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A dynamic damage model for the rock-shed roof under the rockfall

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Abstract: The dynamic response of the rock-shed roof under the rockfall is a complicated mechanical process, which mainly includes the following three deformation stages, e.g. the elastic compression, plastic damage compression and elastic resilience stages of the rock-shed roof. However, the existing models based on Hertz elastic-perfectly plastic contact theory cannot perfectly reflect the above mechanical process. Therefore, on basis of the classical Hertz contact theory, the damage of the rock-shed roof induced by the rockfall is firstly introduced to consider its effect on the material elastic modulus, and then the revised Hertz contact theory considering the damage is proposed. Secondly, in view of the existing calculation method of the maximum rockfall impact force based on the theorem of impulse, a new calculation method is proposed by combining the revised Hertz contact theory. Thirdly, according to the dynamic mechanical response process of the rock-shed roof under the rockfall and in view of the revised Hertz contact theory, a dynamic damage model for the rock-shed roof under the rockfall is proposed, which can perfectly illustrate the variation law of the impact force with the deformation of the rock-shed roof during the rockfall. Finally, the proposed model is verified with other models for the maximum rockfall impact force. In all, the proposed model can perfectly describe the dynamic mechanical behavior of the rock-shed roof under the rockfall, which can be referred for the engineering design.

Key words rockfall • impact force • the rock-shed roof • a dynamic damage model • Hertz contact theory

Declarations

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Conflict of interest/Competing interests

The authors declare that they have no conflict of interest.

Availability of data and material

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31 **Authors' contributions**

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33 **Ethics approval**

34 I certify that this manuscript is original and has not been published and will not be submitted elsewhere for
35 publication while being considered by Natural Hazards. And the study is not split up into several parts to increase
36 the quantity of submissions and submitted to various journals or to one journal over time. No data have been
37 fabricated or manipulated (including images) to support the conclusions. No data, text, or theories by others are
38 presented as if they were our own.

39 **Consent to participate**

40 Not applicable

41 **Consent for publication**

42 The author agrees to publication in Natural Hazards.

43

44

45 **1 Introduction**

46 In many mountainous areas, rockfall has become the most serious and frequent geological hazard except for the
47 landslides. Because of the high speed, suddenness, randomness and kinetic energy, rockfall poses a serious threat
48 to many infrastructures and buildings even casualties, and therefore it attracts much attention to predict its
49 movement trajectories and control measures (Bunce et al., 1997; Volkwein et al., 2011; Li and Lan, 2015; Ferrari
50 et al., 2016; Zhu et al., 2019). In practice, many types of rockfall protection structures are designed to reduce the
51 disasters induced by the rockfall such as embankment (Lambert and Bourrier, 2013), rock-shed (Ouyang et al.,
52 2019; Zhao et al., 2018), flexible net (Yang et al., 2019; Zhao et al., 2020) and pile-plate retaining wall (Hu et al.,
53 2019). Among them, the rock-shed is one of the important structures for reducing damage from rockfall on roads
54 and railways, which is constructed by the reinforced concrete with backfilled gravel soil cushions on its top
55 (Kawahara and Muro, 2006). The role of the latter is to absorb the rockfall impact energy to reduce the impact
56 force on the underlying reinforced concrete. However, the destruction of the rock-shed roof often occurs due to the
57 rockfall, shown as Fig.1 (Wyllie, 2014).

58 Therefore, it is very significant to conduct the study on the dynamic response of the rock-shed structure under
59 the rockfall for its design. Many researches have been done in this field, which can be classified into the following
60 three aspects namely model or field experiment, theoretical model and numerical simulation. First of all, many
61 researchers have conducted the relevant experiments. Pichler et al. (2005) designed the rockfall experiments to
62 study the relations between the penetration depth, the impact duration, the impact force and the rock boulder mass,
63 fall height and the indentation resistance of the gravel. Calvetti (2011) conducted the real scale tests to evaluate the
64 rockfall impact force acting at the boulder-soil interface and the dynamic excitation of the sheltering tunnel.
65 Calvetti and Prisco (2012) conducted a series of rockfall tests on a sheltering tunnel, in which the rockfall is a
66 reinforced-concrete sphere with mass 850kg, diameter 0.9m dropping from 5~45m high. The impact force and its
67 deflection of the shelter are studied. Zhao et al. (2021) conducted a systematic experiment to study the ability of
68 two kinds of composite cushion in protecting the rock-shed under multiple rockfalls. It shows that the sand-EPE
69 (expandable polyethylene) composite cushion is much better than the sand-EPS (expandable polystyrene) one in
70 the multi-impact resistance and durability, and is more suitable to protect the rock-shed in practical engineering.
71 Second, in view of the theoretical study, the existing theoretical models for the rockfall impact force on the
72 reinforced-concrete structure are mainly derived from the classic Hertz contact theory which is based on the elastic
73 mechanics. However, the structure will exhibit the plastic deformation, therefore many researchers have made

74 some improvements to it. Thornton et al. (1997; 1998; 2013) suggested that the normal interaction becomes plastic
75 when a 'limiting contact pressure' reached at the center of the contact area, which originated from Hardy et al.
76 (1971). Vu-Quoc et al. (1999; 2000) proposed an accurate model for the normal force-displacement relation for
77 contacting spherical particles by accounting for the effects of plastic deformation. By considering the
78 strengthening coefficient of the gravel soil, Wang et al. (2020) proposed a theoretical calculation method of the
79 rockfall impact force and penetration depth. Meanwhile the dynamic response of the rock-shed roof under the
80 rockfall is related to not only the rockfall characteristic but also the mechanical property of the rock-shed roof.
81 Therefore, many scholars proposed the dynamic model for the rock-shed roof under the rockfall by combining the
82 Hertz contact theory and rock-shed roof. Olsson (2003; 2010) set up an analytical model for delamination of the
83 orthotropic laminated composite plates under small mass impact based on Hertz contact theory. With the
84 elasto-plastic contact theory, Zheng and Binienda (2007) derived the closed-form approximations of the contact
85 force, indentation and plate central displacement for the impact loading of composite laminates. Finally, many
86 studies have been conducted with the numerical simulation. Yan et al. (2018) used LS-DYNA code to analyze the
87 impact force and dynamic response of the reinforced concrete slab by considering the falling rock's shape and
88 impact angle. Shen et al. (2019) investigated the mechanism of rockfall impact against a granular soil buffering
89 layer above a concrete/rock shed by discrete element method, which indicates that the maximum impact force
90 increases linearly with the rockfall sphericity. Naito et al. (2020) used a discrete element method to investigate the
91 cushioning performance of a sand cushion and proposed the effective and rational measures for the protection of
92 the rock-shed.

