Physical experimentations and FEM simulations were used to verify the proposed method of calculation. This methodology is attractive in the sense that it can be simply done by hand calculations. Every step of the methodology presented is transparent. Thus engineers will be able to apply it with confidence.

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