

A Showcase to Components Replacement in Existing Steel Flexible Barrier System

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ABSTRACT

Steel flexible barrier system is commonly adopted as natural terrain hazard mitigation measures for energy absorption of rockfalls from hillside. The conditions and effectiveness of the steel flexible barrier system installed at hillside may deteriorate with time, so maintenance works including replacement of the components may be required. The original supplier for the main components, such as proprietary energy dissipating devices, may be no longer operated in the market, and the replacement of these main components can only be carried out by using similar products from other available suppliers. To check the compatibility of the replacement components with the original steel flexible barrier system, numerical analysis is carried out to analyze whether the performance of the steel flexible barrier system could be maintained after replacing the components. This paper discusses the steps on how to check the conditions of the existing steel flexible barrier system, and the numerical analysis for assessing the compatibility of the replacement components.

1 INTRODUCTION

A steel flexible barrier system was constructed on the natural hillside above a public housing site in 2002. A specialist supplier was engaged for the design, supply and construction of the steel flexible barrier system to mitigate the potential hazards of the small boulders with dimension less than 1m from natural hillside. The steel flexible barrier system acted as a passive protective barrier system to intercept the trajectory of falling, bouncing, and rolling rocks and retain such falls through a controlled process of energy absorption.

Site reconnaissance was conducted recently to review the existing conditions of the steel flexible barrier system, and rusting was observed at some components including wire clips, thimbles, shackles and energy dissipating devices. Minor rusted components could be repaired by application of rust preventive painting, while some severely rusted components, such as energy dissipating devices, could only be replaced. However, the original supplier for these energy dissipating devices was no longer operated in the market. Therefore, an alternative way was to replace them by using similar components of other brands, and so further numerical analysis for assessing the compatibility of new components was considered necessary.

AECOM has reviewed the available suppliers of energy dissipating devices in Hong Kong, with the consideration of the following criteria to find the appropriate energy dissipating devices as replacement:

- Construction feasibility with minimal disturbance to the existing system
- Similar operation and energy release mechanisms
- Availability and extensive implementation in Hong Kong

After the assessment, two brands were identified and considered in the numerical analysis for comparison with the existing system performance.

2 INITIAL CONDITION REVIEW

The site reconnaissance was carried out on the existing steel flexible barrier system in April 2022. To simplify the repairing works proposal, the overall state of the rusted components was classified into 3 categories and the proposed repairing works were shown in Table 1.



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Table 1: Proposed Repairing Works for Different Conditions of Rusting

Category	Condition of Rusting	Proposed Repairing Works
Class 0	No rusting	No works
Class 1	Minor rusting	Painting Works
Class 2	Severe rusting	Replacement of components

According to the results of field inspection, energy dissipating devices, wire clips, thimbles and shackles were in Class 2 severe rusting condition. Therefore, replacement was proposed for those components. For the energy dissipating devices, since they were the main components in steel flexible barrier system, further numerical modelling analysis were carried out.

3 RESULTS FROM PREVIOUS DETAILED DESIGN

The detailed design of steel flexible barrier system to mitigate boulder fall hazard was carried out in 2000. The schematic disposition of steel flexible barrier system upon impact is shown as Figure 1.

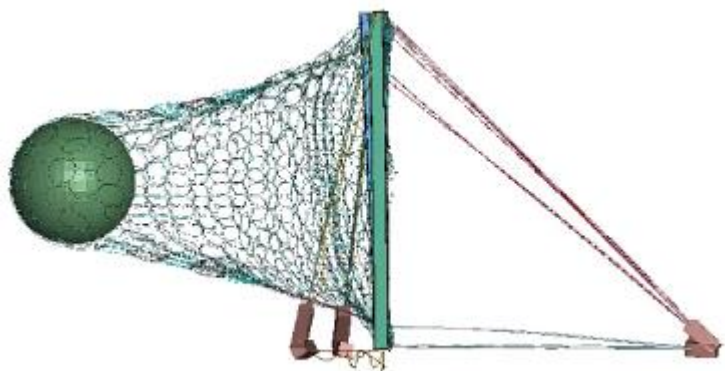


Figure 1: Schematic Disposition of Steel Flexible Barrier System upon Impact

In the design stage, six sections A-A to F-F as shown in Figure 2 were established along the steep slope gradient and significant changes in gradient to represent the most possible and critical boulder flow paths.

The maximum absorption energy of boulder falls at the existing steel flexible barrier system is estimated to be 700kJ based on the “RocFall” program. This value was recommended as the Service Energy Level (SEL) for the steel flexible barrier system.