93 However although many studies have been conducted on this issue, there are still two problems to solve. One
94 is that the dynamic response of the rock-shed roof is an evident dynamic process which can be divided into three
95 stages namely elastic compression stage at the early stage of the collision, plastic deformation stage when the
96 stress of the rock-shed roof induced by the rockfall exceeds its yield strength, and the elastic resilience stage after
97 the maximum compression deformation reaches. Although the study by Zheng and Binienda (2007) is also
98 conducted according to these three stages, they assumed that the elastic modulus of the rock-shed roof was
99 invariable at the second stage which was unreasonable. Because during the plastic deformation stage, the elastic
100 modulus will decrease with increasing its plastic deformation. The other one is that only the variation of the
101 impact force on the rock-shed roof with time is given, but the variation of the impact force with the rock-shed roof
102 deformation is not given (Zheng and Binienda, 2007; Olsson, 2003; Olsson, 2010). Therefore, it is impossible to

103 obtain the permanent deformation of the rock-shed roof under the rockfall, which is not conducive to the safety
104 assessment of the rock-shed in the future.

105 For these two issues above, on basis of the classic Hertz contact theory, the revised Hertz contact theory is
106 firstly proposed by considering the rock-shed roof damage induced by the rockfall. Next, according to the dynamic
107 response process of the rock-shed roof under the rockfall, the dynamic damage model for the rock-shed roof is
108 proposed, and the determination method of the model's parameters are discussed. Finally, its application and
109 validity are made with the calculation examples.

110 **2 Hertz contact theory and its improvement**

111 Fig.2 depicts the contact between two spheres subjected to normal force P (Hertz, 1882). The normal
112 pressure $p(r)$ on the contact surface can be expressed as

$$113 \quad p(r) = \frac{3P}{2\pi a^2} \left[1 - \left(\frac{r}{a} \right)^2 \right]^{1/2} \quad (1)$$

114 where, a is the radius of the contact area, $r(0 \leq r \leq a)$ is the distance from the center of the contact area to any point
115 of the contact area, P is the contact force.

116 Therefore, the maximum normal pressure p_{\max} at $r=0$ can be expressed as

$$117 \quad p_{\max} = \frac{3P}{2\pi a^2} \quad (2)$$

118 The contact deformation is composed of the following two parts.

$$119 \quad \delta = \delta_1 + \delta_2 \quad (3)$$

120 where, δ_1 and δ_2 are the deformations of these two contact spheres respectively.

121 The relationship between the contact deformation and the contact area is

$$122 \quad a^2 = R\delta \quad (4)$$

123 where, R is the equivalent radius, $\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$, R_1 and R_2 are the radii of these two contact spheres
124 respectively.

125 The relationship between the contact force P and the contact deformation δ can be expressed as (Hertz, 1882)

$$126 \quad P = \frac{4}{3} ER^{\frac{1}{2}} \delta^{\frac{3}{2}} \quad (5)$$

127 where, E is the equivalent elastic modulus, $\frac{1}{E} = \frac{1-\mu_1^2}{E_1} + \frac{1-\mu_2^2}{E_2}$, E_1 , μ_1 , E_2 and μ_2 are the elastic moduli and
 128 Poisson's ratio of these two contact bodies respectively.

129 The abovementioned Hertz contact theory is only suitable for the material in the elastic stage, therefore the
 130 contact force obtained with it is always rather large in the practical engineering. This is because the plastic
 131 deformation will occur in the material when the contact compressive stress exceeds the material's yield strength,
 132 so the classic Hertz contact theory is unsuitable. In view of this, many improvements have been made which can
 133 be classified into the following two models, e.g. Hertz plastic contact theory and Hertz damage contact theory. As
 134 for the former, Thornton (1997; 1998) proposed the Hertz plastic contact theory by introducing the perfectly
 135 elasto-plastic model into the classic Hertz contact theory, with which the prediction is in more agreement with the
 136 practical one. Meanwhile with the development of the damage mechanics, many researchers begin to introduce it
 137 into the classic Hertz contact theory. For instance, Travares and King (2002) and Travares (2002) set up the
 138 impact damage model for the spherical particles according to their force-deformation characteristic under impact
 139 loading on basis of the classic Hertz contact theory and continuum damage theory.

$$140 \quad P = \frac{d^{0.5}}{3} \tilde{K} \delta^{\frac{3}{2}} = \frac{d^{0.5}}{3} K (1-D) \delta^{\frac{3}{2}} \quad (6)$$

141 where, d is the diameter of the spherical particle, K and \tilde{K} are the initial and effective stiffness of the spherical
 142 particle respectively, D is the damage of the spherical particle induced by impact loading, which is defined as

$$143 \quad D = \left(\frac{\delta}{\delta_c} \right)^\gamma \quad (7)$$

144 where, δ_c is the compression deformation of the spherical particle when the impact failure occurs, when $\delta = \delta_c$, $D = 1$.
 145 γ is the impact damage index.

146 It can be seen from Eq.(7) that the spherical particle's any contact deformation induced by impact loading
 147 will lead to damage. However, according to the classic Hertz contact theory, when the spherical particle's contact
 148 deformation δ is less than its yield deformation δ_y , the spherical particle is in the elastic contact condition with no
 149 damage occurs, namely $D=0$. It is evident that Eq.(7) cannot describe this condition, which is its deficiency.

