Design of a Boulder Fence in Hong Kong

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Synopsis: In 1982, the Geotechnical Control Office of Hong Kong Government as part of its Landslip Preventive Measures Programme started on a pilot scheme of boulder stabilization on a large boulder field of an area of 45,000 m^2. The stabilization basically comprises a boulder fence along the lower boundary to catch small boulders, plus insitu treatment of larger boulders. The design of the fence was preceded by mapping of the boulders and evaluation of probable boulder velocities. The fence adopted is of collapsible type, composes of mild steel posts of square hollow section on a concrete foundation, connected together by steel wire ropes. This paper gives a brief description of the field mapping, the prediction of boulder velocity, the fence design and the associated testings.

INTRODUCTION

Although Hong Kong is immensely urbanised, a large proportion of its territory still remains in its natural state. Among these areas, many are steep natural slopes strewn with boulders. The boulders are either remains of insitu decomposition of the basal rock, remaining in place or being transported from their original positions, or fallen debris from natural degradation of cliff faces higher up. Although less frequent than other forms of landslips, boulder fall is not uncommon in Hong Kong. In the years 1981-1983, the number of failure incidents involving boulders dealt with by the Geotechnical Control Office exceeded 20 each year.

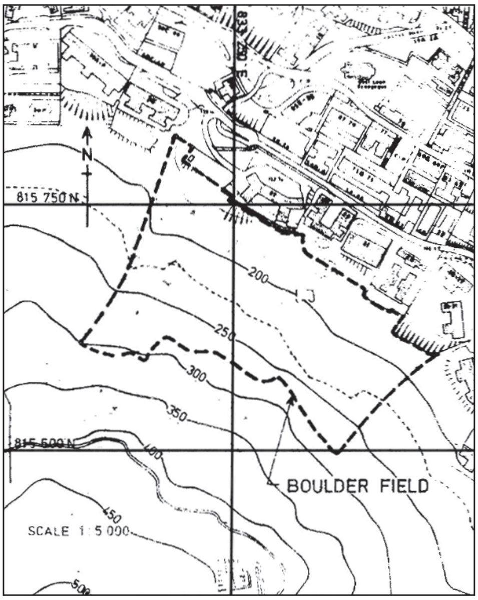

Figure 1. Site plan of the boulder field

THE SITE

The boulder field treated under this scheme is the natural hillside above Conduit Road in the Mid-Levels Area of Hong Kong Island about 300 metres wide (in E-W direction) and extends from the rear of the buildings (contour 150 mPD) southwards up to the toe of the Seymour Cliffs (contour 280 mPD) (See Figure 1 and Plate 1). The area is of an average gradient of 35° and is covered by a layer of boulderly colluvium of 0-20 m thick. The colluvium is largely volcanic in origin and its boulder content is as high as 75% to 100%. (See Plate 2). The boulders are believed to have been dislodged from the Seymour Cliffs during the last Ice Age.

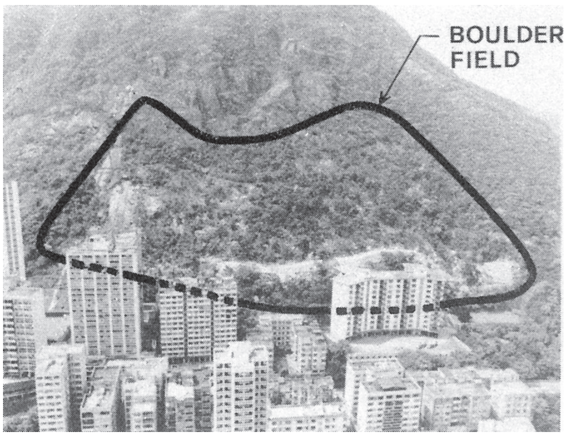

Plate 1. Aerial view of the boulder field

Plate 2. A close-up view of the boulder field

PRE-DESIGN BOULDER MAPPING

For the purpose of obtaining necessary information for design and cost estimation, a pre-design boulder mapping exercise was undertaken. A method of mapping in strips was employed in order to keep the job within a manageable scale and to limit the undergrowth clearance.

