Design of Barriers for Natural Terrain Landslides

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Abstract: The demand for land in the hilly terrain of Hong Kong means there is increasing pressure for developments to encroach onto the natural terrain. This paper examines some salient aspects of the design of barriers against natural terrain landslides and channelised debris flows. The various approaches suggested in the literature in evaluating the impact load are reviewed. The authors suggest that the impact pressure due to the landslide debris could be taken as three times that given by the equation based on the consideration of the rate of loss of momentum of an equivalent fluid impacting onto a rigid surface. The impact load due to boulders in the debris could be estimated using the flexural stiffness method or taken to be nominally one-tenth of that given by the Hertz equation.

INTRODUCTION

The demand for land in the hilly terrain of Hong Kong means that there is increasing pressure for developments to encroach onto steeper areas of natural terrain. Typically more than 300 natural terrain landslides occur in Hong Kong every year (Evans & King 1998). The vast majority of these are shallow failures involving the top few metres of the ground surface and some may develop into channelised debris flows with long runout. Given the close proximity of some of the developments to natural hillsides, even a relatively small unchannelised failure can potentially result in serious consequences.

Preventive works on the hillside can be extensive and prohibitively expensive. Landslide barriers may prove to be a cost-effective solution in certain situations. This paper examines some salient aspects of the design of barriers for natural terrain landslides. Key data on some of the barriers constructed in Hong Kong are presented. The various approaches suggested in the literature in evaluating the impact load are reviewed and some guidance on the assessment of the impact load is put forward.

REVIEW OF BARRIERS IN HONG KONG

Table 1 shows the types of debris- and boulder-resisting barriers that have been, or are being, constructed in Hong Kong. These include rock fences, gabions, reinforced concrete retaining walls, earthfill berms and check dams. These structures are generally less than 10 m in height, with the majority being less than 5 m.

Boulder barriers (or fences) are constructed to mitigate boulder hazards and are generally designed to arrest boulders up to a certain size, above which insitu stabilisation is carried out to avoid the need for excessively bulky and expensive structural members. Debris-resisting barriers commonly employed in Hong Kong comprise predominantly reinforced concrete L- or T-shaped retaining walls. To enhance the impact capacity, some of these structures are founded on minipiles and some are integral with the building structure. In one case, an earthfill berm has been constructed as a terminal barrier to protect a golf driving range from debris enroachment.

The design approaches adopted for the barriers can be broadly classified into the energy approach

Table 1. Types of barrier structures in Hong Kong

Type of barriers	Height (m)	Hazards	Design event
steel fences	1.5 – 4	boulders	0.3 - 1.3 m (diameter)
gabion walls	3 – 7	boulders	2 - 5 m (diameter)
reinforced concrete cantilever walls	2 – 4	boulders	1.0 m (diameter)
gabion walls	3	debris	300 m^3
reinforced concrete L- or T-shaped walls	3 – 5	debris	70 - 125 m^3
reinforced concrete L- or T-shaped walls	7 – 9	debris/boulders	600 - 2225 m^3
check dams	5	debris	3000 m^3
reinforced concrete check dams	6	debris/boulders	1400 m^3
earthfill terminal berms	1.5	debris	1500 m^3

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and force approach. The energy approach is generally adopted for boulder barriers which are customarily designed as sacrificial structures undergoing deformation upon impact. The kinetic energy of the boulder is equated to the work done to deform some of the structural components of the barrier. Generally, the maximum energy-absorbing capacity of the barrier system is designed to be mobilised assuming that the barrier undergoes permanent deformation rather than elastic deformation; otherwise, very massive structural members will be needed (Chan et al. 1986). Given the energy of the boulder just prior to impact, sizing of the various components of the boulder barrier can be done in accordance with structural engineering principles. Proprietary rock fences are also available to meet different energy-absorbing requirements.