150 Because the rock and reinforced concrete are the natural damage materials, the collision between them will
 151 inevitably lead to the occurrence, propagation and coalescence of the microcracks which will lead to the
 152 deterioration of their physical and mechanical property, even failure. Therefore, the damage induced by collision

153 can be defined as the deterioration of the elastic modulus. The typical force-deformation under collision can be
 154 divided into the four stages, e.g. the initial collision one, elastic collision one, plastic damage collision one and
 155 unloading resilience one. Because the first stage is short, it is often ignored. At the second stage, the
 156 force-deformation between the particles fits with the classic Hertz contact theory, and accordingly no damage
 157 occurs. When the contact stress exceeds the particle's initial yield strength, the force-deformation curve will be not
 158 linear any more, and the damage occurs, which is the third stage. When the contact force reaches the peak, the
 159 fourth stage will begin, in which the particle's deformation is elastic and the damage keeps constant. Therefore,
 160 the particle's damage D can be defined as

$$161 \quad D=1-\frac{\bar{E}}{E}=\begin{cases} 0 & \delta \leq \delta_y \\ \left(\frac{\delta-\delta_y}{\delta_c-\delta_y}\right)^\gamma & \delta_y < \delta \leq \delta_m \end{cases} \quad (8)$$

162 where, \bar{E} and E are the particle's effective and initial elastic modulus. δ_y , δ_m and δ_c are the contact deformation
 163 at the initial yield of the particle, the maximum contact deformation and the contact deformation when the particle
 164 completely fails, therefore $\delta_y < \delta_m \leq \delta_c$ satisfies.

165 So the relation between the contact stress and contact deformation considering the material damage is

$$166 \quad P = \frac{4}{3} E (1-D) R^{\frac{1}{2}} \delta^{\frac{3}{2}} \quad (9)$$

167 **3 The dynamic response of the rock-shed roof under the rockfall**

168 **3.1 Impact force induced by the rockfall on the rock-shed roof**

169 Assume the rockfall is a moving mass point with velocity v_0 , and the rock-shed roof is a stationary plane
 170 without overlying buffer material, the corresponding model is shown as Fig.3.

171 The total velocity of the rockfall can be decomposed into the horizontal and vertical components as follows.

$$172 \quad v_x = v_0 \cos \theta, \quad v_y = v_0 \sin \theta \quad (10)$$

173 where, v_0 , v_x and v_y are the rockfall total velocity, horizontal and vertical velocity components respectively at the
 174 moment the rockfall reaches the rock-shed roof. θ is the impact angle.

175 Because the failure of the roof is induced mainly by the vertical impact, only the vertical impact by the
 176 rockfall is considered here. According to Newton's second law, there is

177
$$P = m_1 \frac{dv_1}{dt} = -m_2 \frac{dv_y}{dt} \quad (11)$$

178 where, m_1 and m_2 are the masses of the rock-shed roof and rockfall respectively, v_1 is the movement velocity of the
179 rock-shed roof, g is the gravitational acceleration, and P is the impact force on the rock-shed roof by the rockfall.

180 From Eq.(11), we obtain

181
$$-\frac{(m_1 + m_2)P}{m_1 m_2} = \frac{d(v_y - v_1)}{dt} = \frac{d^2 \delta}{dt^2} \quad (12)$$

182 Combining Eqs.(5) and (12) yields

183
$$\frac{d^2 \delta}{dt^2} = -\frac{4}{3m} ER^{\frac{1}{2}} \delta^{\frac{3}{2}} \quad (13)$$

184 where, m is the equivalent mass, $\frac{1}{m} = \frac{1}{m_1} + \frac{1}{m_2}$.

185 Integrating δ and with the initial conditions $\delta|_{t=0} = 0$, $\delta'|_{t=0} = v_0 \sin \theta$, we obtain

186
$$\frac{1}{2} \left[(v_0 \sin \theta)^2 - \left(\frac{d\delta}{dt} \right)^2 \right] = \frac{8}{15m} ER^{\frac{1}{2}} \delta^{\frac{5}{2}} \quad (14)$$

187 When $\delta = \delta_{\max}$, $\frac{d\delta}{dt} = 0$, substituting it into Eq.(14) yields

188
$$\delta_{\max} = \left[\frac{15m(v_0 \sin \theta)^2}{16ER^{\frac{1}{2}}} \right]^{\frac{2}{5}} \quad (15)$$

189 Substituting Eq.(15) into Eq.(5), we obtain the maximum impact force $P_{\max 0}$ induced by the rockfall on the
190 rock-shed roof.

191
$$P_{\max 0} = \frac{4}{3} E^{\frac{2}{5}} R^{\frac{1}{5}} \left[\frac{15m(v_0 \sin \theta)^2}{16} \right]^{\frac{3}{5}} \quad (16)$$

192 When the effect of the material damage induced by the rockfall is considered, the revised maximum impact
193 force P_{\max} of the rockfall on the rock-shed roof can be obtained by substituting Eq.(8) into Eq.(16).

194
$$P_{\max} = \frac{4}{3} [E(1-D)]^{\frac{2}{5}} R^{\frac{1}{5}} \left[\frac{15m(v_0 \sin \theta)^2}{16} \right]^{\frac{3}{5}} \quad (17)$$

195 3.2 The dynamic mechanical response of the rock-shed roof

196 The engineering practice indicates that the rockfall impact force will cause some damage to the rock-shed
197 roof, so the Hertz contact theory considering damage is more reasonable.

198 From the previous studies, the relation between the impact force and deformation of the rock-shed roof under
199 the rockfall can be divided into the following three stages (Olsson, 2010; Zheng and Binienda, 2007).

200 ① Stage I: the linear loading stage at the initial collision

201 At the initial stage of collision, the impact force induced by the rockfall on the rock-shed roof is small, and
202 accordingly the deformation of the rock-shed roof is also little. So it is in the elastic deformation condition, and the
203 contact force between them satisfy the classic Hertz contact theory, namely

$$204 P(\delta) = \frac{4}{3} ER^{\frac{1}{2}} \delta^{\frac{3}{2}} \quad (0 \leq \delta \leq \delta_y) \quad (18)$$

205 where, δ_y is the deformation of the rock-shed roof when the initial yield occurs.

206 ② Stage II: the damage loading stage

207 With the impact loading continuing, the impact force and deformation of the rock-shed roof both increase.
208 When the impact force exceeds the rock-shed roof yield strength, the plastic deformation will produce in the
209 rock-shed roof and accordingly the damage occurs. Therefore, the impact force should satisfy the revised Hertz
210 contact theory considering damage, namely

$$211 P(\delta) = 2E(1-D)R^{\frac{1}{2}}\delta_y^{\frac{1}{2}}(\delta - \delta_y) + \frac{4}{3}E(1-D)R^{\frac{1}{2}}\delta_y^{\frac{3}{2}} \quad (\delta_y \leq \delta \leq \delta_m) \quad (19)$$

212 where, δ_m is the maximum deformation of the rock-shed roof.