A 30 x 25 metres grid was set out on site and a metre wide undergrowth cleared along the grid lines. The ground profiles as well as the characteristics of any boulders intercepted by the grid lines were then recorded. These boulder characteristics recorded included their location, shape, angularity, the three principal dimensions, support conditions etc. The information collected was used to estimate the size distribution of the boulders and to obtain an idea of their characteristics in general. The results indicated that in the boulder field there are about 4500 boulders having a size greater than 2 tonnes and most of the boulders are either angular or sub-angular.

SCHEME ADOPTED

In view of the large number of boulders in the boulder field, to opt for merely insitu boulder stabilisation is unacceptable in terms of both construction cost and staff resources required in design and construction supervision. On the other hand, big boulders as heavy as 50 tonnes or more are not uncommon. To use barriers to prevent the down-slope developments from being hit by these large boulders in case of failure would be impractical. These considerations led to adoption of a combined treatment of works involving insitu stabilisation of big boulders and construction of a barrier at a lower level to arrest smaller boulders.

The choice of barrier type is very much dictated by the difficult site access and the lack of reasonable flat areas for massive structures at the toe of the slope. The adopted fence is of collapsible type which by virtue of its deformability absorbs the energy of an impacting boulder. With such a design, members of the fence are of light weight. Also, heavy and complicated foundations are not required.

PROBLEMS IN DESIGN OF BOULDER BARRIERS

Two aspects of knowledge are required for the rational design of boulder barriers. The first relates to the energy or velocity of the boulders. The second is the boulder-barrier interaction.

Unfortunately, information relating to these two aspects in the existing literature is scarce and mostly relates to the first aspect. Also, the limited literature that is available is not sufficiently comprehensive and direct application of the described experience to our design is impossible. Ritchie (1963) and Beggs et al (1985) measured the trajectory of rock fragments falling down slopes but their velocities were not measured. For the purpose of designing rock shelters, Piteau (1978) used a computer to simulate movement of rock fragments down a slope to establish the rock fragment distribution at the toe of slope. The programme however treated the fragments as point masses which is obviously not applicable to the case of rolling fragments. Benitez et al (1977) used classical mechanics to evaluate the variation of kinetic energy of a boulder sliding down a complex slope. For the case of rolling boulder, a spherical body was assumed. This gives the upper bound kinetic energy solution and may be very conservative in our case.

There is very limited mention in the existing literature on barrier design philosophy and procedure. Those barriers having been reported seem to be based on empirical approach (e.g. Bhanderi & Sharma, 1976; Mercer, 1982).

In an attempt to overcome these problems, mathematical models were developed based on Newtonian mechanics to estimate boulder velocity and to predict boulder-barrier interaction.

BOULDER VELOCITY

As mentioned earlier, the boulders in the area under study were derived from the Seymour Cliffs. The fragments when freshly dislodged are usually cubical in shape due to the orthogonal jointing pattern of the rock at the Cliff faces. On rolling down the slope, the corners and edges of the boulders break on impact, thus reducing the angularity of the boulders. (See Figure 2). The degree of reduction in angularity depends on the distance travelled. As the site is not far from the foot of the cliff, most of the boulders are angular to subangular.