The force approach tends to be adopted in the design of barriers which act as permanent structures, particularly where a structural wall or a mass barrier has been used. Two methods have been used to estimate the impact force: one assumes that the entire debris mass will move with the barrier as a unit upon impact and the unit will then decelerate at a rate controlled by the sliding resistance at the base of the barrier. The other involves the determination of the rate of change of momentum of the debris upon impacting the barrier. The former method, which assumes that the entire debris mass contributes towards the impact momentum, may not adequately model the impact process of a deformable body. It also requires an assumption on the proportion of the wall section that would move with the debris. In the latter approach, the impact duration has sometimes been arbitrarily defined. Alternatively, the impact force has been estimated based on the rate of debris losing momentum upon impact on the barrier. This approach, which seems to be the practice favoured in a number of countries, will be further examined below.

REVIEW OF OVERSEAS DESIGN PRACTICES

Various approaches adopted in the estimation of debris and boulder impact loading have been reviewed in order to identify practical methods for design purposes.

Debris Impact

Empirical Approach

The debris impact loading on the barriers is sometimes estimated assuming a hydrostatic pressure distribution together with an “enhancement factor”. In Switzerland, the “enhancement factor” is typically assumed to be 3, whereas in Austria, this is usually taken to be 3 to 5 (Thurber Consultants Ltd 1984).

The basis of the empirical approach is not clearly documented but it may be compared to measurements reported in the literature. For example, Scotton & Deganutti (1997) used a 9.5 m-long flume together with coal slag with an average particle size of 5.7 mm and different fluids to examine the effect of viscosity on the impact pressure on barriers. The flume was inclined at 10°, 15° and 20° in the model tests. The results are expressed in terms of the ratio of the measured impact pressure to the hydrostatic pressure at the base. This ratio was found to fall within a wide range between about 2.5 and 7.5, with a mean of 5.3 for a more viscous flow and 3.5 for a less viscous fluid. Although the mean of the above ratio is similar to the empirical values adopted, it is noteworthy that the scatter of the measurements is considerable.

Table 2. Empirical impact pressure values derived from Russian studies on debris flows (Wu et al. 1993)

Scale of debris flow	Maximum flow depth (m)	Diameter of the largest entrained boulder (m)	Impact pressure (kPa)
Small	< 2	< 0.5	50-60
Medium	2-3	< 0.7	70-80
Medium-large	3-5	< 1.5	90-100
Large	5-10	2.5-3	110-150

Wu et al. (1993) reported that empirical impact pressures have been prescribed for the design of barriers in Russia. The impact pressure is dependent on the magnitude of debris flow events, the flow depth and the particle size of the entrained materials (Table 2).

Analytical Approach

The average debris impact pressure imposed on a mass barrier can be estimated based on the consideration of the rate of loss of momentum upon impact (Hungr et al. 1984, Du et al. 1987, Public Works Research Institute (PWRI) of Japan 1988, VanDine 1996) as follows:

$$p = \rho_d v_d^2 \sin\beta \qquad (1)$$

where p = average impact pressure, ρ_d = density of debris, v_d = velocity of debris at impact, and β = angle between impact face of barrier and direction of debris motion. The average impact pressure is assumed to be uniform over the depth of the debris.

Field measurements of debris impact load may be interpreted using the above equation. The results of a Japanese study on the field measurement of debris impact loads were reported by Wu et al. (1993). In the study, the impact load on a 15 cm by 15 cm plate was recorded. Figure 1 shows that the measured values are up to several times greater than values computed using Eq. (1). Wu et al. (1993) suggested that most of the measurements could have been influenced by boulders or hard inclusions hitting the sensors.

Another instrumented field study of debris impact pressure, velocity and density of debris was reported

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Table 3. Summary of formulations for determination of debris impact load

Hungr et al. (1984)	Du et al. (1987)	Thurber Consultants Ltd (1984)	Scotton & Deganutti (1997)
$p = \rho_d v_d^2 \sin\beta$ $F = \rho_d A v_d^2 \sin\beta$	$p = 3\rho_d v_d^2 \sin\beta$	$F = \dfrac{\alpha\rho_w g d^2}{2}$	$p = \alpha g \rho_d h$
p = impact pressure F = impact force ρ_d = density of debris flow v_d = velocity of debris flow A = cross-sectional area of flow β = angle between velocity vector and surface of obstruction		ρ_w = density of water d = debris height against barrier α = impact load factor g = gravitational acceleration	h = flow depth α = 5.3 for more viscous fluid to 3.5 for less viscous fluid

by Du et al. (1987) for a number of debris flow events in China. Again, there was considerable scatter in the measured impact pressures. This could be due to, among other things, the sensors being hit by debris at an oblique angle, effects of splashes or the heterogeneous nature of the debris. Table 3 shows the field measurements for direct hits on the sensors. Figure 1 shows that the computed impact pressures obtained using Eq. (1) are in general only a fraction of the measured values. In China, a factor of 3 is generally applied to Eq. (1) in the design of barriers (Du et al. 1987, Wu et al. 1993). Other alternative theoretical formulations have been reported in the literature (see Table 3 for examples).