213 ③ Stage III: the unloading stage

214 When the deformation of the rock-shed roof reaches the maximum, the rockfall velocity will decrease to zero,
215 and then the elastic deformation energy stored in the rock-shed roof will release and its resilience deformation will
216 happen. During this stage, no new damage occurs in the rock-shed roof, but the existing damage will not recover
217 any more. So the rock-shed roof elastic modulus is the same as that at its maximum deformation, and accordingly
218 its relation between the contact force and deformation is

$$219 P(\delta) = 2E(1-D_m)R^{\frac{1}{2}}\delta_y^{\frac{1}{2}}(\delta_m - \delta_y) + \frac{4}{3}E(1-D_m)R^{\frac{1}{2}}\left(\delta_m^{\frac{3}{2}} - \delta_y^{\frac{3}{2}} + \delta_y^{\frac{3}{2}}\right) \quad (\delta \leq \delta_m) \quad (20)$$

220 where, D_m is the maximum damage of the rock-shed roof corresponding to its maximum deformation δ_m before
221 unloading.

222 When unloading completes, the contact force $P(\delta)$ should be the rockfall gravity m_2g , and then the
 223 corresponding residual deformation δ_0 of the rock-shed roof can be obtained with Eq.(20). It is the plastic
 224 deformation of the rock-shed roof induced by the rockfall.

225 3.3 Determination of the parameters in the proposed model

226 When the proposed model is adopted to analyze the dynamic response of the rock-shed roof under the
 227 rockfall, the parameters δ_y and δ_m must be determined first.

228 (1) Determination of δ_y

229 The deformation δ_y of the rock-shed roof is corresponding to its initial yield strength σ_{py} , which can be
 230 obtained with the material mechanics test. On basis of Hertz contact theory, Vu-Quoc et al. (1999; 2000) assumed
 231 that when Von Mises yield criterion satisfies, the relation between the contact force P_y induced by the rockfall on
 232 the rock-shed roof and its yield strength σ_{py} is

$$233 P_y = \left(A_y\right)^3 \frac{\pi^3 R^2 (1-\mu^2)^2}{6E^2} \sigma_{py}^3 \quad (21)$$

234 where, E and μ are the material's elastic modulus and Poisson's ratio respectively, A_y is the material constant
 235 related to μ , and it is 1.61 and 1.74 when μ is 0.3 and 0.4, respectively.

236 Meanwhile, the material's initial yield point is the junction of the elastic stage and plastic damage stage,
 237 therefore it belongs to these two stages at the same time. So P_y can be solved with material's yield strength, and
 238 then the corresponding deformation δ_y of the rock-shed roof can be solved with Eq.(5).

239 (2) Determination of δ_m

240 It can be known that the maximum impact force of the rock-shed roof and its maximum deformation occur at
 241 the same time, therefore from Eqs.(17) and (19), we obtain

$$242 P_{\max} = P(\delta) \Big|_{\delta=\delta_m} \quad (22)$$

243 Then we can obtain an equation about δ_m (where δ_c is the material impact deformation corresponding to its
 244 complete failure, and it can be obtained with experiment.), from which δ_m can be obtained by iterative solution.

245 4 Analysis of the calculation example

246 4.1 Description of the calculation example

247 The calculation model is shown in Fig.3. Assume the velocity and its angle of the spherical rockfall are v_0 and
248 θ respectively at the moment it reaches the rock-shed roof. The rock-shed roof and rockfall are supposed to be C20
249 reinforced concrete and granite respectively, whose calculation parameters are show in Tab.1. Because the mass of
250 the rock-shed roof is much larger than that of the rockfall, namely $m_1 \gg m_2$, therefore, the equivalent mass is about
251 the rockfall mass, namely $m \approx m_2$.

252 4.2 Analysis of the calculation results

253 The calculation procedure and results are as follows.

254 ① Stage I: the linear loading stage at the initial collision

255 According to the calculation parameters shown in Tab.1, the impact force P_y leading to the yield of the
256 rock-shed roof is firstly solved to be 0.603MN with Eq.(21), that is to say its maximum elastic force is 0.603MN.
257 Then its corresponding deformation δ_y is solved to be 1.39mm with Eq.(18). Therefore, the deformation of the
258 rock-shed roof under the rockfall linearly increases from 0 to 1.39mm, and the corresponding contact force
259 linearly increases from 0 to 0.603MN.

260 ② Stage II: the damage loading stage

261 Firstly, according to Eqs.(18), (19) and (22), the maximum deformation δ_m of the rock-shed roof under the
262 rockfall is solved to be 15.42mm. Then some points of δ between $\delta_y \sim \delta_m$ are taken, and the corresponding contact
263 force $P(\delta)$ can be solved with Eq.(19). Finally, the damage loading curve of the rock-shed roof can be drawn with
264 these results.

265 ③ Stage III: the unloading stage

266 Firstly, the damage of the rock-shed roof corresponding to the its maximum deformation δ_m is solved to be
267 0.0578 here. Substituting it into Eq.(20) and assuming the rockfall impact force $P(\delta)$ to be m_2g , the corresponding
268 permanent deformation δ_0 of the rock-shed roof is 10.56mm. Then some points of δ between $\delta_m \sim \delta_0$ are taken, and
269 the corresponding contact force $P(\delta)$ can be solved with Eq.(20). Finally, the unloading curve of the rock-shed
270 roof can be drawn with these results.