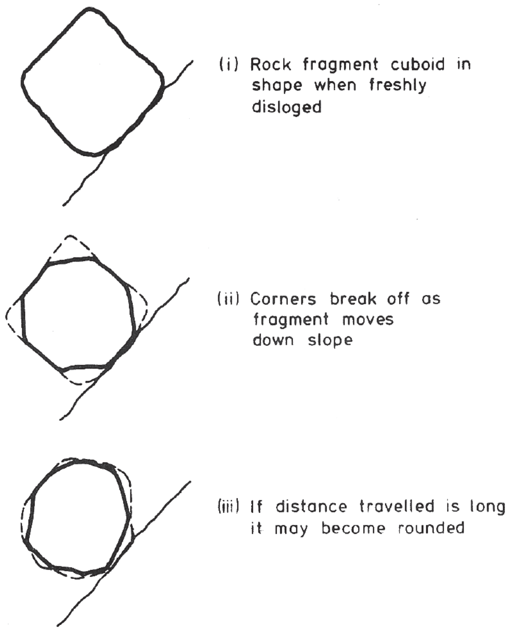

Figure 2. Development of shape of boulder down a slope

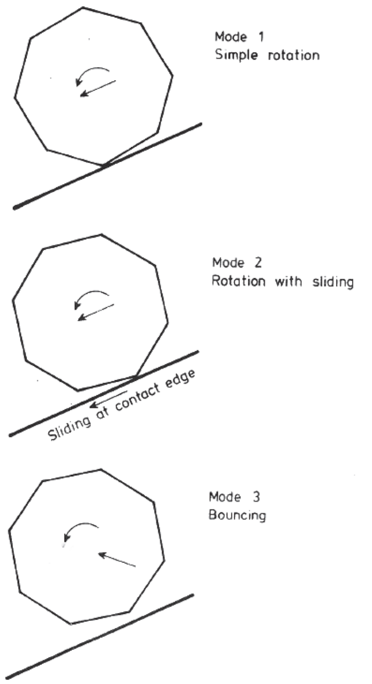

Figure 3. Types of boulder motions

On consideration of this process, it is reasonable to approximate the shape of the boulders to an octagonal prism in the mathematical model. This may still be a very crude starting point for evaluating probable velocities of boulders rolling down an actual slope but it nevertheless is a better simulation than the assumption of spherical boulders.

Regarding the rolling motion of a prism down a plane, it will not normally continue to rotate in its simplest form once it is set into rotation. By virtue of the impact between the plane and its sides during the rotation, other modes of motion such as sliding and bouncing will usually come into play. Their occurrences of course depend on the magnitude of the momentary velocity at the time of impact, the coefficient of restitution, the coefficient of friction, to name a few. To facilitate modelling, three types of motions were isolated for consideration. These were (i) simple rotation about its corner edge, (ii) rotation with sliding about its corner edge and (iii) bouncing. (See Figure 3). Solution to the mathematical model was obtained with the aid of computers.

Figure 4 shows a typical time-displacement relationship of an octagonal prism and its comparison with that for a cylindrical prism.

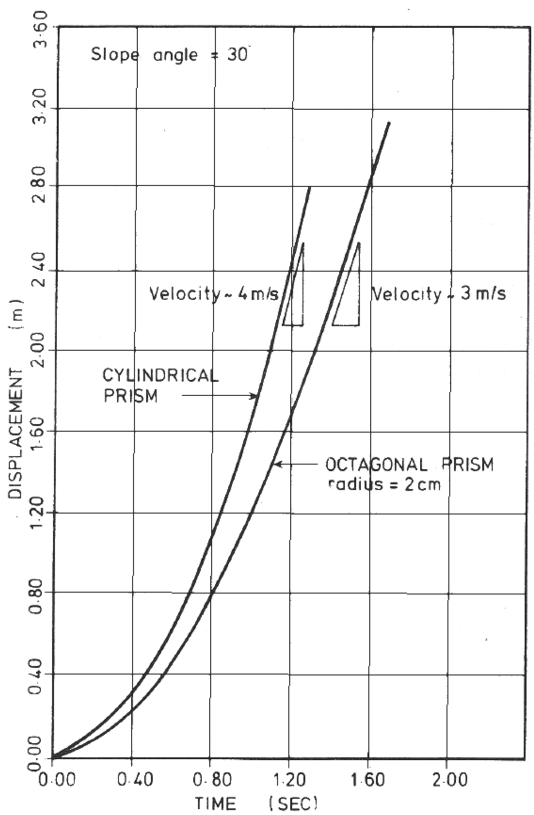

Figure 4. Typical time-displacement relationship for octagonal and cylindrical prisms

BOULDER-FENCE INTERACTION

There are in general two approaches to predict boulder-fence interaction, i.e., the force approach and energy approach. In the force approach, the force on fence by a boulder is found by Newton's 2nd law which says that force is the rate of change of momentum. Simple as it may sound, it is however difficult to apply because the time taken to decelerate the boulder depends on a lot of factors in a complicated manner.

