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Highlights

- A rigorous scheme is proposed for computing energy dissipation by both friction and plastic strain in the Non-smooth contact dynamics (NSCD) framework.
- The structure dissipative capacities computed from simulation results are addressed in terms of the ratio $R_{f/p}$ between the energy that is dissipated by friction to that dissipated by plastic strain.
- The structure dissipative capacities assessed from simulation results, including the ratio $R_{f/p}$, reveal sensitive to the way how the model parameters were calibrated and, to a larger extent, to the impact conditions.
- The ratio $R_{f/p}$ appears relevant for describing the whole structure response over a wide range of realistic impact conditions.

On the simulation-based quantification of energy
dissipation in rockfall protection structures: Case
of an articulated wall modelled with the NSCD
method

Stéphane Lambert^{1*}, Ritesh Gupta¹, Franck Bourrier^{1,2}, Vincent
Acary²

^{1*}Univ. Grenoble Alpes, INRAE, CNRS, IRD, Grenoble INP, IGE
Grenoble, 38000, France.

²Univ. Grenoble Alpes, Inria, CNRS, Grenoble INP, Institute of
Engineering, LJK Grenoble, 38000, France.

Abstract

This article focuses on the key issue of energy dissipation in passive rockfall protection structures when exposed to impact by a rock block. As an application case, a structure consisting of a wall made of interconnected concrete blocks is considered. A Non-Smooth Contact Dynamics (NSCD) model of this structure was previously developed and calibrated with respect to the spatio-temporal impact response obtained from real-scale impact experiments. The NSCD model accounts for energy dissipation due to friction between the system bodies and to plastic strain at contacts. The energy dissipation computation method is detailed and its exactness is demonstrated considering two impact cases. The evolution with time of energy dissipation by each dissipative mechanism provides insights into the global structure response with time in terms of displacement and contact force amplitude. The influence of the model parameters on the contribution of these two dissipative mechanisms is evaluated. A ratio between energy dissipation by friction to energy dissipation by plastic strain is proposed as a criterion for structural response evaluation. The variability in energy dissipation varying the impact conditions is addressed. In the end, this study reveals the benefits derived

from a precise quantification of energy dissipation in passive rockfall protection structures. Beyond the considered application case, such an approach focusing on energy dissipation opens up promising prospects for improving the design of all passive rockfall mitigation structures.

Keywords: rockfall, impact, NSCD model, energy dissipation

1 Introduction

Passive rockfall protection structures such as flexible barriers, galleries, walls and embankments are often built on slopes to intercept or deviate rock blocks with kinetic energies sometimes exceeding 10 MJ (Volkwein et al, 2011). These protection structures are thus designed to withstand the severe localised dynamic loading they are exposed to during their normal operation. During impact, the structure experiences displacement and damage, with an amplitude that depends on the reduction in rock block kinetic energy over the impact duration. The kinetic energy lost by the rock block is progressively dissipated in the structure and, to a lesser extent, transferred to its foundation such as anchors, if any, and then to the surrounding environment which most often consists of ground or bedrock. The structure's mechanical response and efficiency with respect to its purpose is highly dependent on its capacity to transfer and dissipate energy.

Energy dissipation in structures exposed to impacts by rock blocks is more and more addressed dealing with flexible barriers (Duan et al, 2023; Dhankal et al, 2012; Xu et al, 2018; Liu et al, 2018; Yu et al, 2019; Castanon-Jano et al, 2019; Di Giacinto et al, 2020; Previtali et al, 2021), embankments and walls (Ronco et al, 2009; Furet et al, 2022; Marchelli and Deangeli, 2022), steel posts (Zhao et al, 2021; Ng et al, 2023), cushion materials and energy dissipators (Previtali et al, 2021; Yan et al, 2022; Liang et al, 2022; Yang et al, 2024). Dissipation in rockfall protection structures mainly

21 results from plastic damage (or plastic strain) of the structure materials and com-
22 ponents and from friction within materials or at the interface between the structure
23 components. Other dissipative mechanisms, such as thermal dissipation, are gener-
24 ally negligible or considered as such. The prevailing dissipative mechanism depends
25 on the structure type, its constitutive materials and design as well as on the inci-
26 dent rock block kinetic energy. The vast majority of research works addressing energy
27 dissipation are based on simulation results, making use of commercially available or
28 in-house codes which are based on finite element, finite difference or discrete element
29 methods (FEM, FDM and DEM resp.). All these models rely on simplifications and
30 assumptions in particular concerning the realism of the structure description and the
31 considered constitutive laws. In the best case, the model parameters are calibrated
32 and/or validated against results from experiments on real-scale structures.