271 Then the relation of the impact force on the rock-shed roof induced by the rockfall with its damage and
272 deformation is shown in Fig.4. It can be seen that it can be divided into three stages, e.g. the linear loading stage,
273 the damage loading stage and the unloading stage. During the first stage, the rock-shed roof produces elastic
274 deformation, namely its impact force induced by the rockfall is linear with its deformation. When the impact force
275 increases to the yield strength of the rock-shed roof, it will go into the damage loading stage. It is found from the

276 slope of the curve that the slope of the damage loading stage is larger than that of the elastic loading stage, which
277 indicates that the reinforced concrete will exhibit a plastic strengthening phenomenon after it goes into the plastic
278 deformation. At the peak of the impact force, the rockfall velocity reduces to zero. After that the unloading
279 resilience of the rock-shed roof begins, and the elastic deformation component gradually recovers in which the
280 rockfall impact force and total deformation of the rock-shed roof both gradually decreases. When the rockfall
281 impact force reduces to zero, the corresponding deformation of the rock-shed roof is its permanent deformation
282 namely the residual plastic deformation. Meanwhile, it can be seen from the damage-deformation curve that the
283 damage only occurs at the stage II and its maximum damage is only 0.0578. It shows that the damage of the
284 rock-shed roof induced by the rockfall is little in this calculation example. However it is noted from Eq.(7) that the
285 damage of the rock-shed roof is related to δ_c and γ , and the accurate description of the damage evolution greatly
286 depends on the accurate determination of these two above damage parameters.

287 **4.3 parametric sensitivity analysis**

288 It can be seen from the proposed model that the dynamic response of the rock-shed roof under the rockfall is
289 related to not only its physical and mechanical property but also the parameters of the rockfall to large extent.
290 Therefore, the parametric sensitivity analysis is adopted to study the effect of the parameters of the rockfall and
291 rock-shed roof on the calculation results.

292 (1) Effect of the rockfall velocity

293 The rockfall velocity is assumed to be 2, 3, 4 and 5m/s, and the other parameters are as shown in Tab.1. The
294 following conclusions can be obtained from Fig.5. First of all, with increasing the rockfall velocity, the maximum
295 deformation of the rock-shed roof increases from 5.27mm to 8.3, 11.61 and 15.42mm respectively, and
296 accordingly the corresponding maximum impact force on the rock-shed roof also increases from 3.12MN to 5.07,
297 7.12 and 9.15MN respectively. It indicates that the impact force and deformation of the rock-shed roof induced by
298 the rockfall is linear to the rockfall velocity. Secondly, with increasing the rockfall velocity, the residual
299 deformation of the rock-shed roof increases from 2.47mm to 4.80, 7.39 and 10.56mm respectively. It indicates that
300 the plastic deformation of the rock-shed roof increases with the rockfall velocity, which shows that the total
301 damage of the rock-shed roof induced by the rockfall increases. Finally, the rockfall velocity does not change the
302 linear stage of the curve, this is because it is determined by both the material yield strength and Hertz contact
303 theory, and not affected by the rockfall velocity. It agrees with the conclusions obtained by other researcher (Ning,

304 1995). However it is noted that the material yield strength is assumed to be not related to the rockfall, which
305 agrees with the practical condition when the rockfall velocity is small. However, when the rockfall velocity is
306 large, the more evident dynamic response of the rock-shed roof under the rockfall will occur, and accordingly the
307 material dynamic yield strength will increase with the load strain rate. But its increase extent is much related to the
308 material mechanical property, which should be tested with the experiment (Kumar, 1968).

309 (3) Effect of the rockfall radius

310 The rockfall radius is assumed to be 0.25, 0.5, 0.75 and 1m, accordingly the corresponding rockfall mass is
311 164, 1309, 4418 and 10472kg, and the other parameters are as shown in Tab.1. The following conclusions can be
312 obtained from Fig.6. First of all, with increasing the rockfall radius, the maximum deformation of the rock-shed
313 roof increases from 3.74mm to 7.47, 11.27 and 15.42mm respectively, and accordingly the corresponding
314 maximum impact force on the rock-shed roof also increases from 0.59MN to 2.34, 5.25 and 9.15MN respectively.
315 It indicates that the impact force and deformation of the rock-shed roof induced by the rockfall is linear to the
316 rockfall radius. Secondly, with increasing the rockfall radius, the residual deformation of the rock-shed roof
317 increases from 2.53mm to 5.0, 7.65 and 10.56mm respectively. It indicates that the plastic deformation of the
318 rock-shed roof increases with the rockfall radius, which shows that the total damage of the rock-shed roof induced
319 by the rockfall increases. However, it is noted that the damage evolution of the rock-shed roof is assumed to be the
320 same, namely the damage parameters δ_c and γ in Eq.(9) are assumed to be constant under different conditions,
321 which will inevitably lead to some error.

322 (3) Effect of the damage parameter of the roof

323 In the proposed method, δ_c and γ are two important damage parameters, whose effect on the calculation
324 results are shown in Fig.7. The following conclusions can be obtained. First of all, with increasing δ_c , the impact
325 force-deformation curve of the rock-shed roof has some difference, but its extent is little. When δ_c increases from
326 25mm to 30, 35 and 40mm, the maximum impact deformation of the rock-shed roof only decreases from 16.71mm
327 to 15.42, 15.17 and 15.05mm, and accordingly the corresponding maximum impact force only increases from
328 8.67MN to 9.15, 9.26 and 9.31MN respectively. Meanwhile, the residual deformation of the rock-shed roof only
329 decreases from 11.66mm to 10.56, 10.40 and 10.30mm respectively, which indicates that the increase in δ_c has
330 little effect on the dynamic response of the rock-shed roof. Moreover, it can be seen from Fig.7(a) that only the
331 curve with $\delta_c=25$ mm has much difference with other three ones, which indicates that the effect of δ_c on the
332 calculation results is little when it increases to some extent. Secondly, with γ increasing from 2 to 3, 4 and 5, the
333 maximum deformation the rock-shed roof gradually decreases from 16.41mm to 15.34, 15.05 and 14.96mm

334 respectively, and the corresponding maximum impact force gradually increases from 8.77MN to 9.19, 9.31 and
 335 9.35MN respectively. Meanwhile the residual deformation of the rock-shed roof decreases from 11.41mm to 10.49,
 336 10.30 and 10.20mm respectively, which indicates that the effect of γ on the dynamic response of the rock-shed
 337 roof firstly increases rapidly, and then the increase extent decreases.

338 **5 Verification of the proposed model**

339 In order to validate the proposed model, the calculation models of the maximum rockfall impact force
 340 proposed by Labiouse et al. (1966), Kawahara et al. (2006), Pichler et al. (2006) and Hertz (1882) namely Eqs.(23),
 341 (24), (25) and (5) are adopted here.