In the energy method, work done to deform the fence can be directly related to the kinetic energy of the impacting boulder. The fence is regarded as satisfactory if the design boulder causes an acceptable degree of deformation. The designer will usually choose to use permanent deformation (plastic method) to absorb energy from the boulder, though use of temporary deformation (elastic method) is a possible alternative. A fence designed by the elastic method calls for heavier members and foundations but requires less repairs. For fences designed by plastic method the reverse is true.

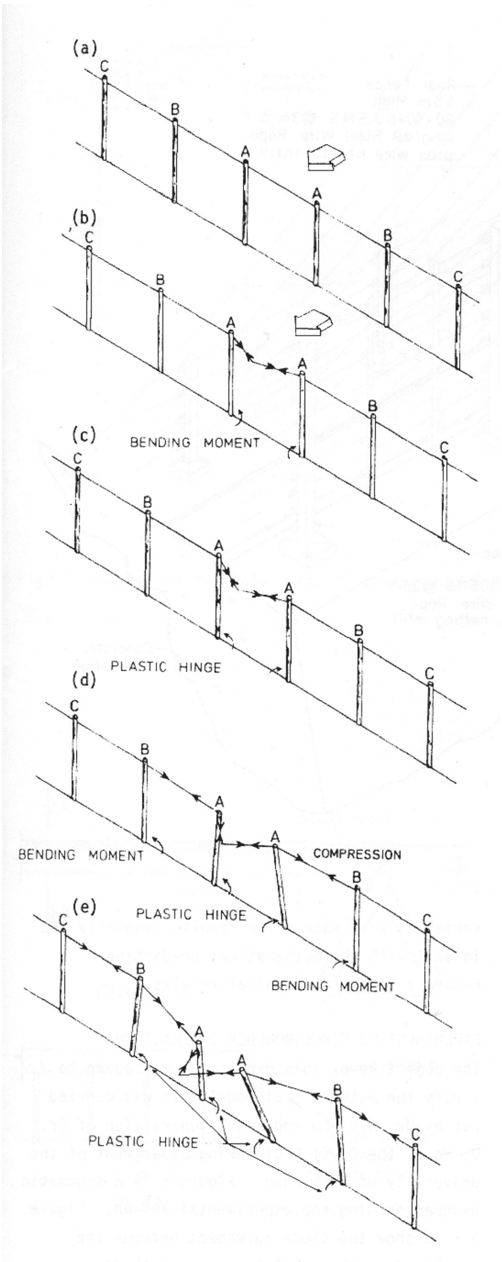

Figure 5. Boulder impact on a hypothetical fence

The fence used in this case was designed by plastic method. To illustrate the design principle, it is perhaps worthwhile to consider a hypothetical fence consisting of an array of posts connect by a single row of wire rope at the top. (See Figure 5). Upon impact, the wire rope moves forward inducing forces on the posts. This, in its extremity, leads to formation of plastic hinges at the base of the posts thus allowing them to rotate and absorb energy (Figure 5c). As the first pair of posts rotate, the adjacent pair of posts are pulled till plastic hinges form also at their bases (Figures 5d & e). The process may repeat for the further pair of posts until the kinetic energy of the boulder is completely absorbed.

The actual fence was extended from this hypothetical case by provision of multi-row wire ropes between the posts, and another similar but smaller, less substantial fence at the up-hill side to arrest smaller boulders. It is believed that this arrangement is most suitable for this site as the lightweight members permit transportation through the difficult access (foot paths in most cases). Due to the limited loads transmitted, the foundation will be simple spread footing sitting either directly on the slope surface or supported by micropiles where the ground conditions are unfavourable.