4 NUMERICAL MODELLING ANALYSIS

In this study, the University of Hong Kong was engaged to use finite-element program LS-DYNA to investigate the response of the steel flexible barrier system under single boulder impact load. Explicit time integration is used to solve the governing equations of mass, momentum and energy conservation for dynamic impact problems involving large deformation. The same numerical model, modelling procedures, and input parameters were adopted as those reported by Koo et al. (2016), which has been validated using field-scale physical data of a rock falling on a flexible barrier as reported by Volkwein (2014).

Figure 2 shows the finite-element model used in this study, which simulates a three-panel segment of the steel flexible barrier system installed at the natural hillside. The barrier is 4-m high and consists of three 10-m wide ring net panels forming the single panel with surface area of 40 m². A three-panel configuration was selected to enable comparisons between the design calculations in steel flexible barrier system design report and the full-scale crash tests according to ETAG (2008).

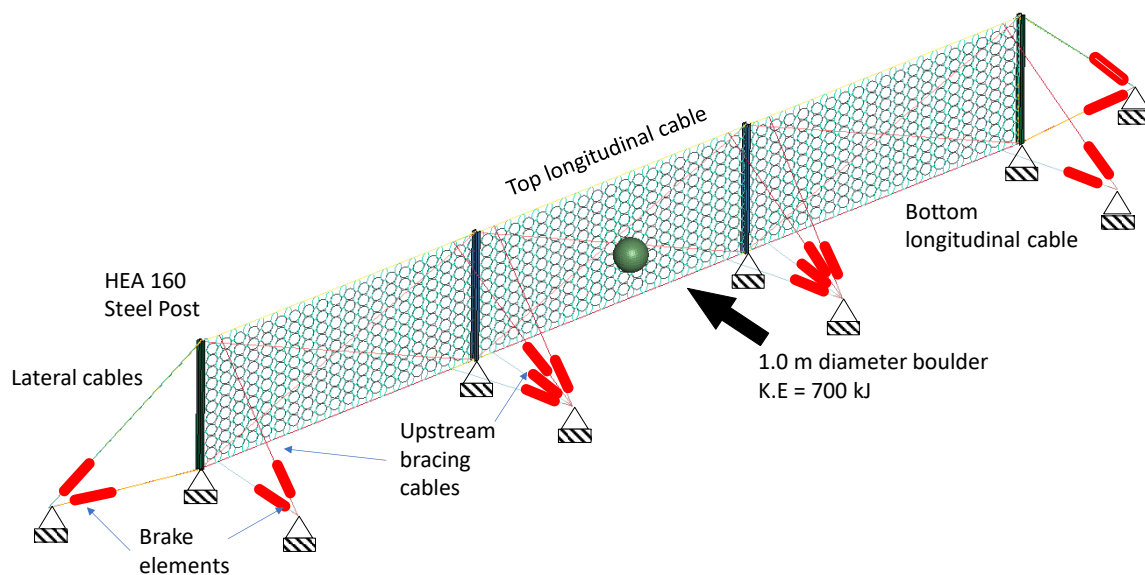


Figure 2: Numerical Model Setup of Steel Flexible Barrier System Oblique 3D with Boulder

The rigid boulder is modelled as a constant stress solid element with reduced integration and hourglass control. The 4-m high steel posts of the barrier were modelled as fully integrated quadrilateral thin shell elements. The steel posts are held in position by upstream and lateral bracing cables anchored to the ground. Longitudinal steel wire ropes running along the top and bottom of the entire barrier are anchored to the ground at both ends of the barrier. Upslope bracing cables are connected via shackles and wire ropes to the top and bottom longitudinal ropes to support the steel posts in their inclined configuration along the slope. Additionally, lateral bracing cables are used to support the steel posts from lateral deflection during impact. All the steel wire rope cables are made of individual wire rope core (IWRC) with yield strength of 1770 MPa. The IWRC steel cable ropes are modelled as resultant beams with cross section integration based on the approach proposed by Reese et al. (2016) to not only capture the axial stiffness but also the bending and flattening behaviour of wire-rope cables.

In a steel flexible barrier system, energy dissipating devices are main components because they limit the peak loads transferred to other barrier components through large elastoplastic deformation. These energy dissipating devices are typically attached to the main longitudinal cables as well as upstream bracing cables. These devices dissipate energy either by friction, plastic deformation, or a combination of these mechanisms

(Castanon-Jano et al., 2017). When subjected to an impact force, these energy dissipating devices are subjected to tensile loading, and they elongate for a long distance at its yield load, thereby gradually absorbing the impact energy and limiting the peak loads. The deformation of the energy dissipating devices also creates an irreversible elongation of the cables, and this further reduces the stiffness of the barrier. Bilinear load-displacement curves were implemented into the finite-element model to simulate the load behavior in Figure 3.