342 The model proposed by Labiouse et al. (1966) is

$$343 \quad P_{\max} = 1.765M_E^{2/5}R^{1/5}(WH)^{3/5} \quad (23)$$

344 where, P_{\max} is the maximum impact force (kN), M_E is the modulus of subgrade obtained from a standardized plate
 345 bearing test on the soil cushion (kPa); R is the radius of the rockfall part in contact with the soil cushion (m), W is
 346 the weight of the rockfall (kN), H is the falling height of the rockfall (m).

347 The model proposed by Kawahara et al. (2006) is

$$348 \quad P_{\max} = 2.108\lambda^{2/5}(Mg)^{2/3}H^{3/5} \quad (24)$$

349 where, λ is the Lamé's constant (kPa), M is the weight mass (t), g is the gravitational acceleration (m/s^2), H is the
 350 falling height of the rockfall (m).

351 The model proposed by Pichler et al. (2006) is

$$352 \quad P_{\max} = 2Mv/\Delta t \quad (25)$$

353 where, M , v and Δt are the rockfall weight mass (kg), velocity (m/s) and impact loading time (s), respectively.

354 The following conclusions can be drawn from Fig.8. First of all, the impact force increases nonlinearly with
 355 the rockfall radius (or rockfall mass), especially when the rockfall radius is rather large, the rockfall maximum
 356 impact force increases rapidly with the rockfall radius. Second, in view of the magnitude of the rockfall impact
 357 force, the calculation result of the proposed model is between that of the other four models. Meanwhile it is much
 358 closer to that of Hertz (1882) and Labiouse et al. (1966), however their gap becomes larger with increasing the
 359 rockfall radius. Take the rockfall radius $r=1m$ for instance, the results of Hertz (1882) and Labiouse et al. (1966)
 360 are much closer, which are 11.50 and 11.03MN respectively. However, the results of Kawahara et al. (2006) and

361 Pichler et al. (2006) are much closer, which are 2.13 and 3.74MN respectively. The result of the proposed model is
362 9.15MN, which is much closer to that of Hertz (1882) and Labiouse et al. (1966), and the errors between them are
363 17.04% and 20.43% respectively. While, the results of Kawahara et al. (2006) and Pichler et al. (2006) are 4.30
364 and 2.45 times that of the proposed model. Finally, it is noted that some calculation parameters in these models are
365 difficult to accurately test, and therefore they are adopted by experience. It will lead to some errors which is also a
366 main reason leading to the result shown in Fig.8. In the future, the selection of these parameters in these models
367 should be studied further. In all, it can be seen from Fig.8 that the proposed model for the rock-shed roof under the
368 rockfall is reasonable.

369 **6 Conclusions**

370 For the shortcoming that the classic elastic Hertz contact theory cannot consider the damage of the material
371 induced by collision, this research firstly proposes the revised Hertz contact theory by considering the material
372 damage. And then on basis of the existing study, the revised calculation method of the rockfall maximum impact
373 force on the rock-shed roof is proposed by taking into account the material damage. Finally, according to the
374 dynamic response of the rock-shed roof under the rockfall, the dynamic damage model for the rock-shed roof
375 under the rockfall is proposed. The revised Hertz contact theory by considering the damage and the dynamic
376 model for the rock-shed roof under the impact loading are not new indeed. However, without the incorporating,
377 these models alone cannot yield the completely dynamic force–deformation relations of the rock-shed roof. The
378 proposed model can perfectly capture the dynamic response of the rock-shed roof under the rockfall.

379 The proposed model is validated by the comparison with other methods, which indicates that it can
380 reasonably determine the variation of the rockfall impact force with the deformation of the rock-shed roof. The
381 influence of the rockfall velocity, radius and damage parameters on the dynamic behavior of the rock-shed roof are
382 accordingly studied. Overall, the proposed model provides a way to simulate the dynamic behavior of the
383 rock-shed roof under the rockfall.

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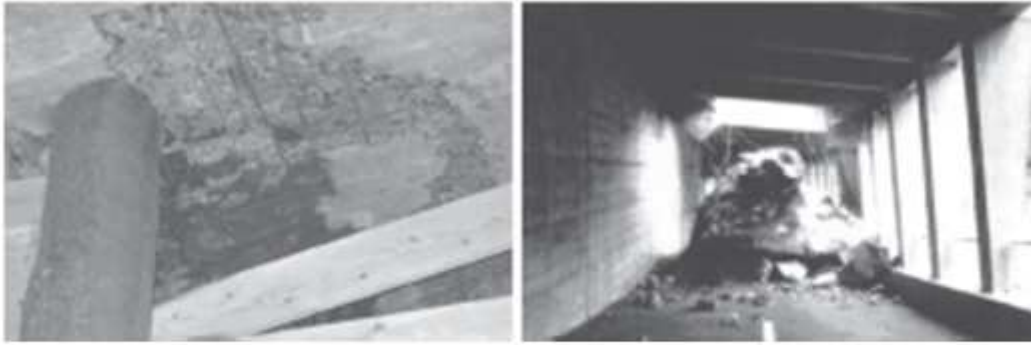
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Figures



(a) Slight spallation

(b) Totally destroyed

Figure 1

Damages of the rock-shed due to rockfall

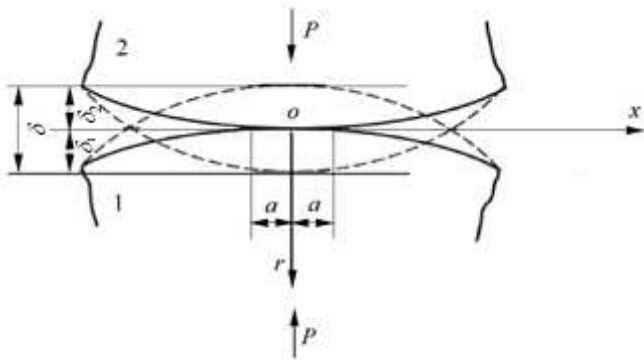


Figure 2

Contact problem of Hertz of two spheres. a is the radius of the contact area, P is the contact force, δ_1 and δ_2 are the deformations of these two contact spheres respectively.