A computer programme was again developed to evaluate the member deformation and force relationship. The most effective combinations of steel post and wire rope dimensions and configurations were examined. The final downhill fence comprises 3 m high SHS 150 x 150 x 10 steel posts at 3 m c/c connected together by Ø14 steel wire ropes at 200 c/c and 350 c/c at bottom and top half of the fence respectively plus wire netting infill. The upper fence comprises 1.5 m high SHS 80 x 80 x 6.3 steel posts at 3 m c/c, linked by Ø9 steel wire ropes at 350 c/c plus wire netting infill.

Figure 6 is an isometric view of the fence. The fence can absorb 100 kN-m energy when a total of 6-7 posts are permanently deformed.

CONFIRMATORY EXPERIMENTS

Following the preliminary design, experiments and tests to check on the validity of the design were carried out. A total of three such tests/experiments have been carried out of which two were executed in cooperation with University of Hong Kong. They include the experiments on boulder velocity, fence/bounder interaction and loading tests on steel hollow sections. The details are described below.

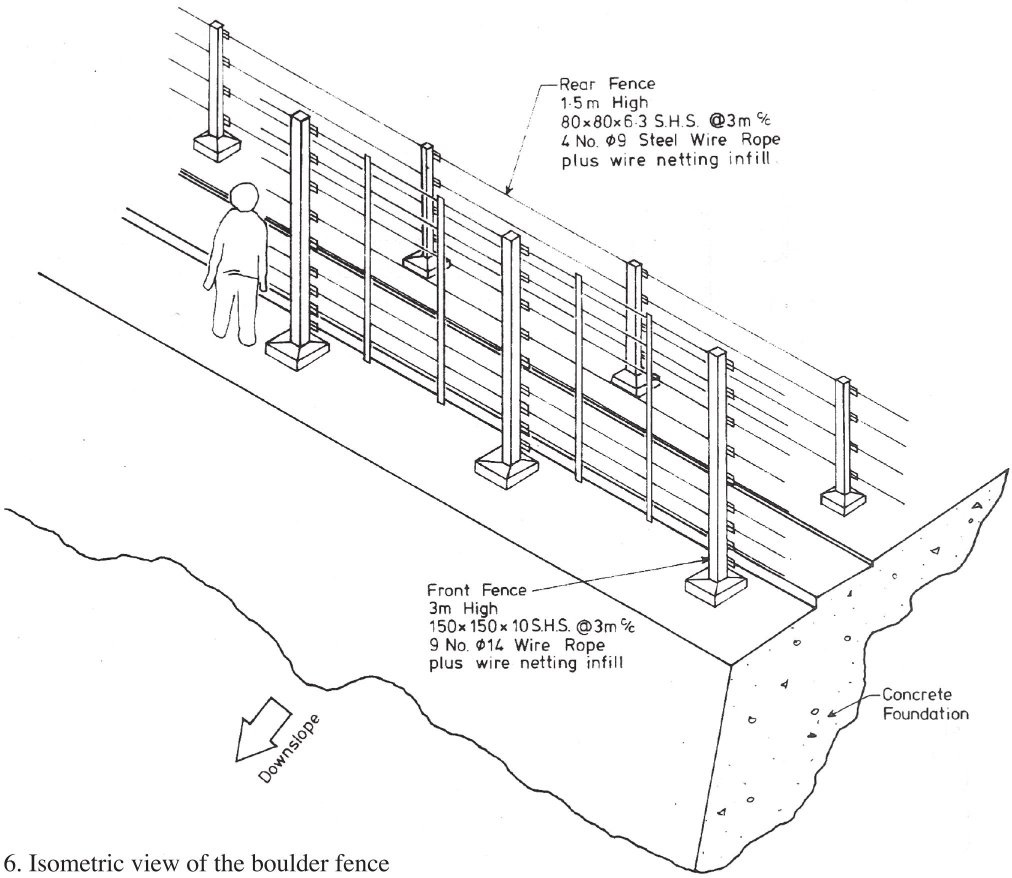

Figure 6. Isometric view of the boulder fence

EXPERIMENT ON BOULDER VELOCITY

The purpose of this experiment was to verify the mathematical derivations. It consisted of rolling polygonal prisms down a 5 metre long inclined plane. The motions of the prisms were monitored by a video camera with frame spacing of 1/25 sec. The time-distance relationship was then measured from television screen when the tapes were played back. Five variables have been considered in the experiment i.e., gradient of the plane, number of sides and diameter of prisms, coefficient of