The influence of the shear strength of debris on impact pressure was investigated by Armanini & Scotton (1992) using a 6 m-long flume. Their results show that for similar velocities, debris with a higher shear strength has higher impact pressures than that with a lower shear strength. In experiments where debris with a high shear strength impacted the barrier, Armanini & Scotton (1992) observed reflection waves bouncing off the barrier and the measured impact pressure was approximately twice that given by Eq. (1). This suggests that the debris does not only lose its original velocity upon impact as assumed implicitly in Eq. (1) but also is likely to attain a velocity opposite in direction to its original value, hence resulting in a larger impact pressure.

A possible explanation of the measurement of some relatively high impact pressures in China may be the size effect of the sensor relative to the particle size of debris. If the size of the sensors is small, the measured pressure is likely to be significantly affected by impact of large particles giving rise to local peak values, whereas for a larger sensor the measured pressure is expected to be closer to the average effect of the debris.

Another plausible explanation is that when the sensors are buried by the debris, drag develops on the edges of the sensors as well as on the mass of debris in front of them, resulting in an increase in the impact pressure.

It is important to recognise that the formulation of Eq. (1) corresponds to the average pressure developed upon impact on the barrier by a fluid. Based on the available information described above, it appears that the debris impact pressure could well be several times that given by Eq. (1), depending on the solids concentration as well as the shear strength of the debris.

Boulder Impact

Boulders can be entrained within landslide debris and it is important that suitable allowance be made in barrier design. An overview of selected methods

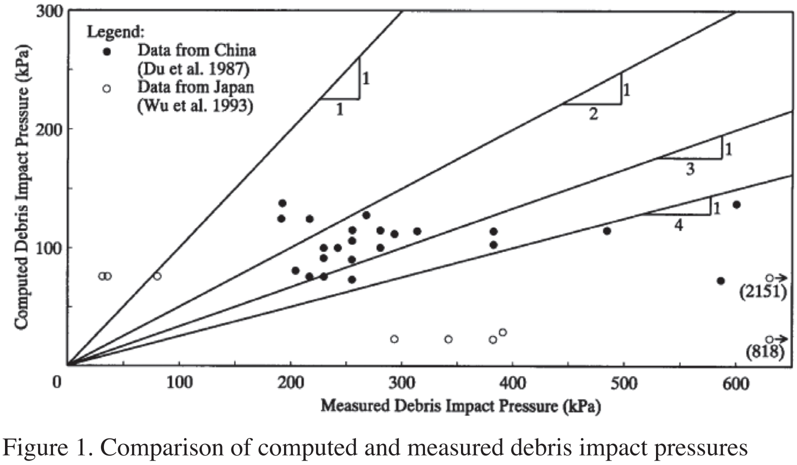

Figure 1. Comparison of computed and measured debris impact pressures

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in estimating boulder impact load (Table 4) is given below.

PWRI (1988) recommended that the estimation of boulder impact force should be determined using the Hertz equation (Table 4), which was derived for an elastic sphere impacting an elastic medium. In determining the boulder impact force, it was recommended that the velocity of the boulder should be taken as that of the debris flow and that the design boulder size should be taken as the maximum size which can be mobilised by the debris. Hungr et al. (1984) suggested that the design boulder size should be assumed to be a sphere with its diameter equal to the flow depth.

As the actual impact may not be perfectly elastic and that material crushing may occur at the contact, Hungr et al. (1984) cautioned that the contact forces computed using the Hertz equation could be extremely conservative and suggested to reduce them nominally by a factor of 10. Zhou et al. (1991) reported field measurements in Japan which showed the measured boulder impact forces to be about 4% to 11% of those computed using the Hertz equation. Based on the above measurements, they suggested that the boulder impact force computed using the Hertz equation should be reduced by a factor of 5 to 10.