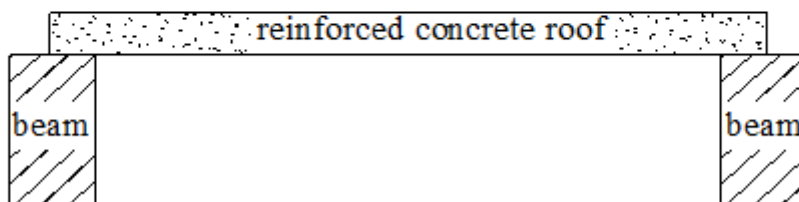
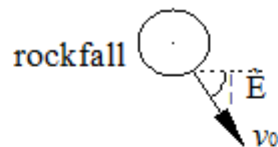


Figure 3

The model for the rock-shed roof under the rockfall. The velocity and its angle of the rockfall are v_0 and θ respectively. The rock-shed roof is made of reinforced concrete and it can be seen to be fixed at two ends.

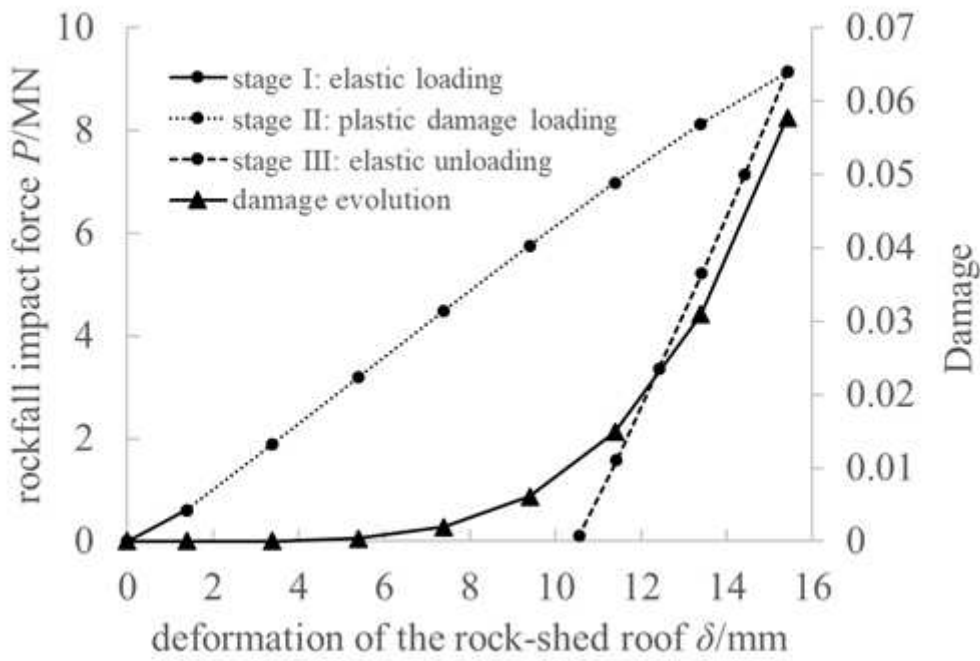


Figure 4

The impact force-deformation curve of the reinforced concrete under the rockfall

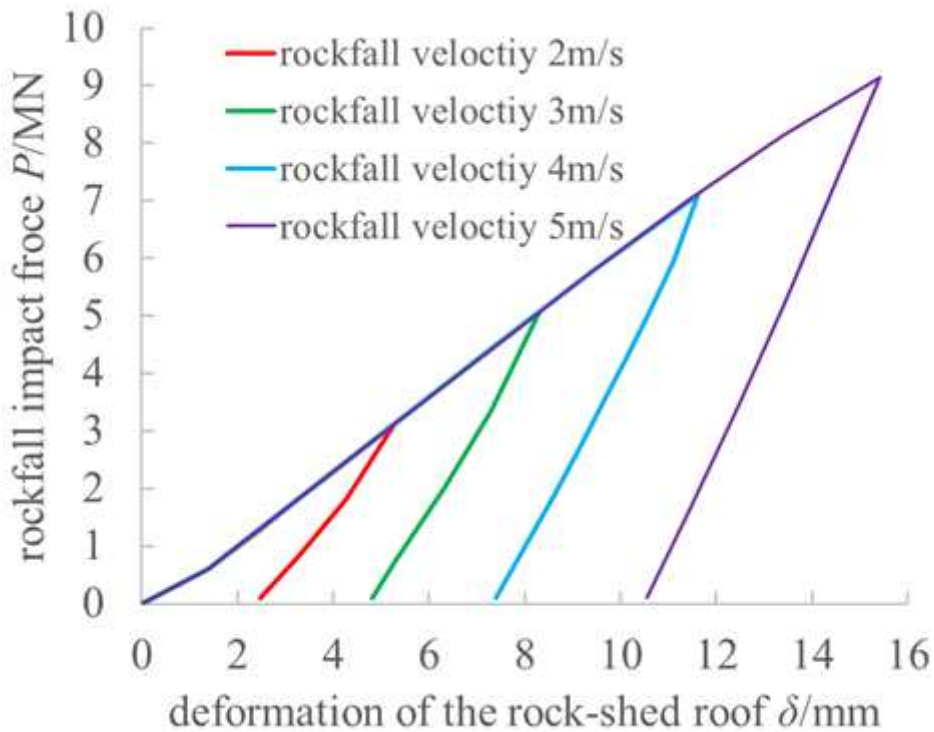


Figure 5

The impact force-deformation curve of the rock-shed roof with different rockfall velocity