restitution and dynamic coefficient of friction. A total of four prisms made of hard wood were used. Three of them were 90 mm in circum-diameter and were of regular hexagon, octagon and 16-sided polygon in cross-section. The other one was an octagonal prism with a 50 mm circum-diameter. The relatively small boulder size was used to ensure an adequate size/travel-distance ratio. Different coefficients of friction were introduced by covering the prism surfaces with papers of different texture. The timber plane was also covered with different materials to give different coefficient to restitution. The gradient of the inclined plane could conveniently be varied by adjusting the support height. Over 1000 runs involving 29 combinations of variables were made. The results generally tie in well with the mathematical prediction. Figure 7 gives some typical results.

EXPERIMENT ON FENCE-BOULDER INTERACTION

The objective of this experiment was again to verify the mathematical model. It was carried out by Mr W.H. Lo under the supervision of Dr. D. Ho of the Civil Engineering Department of the University of Hong Kong. Figure 8 is a schematic diagram showing the experimental set-up. Figure 9 &10 show the close agreement between the results from the model testing and that predicted by mathematical simulation.

TEST ON LOCAL BUCKLING

The experiment was intended to establish the local buckling behaviour of steel hollow sections at large deformation and methods of strengthening the members.

The ability of the design hollow section to deform without buckling to the required 30° plus was doubtful.

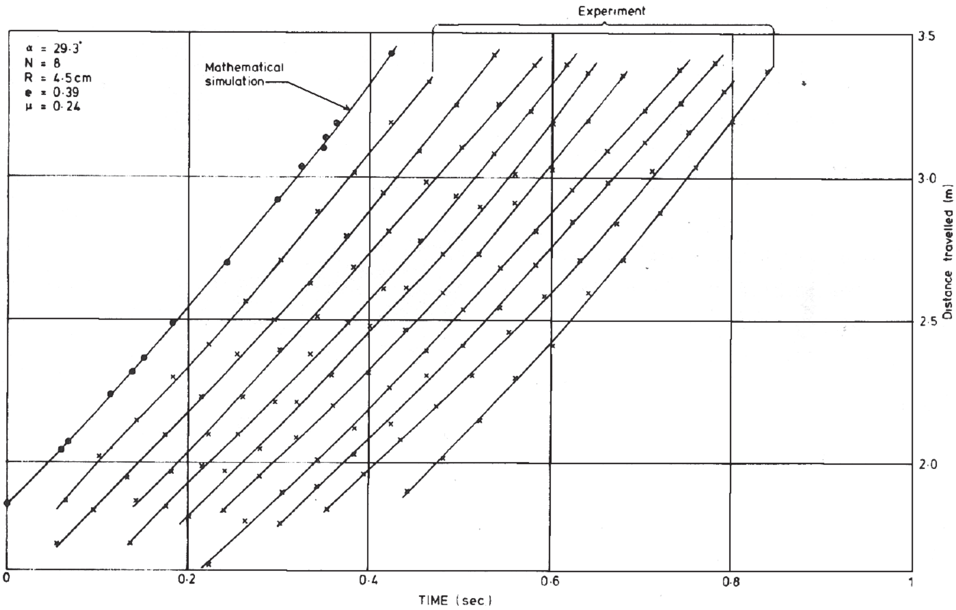

Figure 7. Typical experimental results compared with that predicted by mathematical simulation