For certain structural elements (e.g. bridge piers), flexural deformations could be more important than contact deformations in governing the magnitude of the force generated by boulder impact. The impact force on such structures can be estimated by equating the kinetic energy of the boulder with the work (or energy) expanded by the structure in undergoing flexural deflection, as follows (Hungr et al. 1984, Zhang et al. 1996):

$$F = v_b \sin\beta \sqrt{m_b K_B} \qquad (2)$$

where F = impact force, m_b = boulder mass, β = angle between impact face of barrier and debris motion direction, v_b = boulder velocity, and K_B = stiffness factor of barrier structure. The flexural stiffness factors for the case of simply-supported and cantilever structures are derived and summarised in Table 4. It can be seen that the impact force is proportional to the bending stiffness of the structure.

According to Huang (1996), a slightly different form of the above equation was adopted by the Chengdu Railroad Research Institute in the estimation of boulder impact force (see Table 4 - Compressible barrier method). The coefficient η denotes the proportion of kinetic energy of the boulder imparted onto the barrier. According to Huang (1996), the value of η is normally assumed to be 0.3 for a circular impact surface, and that the sum of the coefficients of elastic deformation of the boulder and barrier may be assumed to be 0.005 m/kN for bamboo or wooden rafts impacting bridge piers.

Zhang et al. (1996) noted that when a boulder impacts a barrier, the impact load will propagate at the velocity of a compression wave from the contact point to other parts of the boulder. The formula for estimating the force using wave theory depends on, among other things, the velocity of compression wave and the contact area. The former is generally determined either from the elastic modulus and the density of the boulder, or is taken to be about 4000 m/s. The latter, however, is very difficult to estimate with confidence in practice.

Wu et al. (1993) reported that the boulder impact force could be estimated from the change in momentum of the boulder upon impact, with the duration over which the change in momentum takes place being assumed to be 1 second.

Haller & Gerber (1998) conducted a series of field tests in which boulders up to 2700 kg in weight impacted flexible rock fences at velocities of up to

Table 4. Summary of formulations for determination of boulder impact force

Hertz equation (PWRI 1988)	Flexural stiffness method (Hungr et al. 1984, Zhang et al. 1996)	Compressible barrier method (Huang 1996)	Allowance for sliding of barriers (Threadgold & McNicholls 1984)	Wave theory (Zhang et al. 1996)	Momentum equation (Wu et al. 1993)
$F = n\left(\frac{5 m_b v_b^2}{4n}\right)^{\frac{3}{5}}$ $n = \frac{4 r_b^{\frac{1}{2}}}{3\left(\frac{1-\mu_b^2}{E_b} + \frac{1-\mu_B^2}{E_B}\right)}$ The above can be rewritten as: $F = 1.14 v_b^{1.2} n^{0.4} m_b^{0.6}$ m_b = mass of boulder v_b = velocity of boulder r_b = radius of boulder μ_B = Poisson's ratio of barrier E_B = elastic modulus of barrier μ_b = Poisson's ratio of boulder E_b = elastic modulus of boulder	$F = v_b \sin\beta\sqrt{m_b K_B}$ K_B = stiffness factor $= \frac{3EI}{L^3(1-\psi)^2\psi^2}$ for a simply-supported beam $= \frac{3EI}{(\psi L)^3}$ for a cantilever beam or wall EI = bending stiffness of barrier L = length or height of barrier ψ = ratio of distance between impact location and barrier support to length of barrier	$F = \eta v_b \sin\beta\sqrt{\frac{m_b}{c_b + c_B}}$ η = reduction factor, assumed to be 0.3 c_b = coefficient of elastic deformation of boulder c_B = coefficient of elastic deformation of barrier β = angle between the face of barrier and the debris motion direction	$F = \frac{(m_b v_b)^2}{m_b + m_B} \times \frac{1}{2s}$ $s = \left(\frac{m_b v_b}{m_b + m_B}\right)^2 \times \frac{1}{2g\tan\phi}$ The above can be rewritten as: $F = (m_b + m_B)2g\tan\phi$ m_B = mass of barrier s = displacement of barrier ϕ = angle of friction between base of barrier and foundation	$F = \rho_b C_b v_b A_c$ $C_b = \sqrt{\frac{E_b}{\rho_b}}$ A_c = contact area C_b = velocity of compression wave in boulder ρ_b = density of boulder	$F = \frac{m_b v_b}{\Delta t}$ Δt =duration of impact