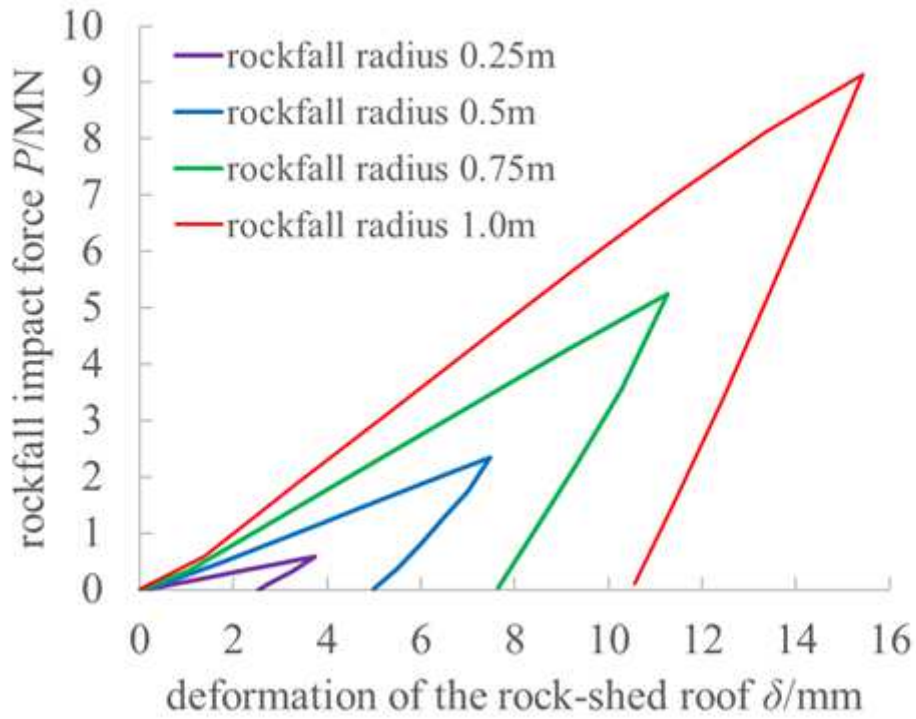


Figure 6

The impact force-deformation curve of the rock-shed roof with different rockfall radius

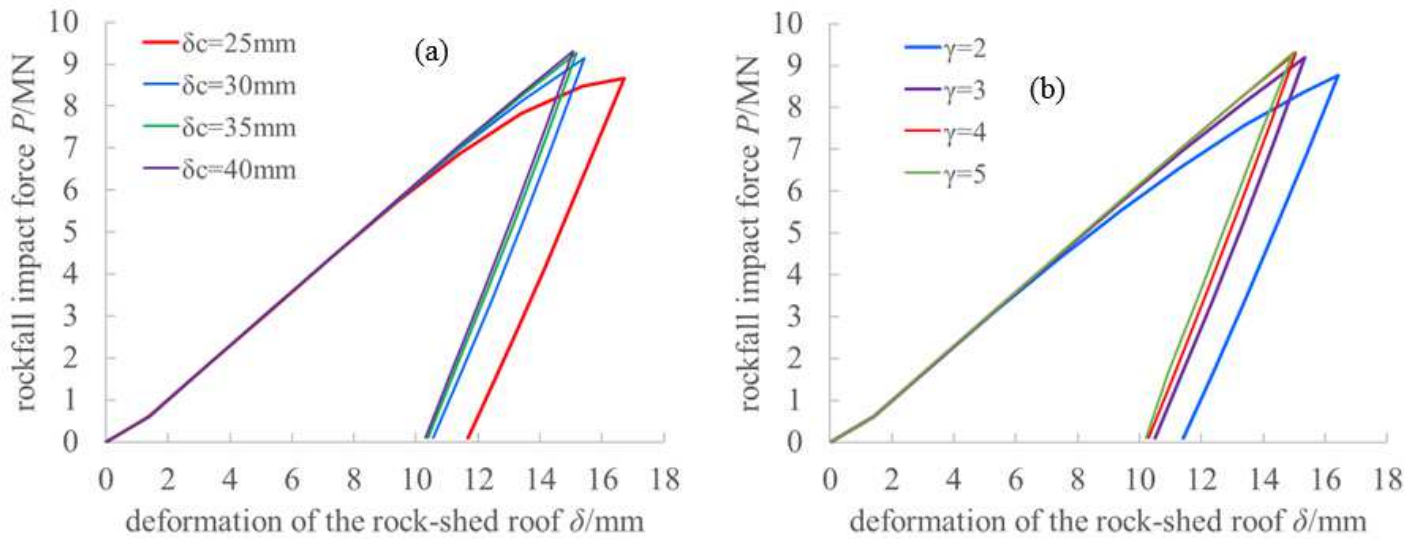


Figure 7

The impact force-deformation curve of the rock-shed roof with different damage parameters

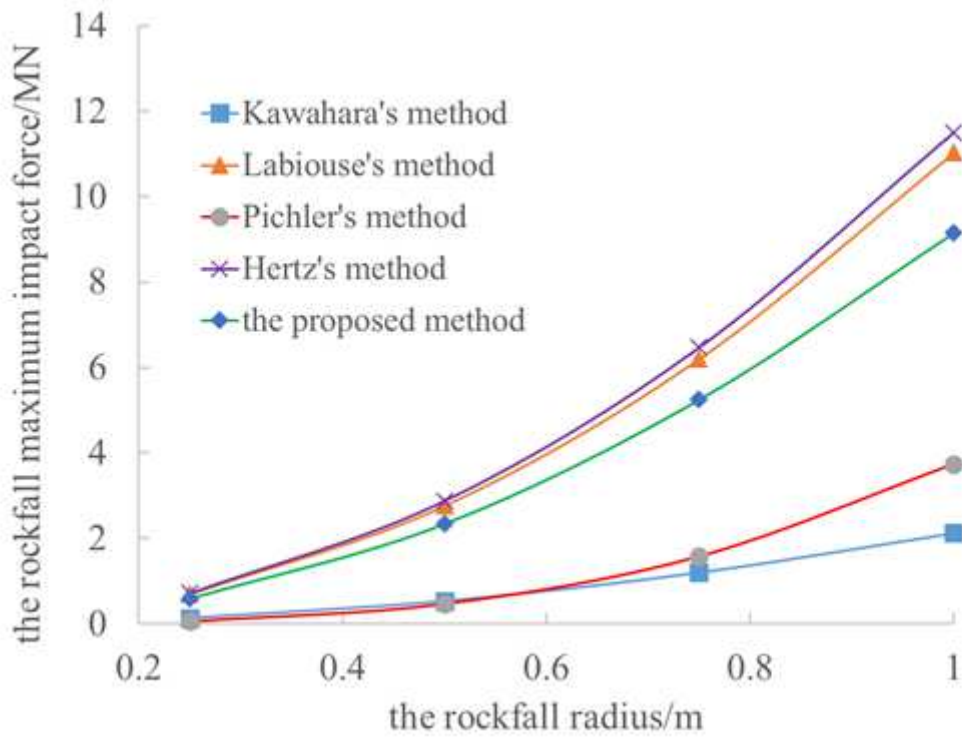


Figure 8

Comparison of the rockfall maximum impact force obtained with the proposed method and other methods