33 By comparison with experiments, numerical simulations give much easier access
34 to the various data necessary for computing energy terms, and in particular the dis-
35 sipative terms. Nevertheless, in all but a few research such as [Ng et al \(2023\)](#), the
36 soundness of the energy terms quantification is debatable for various reasons. In many
37 cases, not all the energy terms were taken into account or mentioned. This is the case
38 for elastic strain energy and for the variation in potential energy, even when large mass
39 components experience significant displacement along the vertical axis. Sometimes,
40 the absence of the term is because some commercially available simulation tools do not
41 provide the user with all necessary data (e.g. [Furet et al \(2022\)](#); [Yang et al \(2024\)](#)).

42 Most often, very limited details are provided concerning the way the various energy
43 terms were computed while the energy balance of the numerical method employed can
44 play an important role. Explicit schemes can artificially inject energy into the system
45 if the time discretisation is too coarse. This problem is often avoided for computational
46 stability reasons by adding viscous dissipation to the system which is not justified by
47 the physics of the phenomenon. Conversely, purely implicit schemes, such as the Euler

48 backward scheme, dissipate a lot of energy numerically, which stabilises the numer-
49 ical simulation. Even though dissipation associated with these numerical artefacts is
50 easy to compute, the provided results may not be conducive to the safety of protective
51 structures. In the end, compliance with the fundamental principle of energy conserva-
52 tion in the system is rarely supported by evidences while it is a prerequisite for giving
53 confidence in the simulation results. In many cases, this compliance is debatable or it
54 can't be checked a posteriori, as for example in [Di Giacinto et al \(2020\)](#).

55 This article proposes a detailed and rigorous investigation of energy dissipation in
56 a particular and complex type of rockfall protection structure made from piled-up and
57 interconnected concrete blocks. This rockfall protection wall is first described. The
58 structure model previously developed under the NSCD framework and implemented
59 in the SICONOS software is briefly presented. The new method by which energy dissi-
60 pation by friction and plastic strain is calculated from the simulation results is then
61 detailed, revealing a particular time integration scheme that meets energy conserva-
62 tion requirements. The investigation that follows is conducted under the hypothesis
63 that the concrete block model and the dissipative mechanisms are appropriate with
64 respect to the addressed topic. A detailed analysis of energy balance computed based
65 on the simulation of the two impact tests performed on the real structures is con-
66 ducted to reveal the interest in considering the dissipative mechanisms for describing
67 the whole structure response with time. The influence of the way the model param-
68 eters are calibrated and of the impact conditions on the respective contribution of
69 friction and plastic strain in energy dissipation is then investigated. The ratio between
70 the amount of energy dissipated by friction to that dissipated by plastic strain is
71 employed for describing the structure response and for characterising its dissipative
72 capacities. Combined with the energy transferred to the structure, this ratio appears
73 relevant for investigating the structure dissipative capacities when considering a large
74 set of realistic impact conditions.

75 **2 Considered rockfall protection structure and its** 76 **model**

77 This research focuses on a specific type of rockfall protection structure made of con-
78 crete blocks interconnected one to another to form articulated walls. This type of
79 massive rockfall protection structure has the advantage of having a reduced footprint,
80 similarly to other structures ([Lambert et al, 2019](#); [Korini et al, 2021](#)). The development
81 of this structure type involved real-scale impact experiments together with numerical
82 modelling.

83 **2.1 Structure description**

84 The structure consists of concrete blocks, 1850kg in mass each, that are piled up in
85 staggered rows (Fig. 1). Superimposed concrete blocks are traversed along the vertical
86 axis by connectors consisting of assemblies of metallic tubes and cables whose aim is
87 to ensure mechanical continuity of the wall. The concrete block shape favours relative
88 rotation between adjoining blocks in the same horizontal row. The wall deformation
89 capacity is further increased by the space left between tubes and concrete blocks,
90 on one side, and between adjoining concrete blocks on the same horizontal row on
91 the other. This innovative technology offers the possibility to build massive vertical
92 walls, with reduced footprint, high deformability and versatility. For example, different
93 geometric arrangements of the concrete blocks along the longitudinal axis can be
94 adopted such as the zig-zag pattern considered in this study or a linear wall, with or
95 without partition walls ([Furet et al, 2022](#)). Such structures are intended to serve as
96 passive protection against gravity-driven natural hazards, and in particular rockfall.
97 A key feature of this structure type lies in the fact that the interconnections between
98 the concrete blocks improve the structure stability preventing excessive concrete block
99 displacements nearby the impact location.

100 Depending on the kinetic energy of the rockfall to intercept, a boulder impact on
101 such an articulated wall may induce concrete crushing and fracture, basal sliding, wall
102 tilting and relative displacement between superimposed concrete blocks with each an
103 amplitude that decreases with the distance to the impact location (see [Furet et al](#)
104 [\(2022\)](#); [Gupta et al \(2023, 2024\)](#)). The structure is described with more details in
105 [Furet et al \(2022\)](#).