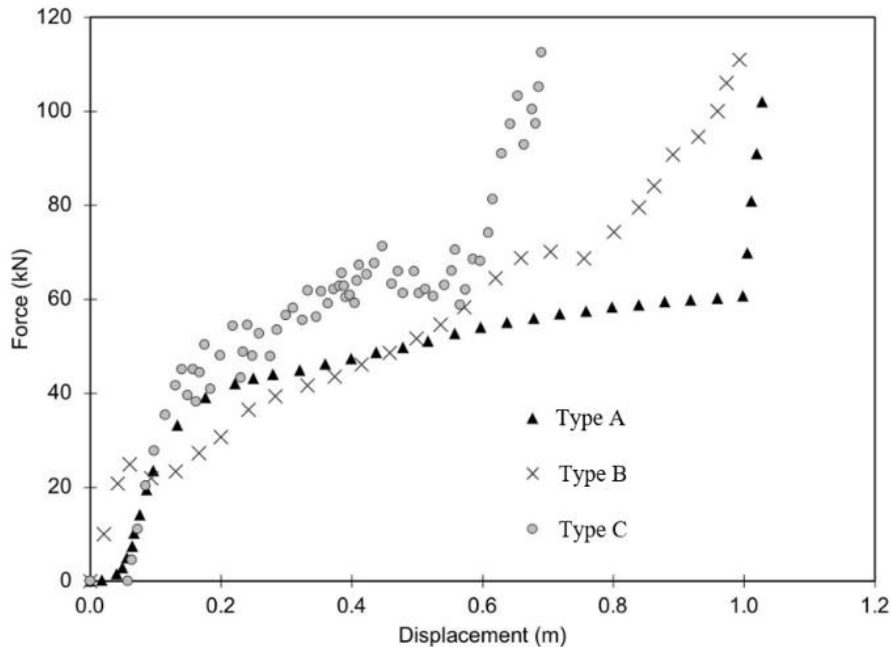


Figure 3: Load-Displacement Curves: (a) Type A - existing energy dissipating device; (b) Type B – Brand A replacement energy dissipating device; and (c) Type C – Brand B replacement energy dissipating device

The interactions between contact surfaces of the rigid boulder and the structural elements are handled using the penalty method discussed by Hallquist (2006). In this approach, the finite-element program searches for intersections between the boulder and the net. It tracks the independent motion of the contacting elements over a small time-step. The penetration of the beam elements into the surface of the boulder results in a normal interface force which is distributed to both elements. The magnitude of this force is proportional to the amount of penetration and is determined using the interface spring stiffness. Furthermore, the sliding of ring nets along the longitudinal wire ropes and lateral cables are modelled using guided cable contact algorithm, which allows frictional sliding of longitudinal rope beam elements along ring net beam nodes.

Based on the detailed design of steel flexible barrier system carried out in 2000, the Maximum Energy Level (MEL) of 1500kJ was selected based on the certified energy absorption capacity for existing steel flexible barrier system. While the impact energy of 700kJ was obtained from the maximum kinetic energy from previous rock fall analysis as the SEL. The input parameters for force and deformation analysis on steel flexible system under MEL and SEL scenarios was shown in Table 4.

Table 4: Summary of Input Parameters

Scenario	Impact Energy (KJ)	Boulder Density (kg/m ³)	Boulder Diameter (m)	Boulder Volume (m ³)	Boulder Mass (kg)	Initial Boulder Velocity (m/s)
MEL	1500	2650	1.5	1.767	4682.94	25.31
SEL	700	2400	1.0	0.524	1256.64	33.37

The computed maximum loads/deformations on each structural member were shown in Table 5.

Table 5: Summary of Simulated Results

Component	From design report	Results in this study using LS-DYNA					
	Type A	Type A	Type B	Type C	Type A	Type B	Type C
Energy Dissipating Devices	Type A	Type A	Type B	Type C	Type A	Type B	Type C
Impact energy	1545 kJ	1500 kJ	1500 kJ	1500 kJ	700 kJ	700 kJ	700 kJ
Max. deformation	7.0 m	8.1 m	7.7 m	7.7 m	6.2 m	6.2 m	5.6 m
Max. boulder impact force	553 kN	477 kN	591 kN	544 kN	150 kN	276 kN	318 kN
Max. longitudinal cable loads	184 kN	201 kN	200 kN	202 kN	173 kN	119 kN	182 kN
Max. upstream cable loads	145 kN	141 kN	107 kN	145 kN	71 kN	108 kN	101 kN
Max. load on lateral bracing cables	76 kN	125 kN	135 kN	135 kN	94 kN	117 kN	136 kN
Max. load on lateral steel posts	Axial: 208 kN	Axial: 184 kN	Axial: 213 kN	Axial: 256 kN	Axial: 126 kN	Axial: 192 kN	Axial: 185 kN
	Shear: 137 kN	Shear: 111 kN	Shear: 107 kN	Shear: 120 kN	Shear: 101 kN	Shear: 107 kN	Shear: 104 kN
Max. load on intermediate steel posts	Axial: 132 kN	Axial: 138 kN	Axial: 118 kN	Axial: 244 kN	Axial: 127 kN	Axial: 160 kN	Axial: 139 kN
	Shear: 137 kN	Shear: 110 kN	Shear: 105 kN	Shear: 101 kN	Shear: 147 kN	Shear: 121kN	Shear: 111 kN