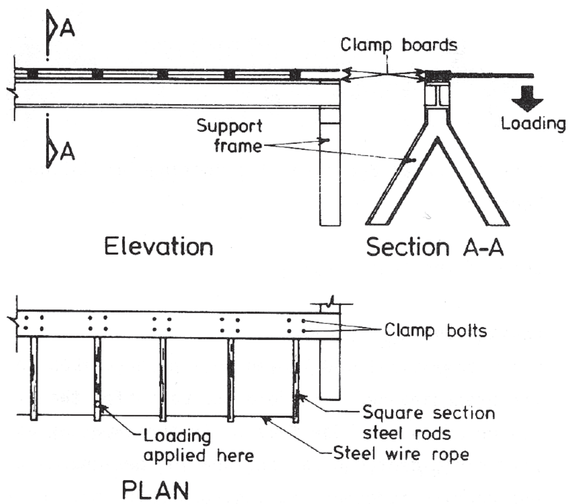

Figure 8. The set-up for experiment on fence-boulder interaction

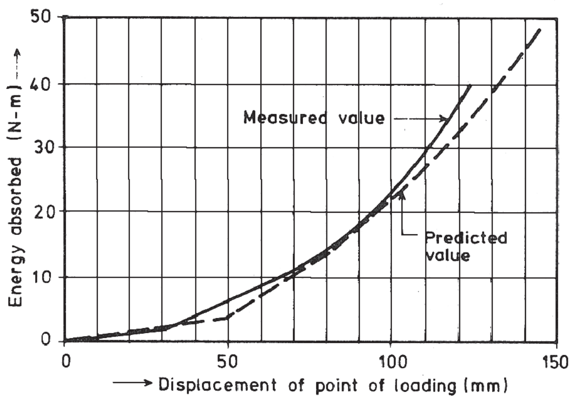

Figure 9. Energy absorption by model fence and its prediction by mathematical simulation

A literature review for information on this aspect proved to be of little use. The only practical solution was to actually load the design members.

Plate 3 shows the set-up of the loading apparatus. The testing indicated that local buckling occurred at less than 10° rotation of the plastic hinge which led to a substantial drop in plastic moment. Plate 4 shows the local buckling at large deformations (approx. 50° rotation). Drop in strength due to local buckling was more pronounced in rectangular hollow sections (RHS) than in square sections (SHS). To prevent the occurrence of local buckling at an early stage of deformation different measures such as infilling the hollow sections with weak concrete and provision of internal or external steel stiffeners were looked into. Members with such modifications were tested. The results showed that square hollow sections with concrete infill gave the highest resistance to local buckling (See Figure 11 for some of the test results).

ENGINEERING JUDGEMENTS

The mathematical models and testing described in the preceding sections form the basis for the design of the boulder fence. In the same way as with other geotechnical engineering design, engineering judgement is indispensable in achieving a successful

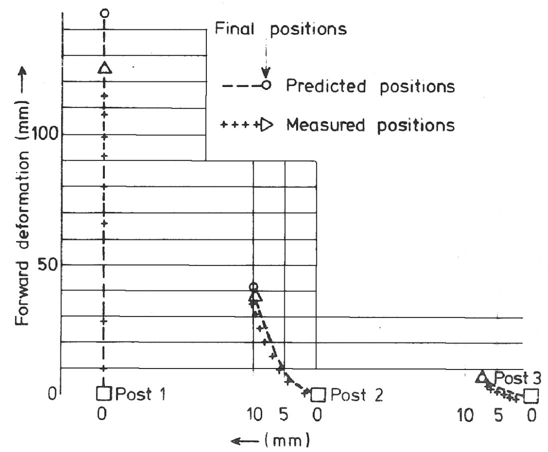

Figure 10. Typical experimental results and the prediction by mathematical simulation