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27 m/s. They used a high-speed (54 frames/second) camera to capture the trajectory and the deceleration process of the boulder. They noted that after the first contact with the rock fence, the boulder underwent a displacement of up to 5 m before coming to a halt. The entire process of bringing the boulder to rest lasted about 0.3 second and the peak deceleration force was estimated to range from 200 kN to 600 kN. For stiffer systems, the impact duration will be much shorter and consequently very large impact forces will result.

COMPARISON OF DIFFERENT METHODS OF ASSESSING BOULDER IMPACT LOADS

Wu et al. (1993) and Zhang et al. (1996) reported a number of landslide events in China in which structures were damaged by boulders. They gave information on the flow characteristics of the debris and estimated the loads under which these structures would have failed. It seems that the failure capacities reported by the original authors might not have accounted for the dynamic effects and hence they would likely be lower than actual values observed in the field. This information has allowed a comparison of the boulder impact loads calculated using different formulae in Table 4. In some cases, the information needed for the computation is not readily available from the published papers and for the purposes of the present comparative study, typical values have been adopted. A summary of the parameters used in the computation is given in Lo (2000). The results are summarised in Table 5.

It can be seen that there is a wide scatter in the predicted results. The impact forces estimated using the Hertz equation are about one to two orders of magnitude higher than the estimated ultimate capacity of the damaged structure. On the other hand, the formula adopted by the Chengdu Railroad Research Institute consistently predicts much lower impact forces which are only a small fraction of the ultimate capacity of the barriers. The principal reasons for the under-estimation of the impact force is likely to be due to the inappropriate use of the coefficient of elastic deformation derived from bamboo and wooden rafts which are much more flexible and ductile than the boulders.

The momentum equation given in Table 4 also tends to underestimate the impact force which suggests that the assumed impact duration of 1 second may not be appropriate. This also highlights the sensitivity of the estimates to the assumption of impact duration which is very difficult to determine reliably. The formula accounting for flexural deformations and that derived from wave theory tend to give estimates closer to the computed ultimate capacities of the structures. It should be noted that in the reported case studies, the only established information is that the boulder impact force exceeded the failure capacity of the structure and therefore no definite conclusion can be drawn as to the relative reliability of the two formulae. It is noteworthy however that the wave theory requires an assessment of the contact area at impact, which is very difficult to determine.

The above exercise serves to illustrate the great uncertainties in the predictions. In practice, expedients such as the possible incorporation of a soft cushion of suitable material, e.g. rubber tires, in front of the barrier may assist in reducing boulder impact loads by extending the duration of impact. The process of boulder impacting onto a barrier may also be studied using computer modelling. An example is LS-DYNA, a non-linear 3-D finite element program which has been used recently to simulate a boulder impacting a steel fence (Ove Arup & Partners Hong Kong 1998) to determine its probable deformations and stresses.

SUGGESTED APPROACH FOR ASSESSMENT OF DEBRIS AND BOULDER IMPACT LOADS

In assessing the various approaches put forward by different investigators for the determination of impact loading, more weight has been given to those which