Three conditions for accepting criteria of numerical modelling analysis results were set as below:

- Condition 1: If the results were less than or within 1.2 times of the calculated loads/deformations in design report, it was considered as satisfied condition.
- Condition 2: If the results were more than 1.2 times of the calculated loads/deformations in design report, they were checked against the minimum breaking loads. If the Results were less than the minimum breaking loads, it was considered as satisfied condition.
- Condition 3: If the results were larger than the minimum breaking load / no data specified, they were checked against the structural capacity of each structural member. If the Results were less than the structural capacity, it was considered as satisfied condition.

The results interpretation was summarized in Table 6.

Table 6: Interpretation of Simulated Results

	Satisfied Condition 1	1.2 × From design report	Satisfied Condition 2	Minimum Breaking Load	Satisfied Condition 3	Structural Capacity
Max. deformation	Yes	8.4m	N/A	-	N/A	-
Max. boulder impact force	Yes	663.6kN	N/A	-	N/A	-
Max. longitudinal cable loads	Yes	220.8kN	N/A	-	N/A	-
Max. upstream cable loads	Yes	174kN	N/A	-	N/A	-
Max. load on lateral bracing cables	No	91.2kN	Yes	163 kN	N/A	-
Max. load on lateral steel posts	No	Axial: 249.6 kN	No	N/A	Yes	Axial: 1667.11 kN
		Shear: 164.4 kN				Shear: 327.95 kN
Max. load on intermediate steel posts	No	Axial: 158.4 kN	No	N/A	Yes	Axial: 1667.11 kN
		Shear: 164.4 kN				Shear: 327.95 kN

According to the result of analysis, the magnitude of computed maximum deformation, boulder impact force, longitudinal cable load and upstream cable load were checked satisfied under Condition 1. Although the maximum load on lateral bracing cables exceeded 20%, it was smaller than the minimum breaking loads specified by the manufacturer, which was also considered as satisfied under Condition 2. For the maximum load

on steel posts, no information was found in the previous design report or from manufacturer. Therefore, the structural capacity analysis was carried out, which implied that the loads on the steel posts were satisfied under Condition 3.

In conclusion, the computed loads and deformations were checked satisfied under three accepting criteria, which implied that the replacement components were compatible with the existing steel flexible barrier system. Therefore, repairing the minor rusted components and replacement of the main components, including energy dissipating devices, were thereafter carried out on site.

5 FUTURE INSIGHT

As the experience of energy dissipating devices replacement in a steel flexible barrier system under the new concept in Hong Kong, great challenges were encountered for this project. Ways to classify the severity of rusted components, to ensure the replacement components compatible with the original design requirements, and to supervise the quality and procedures of replacement were the key factors in completing the project.

By collaborating with specialist suppliers and professionals, the more innovative solutions to assess the conditions of existing structures can be discovered. Furthermore, numerical modelling can be implemented by simulating the load-deformation behaviour of the energy dissipating devices to assess the replacement components with equivalent engineering and material properties and structural performance against the original components. Specialist suppliers also offered the on-site demonstration to ensure the acceptance criteria of installation were followed.

This investigation approach helps to improve the maintenance approach for steel flexible barrier system. Also, as the energy dissipating devices were proprietary products, their replacement was limited by the supplier availability. By verification through numerical modelling method, other brands with similar operation and energy releasing mechanism can be used for replacement, which significantly reduces the construction cost and eliminates the risk of supply chain failure, so that maintenance works on rusted steel flexible barrier system in Hong Kong can be promoted on a large scale using similar analysis approach.

6 CONCLUSIONS

According to the recent site reconnaissance of the steel flexible barrier system constructed on the natural hillside above a public housing site, severe rusting on main components were identified. Minor rusting on other components were also identified. Repairing works were recommended including replacement of severely rusted components such as energy dissipating devices and application of rust preventive painting on minor rusted components. For existing energy dissipating devices with severe rusting, since the original supplier was no longer operated in the market, two other brands were proposed as replacement. After confirmation with the suppliers about the availability, constructability of the replacement components, numerical analysis for assessing the compatibility, serviceability and functionality of the replacement components was conducted. It is concluded that the steel flexible barrier system is checked to have adequate factor of safety with the replaced energy dissipating devices and meet the current geotechnical standards.

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