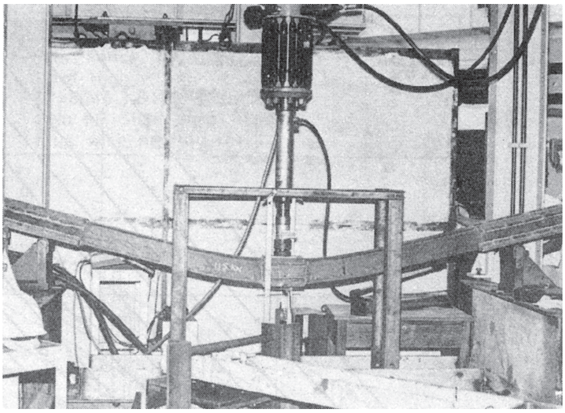

Plate 3. Steel hollow section under loading test

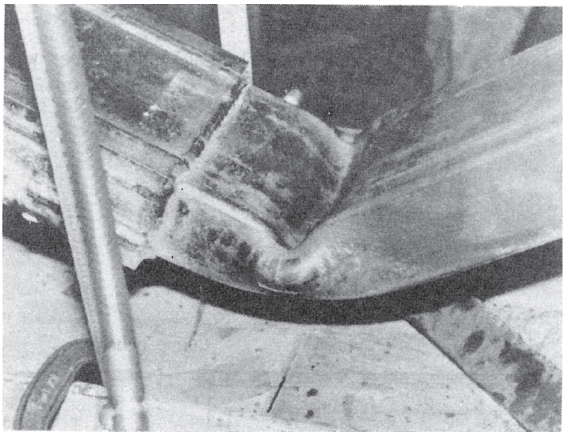

Plate 4. Local buckling of a rectangular hollow section

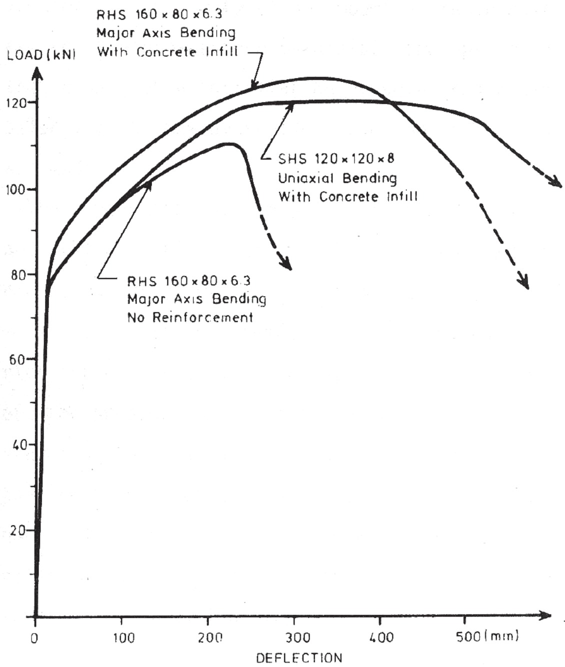

Figure 11. Test results on hollow sections

result. This is especially true in the design of boulder fence.

The theoretical models for boulder velocities and boulder/fence interaction prediction, no matter how refined they are, can only be regarded as a guide to aid the engineer in the formulation of his design. This is because of the inherent difficulties in simulating in the models, with high degree of accuracies, the various factors that will affect the motion of a boulder down a slope. These factors may include the actual shape, angularity and mass of boulders, their probable movement paths before reaching the fence, the slope angle, deformability and irregularity of the ground along the movement paths, the likelihood of the boulders being broken up in the course of motion, etc.

The fence is able to absorb an impact energy of 100 kN-m. Any boulder which will attain a velocity sufficient to give rise to an energy greater than 100 kN-m will be stabilised insitu. The velocity model only gives a crude idea of the relationship between the velocity and distance travelled. A close on-site examination has to be made to assess the factors which may affect the boulder motions as those described above before a decision can be made on which boulder can be retained by the fence and which should require with insitu stabilization. At this particular point, the application of sound engineering judgement is most crucial.

CONCLUSION

This is one of the first attempts in Hong Kong to carry out boulder stabilization on such a scale and under such a restrictive site condition. Past experiences in both design and construction of this kind of work are scarce and considerable effort has been made to overcome this deficiency by developing mathematical models and carrying out tests. Needless to say, considerable experience has been gained through the design already completed and the construction now underway. It is anticipated that through monitoring the performance of the fence at a later date, more valuable information can be obtained. We hope, with the construction of this prototype structure, apart from achieving its primary purpose of safe-guarding the conditions of the boulder field under treatment, we shall be able to advance another step forward towards a better understanding and appreciation of dynamic boulder behaviour and problems associated with stabilization works.

ACKNOWLEDGEMENTS

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