Table 5. Comparison of predicted boulder impact force using various formulations

Case histories	Estimated failure capacity $^+$	Estimated impact force Hertz equation	Flexural stiffness method	Compressible barrier method	Wave theory	Momentum equation
(1) On 7 September 1981, a 6-m diameter boulder entrained in a debris flow severed the centre pier of a bridge on the Chengdu-Kunming Railroad into three fragments (Zhang et al. 1996).	12,000 kN	2,623,000 kN (218.6)	121,000 kN (10.1)	770 kN (0.06)	51,200 kN (4.3)	3,700 kN (0.3)
(2) In June 1983, a 5.5-m boulder entrained in a debris flow buckled two 1 m diameter steel pipes in Dongchuan, Yunnan. (Zhang et al. 1996).	28,600 kN	3,413,000 kN (119.3)	-	770 kN (0.03)	25,600 kN (0.9)	2,800 kN (0.1)
(3) In June 1981, a 3-m diameter boulder entrained in a debris flow severed a concrete bridge pier in Dongchuan, Yunnan. (Wu et al. 1993).	28,770 kN	787,000 kN (27.4)	-	330 kN (0.01)	33,300 kN (1.2)	480 kN (0.02)
(4) On 10 August 1968, a boulder estimated to be 2 m x 3 m x 4 m in size destroyed a reinforced concrete structure in a debris flow event in Dongchuan, Yunnan (Wu et al. 1993).	1,290 kN	123,000 kN (95.3)	4,440 kN (3.4)	340 kN (0.26)	21,300 kN (16.5)	648 kN (0.5)

+ provided by original authors
( ) denotes ratio of the estimated impact force to the failure capacity of the structure

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are supported by field measurements or calibrated against field observations.

Among the various formulations available for the estimate of debris impact pressure, the one derived from rate of fluid losing its momentum upon impact onto a rigid surface (Eq. (1)) resembles closely the dynamics of debris impacting onto barriers. This equation is based on the assumption that the impacting fluid has no shear strength. Unlike fluid, landslide debris exhibits shear strength. The exact relationship between the shear strength of the debris and debris impact pressure is not well understood. However, the work by Armanini & Scotton (1992) and Scotton & Deganutti (1997) showed that the debris impact pressure is dependent on the shear strength of the debris and their measurements showed that it could be up to twice that given by Eq. (1). The comprehensive field measurements of debris impact pressure carried out in China showed that the measured debris impact pressure could be 2 to 4 times that given by Eq. (1). As a first approximation, the debris impact pressure could be taken to be three times that given by Eq. (1), i.e.

$$p = 3\rho_d v_d^2 \sin\beta \qquad (3)$$

As for formulations for boulder impact, the momentum equation and the formulation for ships colliding onto piers tend to underestimate the impact load probably because of an overestimation of the impact duration and that the stiffness of boulders is considerably higher than that of ships. The Hertz equation tends to overestimate the impact force by one to two orders of magnitude. It seems that the impact forces computed using the Hertz equation are very conservative and can be reduced by a factor of at least 10. The flexural stiffness equation and the wave theory yielded relatively reasonable estimates, however, the latter may not be practical in design application because it requires the knowledge of the contact area at impact. The flexural stiffness approach seems to give reasonable boulder impact loads close to the failure capacities of the damaged structures. However, the stiffness factors given in Table 4 are for columnar structures or beam structures which are different from those for mass wall structures. Overall, the order of magnitude of the boulder impact load could be estimated using the flexural stiffness method, or taken to be nominally one-tenth of that given by the Hertz equation. As discussed previously the boulder impact could also be assessed by means of computer programs that have been calibrated against measurements.

It is noteworthy that the dynamic interaction between landslide debris and a barrier is not well established. Therefore, the suggested methods for assessing the debris and boulder impact loads should be used with caution as they have only been shown to produce order of magnitude estimates by comparison with a limited number of field observations. They should be reviewed in the light of further research and field observations.

CONCLUSIONS

Barriers are, in some situations, a practical mitigation measure that can help to reduce the risks posed by natural terrain landslide hazards to vulnerable facilities. The rational design of barriers, in particular the assessment of the design landslide events and the likely impact loads, is however fraught with difficulties. Although some of the design considerations can be determined through more rigorous methods, the determination of some of the parameters is not an exact science and often involves field estimates, rules of thumb and engineering judgement. An under-designed barrier can result in disastrous consequences as it can provide a false sense of security.

Various approaches put forward in evaluating the impact load on barriers have been reviewed and this illustrates, among other things, the considerable scatter in the predictions as well as in some of the reported field measurements. Some guidelines are put forward to facilitate the assessment of impact load in the design of landslide barriers. The authors strongly recommend that the assessment of impact load on barriers should be conducted in a cautious manner, with due allowance for the uncertainties involved. Further research is also recommended to advance the knowledge in the subject.

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