106 **2.2 The NSCD structure model**

107 The structure was modelled using the SICONOS software package ([Acary and Perignon,](#)
108 [2007](#); [Acary et al, 2019](#)) which is based on the Non-Smooth Contact Dynamics (NSCD)
109 approach ([Jean and Moreau, 1987](#); [Jean, 1999](#); [Dubois et al, 2018](#)). The choice of NSCD
110 modelling was preferred over FEM, FDM and DEM for computation time reasons.
111 With NSCD, one simulation with a personal computer typically lasted 20 minutes,
112 compared to 10 hours with the finite difference model proposed by [Furet et al \(2022\)](#).
113 Running thousands of simulations for example in view of investigating the structure
114 response varying the impact conditions thus becomes affordable.

115 The layout of the wall model is presented in [Figure 2](#) comprising of modelled
116 components for blocks, connectors and projectile. The mechanical and geometrical
117 properties of most of the components are directly taken from the real structure. How-
118 ever, five model parameters cannot be directly assigned. Three parameters concerned
119 the contact mechanics, namely the restitution coefficient, e , and two friction coeffi-
120 cients, μ_{cc} and μ_{cs} , for concrete-concrete interfaces and concrete-supporting surface
121 interface respectively. These three parameters are intrinsic to the modelling approach
122 and are not easy to measure precisely under dynamic conditions. The two other param-
123 eters have been integrated into the model to traduce specific features of the structures
124 that are of paramount importance for its functional efficacy. The first parameter,
125 v_p , represents the relative looseness in the cable connecting the concrete blocks and

126 the second one, d_z , defines the position of the virtual disk that enables the contact
127 between the blocks and the tubes. The need for calibration of these two parameters
128 resulted from a large value variability and from difficulty in determining a relevant
129 and precise value from measurements. More details concerning the way the structure
130 was represented are provided in [Gupta et al \(2023\)](#).

131 The main lines of the computation method are described in [Appendix A](#) and an
132 exhaustive description is given in [Acary and Collins-Craft \(2024\)](#), in the case of lin-
133 ear elasto-dynamics. The computation method is based on the [Frémond's](#) approach
134 that consists of using the post-impact velocity instead of the average velocity of the
135 pre-impact and post-impact velocities ([Frémond, 2017](#); [Frémond, 2002](#)). This method
136 differs from the more classical approach which was in particular used by the authors
137 in their previous work ([Gupta et al, 2023](#)). It was preferred in this study because pre-
138 liminary simulations emphasised that the classical approach resulted in slight energy
139 balance discrepancies in the rare case of a sliding velocity reversal during impact.

140 **2.3 Model calibration**

141 The calibration of the five model parameters made use of measures collected during
142 two impact tests on real-scale structures, 14m long and 3.2m high. These impact tests
143 involved a projectile 1.1m in size with kinetic energy at the impact of 520 and 1020
144 kJ ([Furet et al, 2022](#)). The considered measurements were the displacement at four
145 points in the structure, as illustrated in [Figure 2](#), and at three times instants, *i.e.*, for
146 a total of 24 measures. Calibrating the model parameters against this set of data thus
147 allows accounting for the whole structure displacement with time and space, under
148 two different loading conditions.

149 The calibration was conducted based on a complex and innovative approach quan-
150 titatively minimising the model prediction error in terms of wall displacement with
151 time and space. This approach relied on the Bayesian inference statistical learning

152 method, accompanied by the meta-modelling techniques. It is described in [Gupta et al](#)
153 [\(2023\)](#).

154 This approach resulted in the parameter values presented in the first row of Table
155 [1](#) which define the reference model used in the following. These values slightly differ
156 from that in [Gupta et al \(2023\)](#) due to the improvement in the computation scheme
157 presented in section [2.2](#) and Appendix [A](#). The set of model parameters presented in
158 the other rows of this table will be used in section [4](#).

159 The significant effort made for calibrating the five model parameters based on 24
160 data describing the spatio-temporal response of the structure is considered to give
161 confidence in the reference model's predictive capacity. By contrast, it is thought that
162 a calibration based on a smaller data set would have resulted in a less efficient model
163 for predicting the whole structure displacement when varying the impact conditions
164 for example.

165 **3 Energy dissipation computation**

166 This section first introduces the method established for computing energy dissipation
167 from the model simulation results. This method is then applied to two cases for its
168 validation.

169 **3.1 Energy terms computation**

170 This section presents the way energy dissipation terms were computed. In the
171 equations below, the subscripts N , T and k respectively refer to the normal compo-
172 nent, the tangential component and the computation step. The superscripts α , $+$ and
173 $-$ respectively refer to the considered contact point, and the post- and pre-impact
174 situations.

The discrete kinetic energy, K , is defined as:

$$K_{k+1} = \frac{1}{2} v_{k+1}^\top M v_{k+1}, \quad (1)$$

175 with v the generalised velocity vector which contains the centre of mass velocities and
 176 the angular velocities expressed in the body frame and M the mass matrix.

The variation of energy due to the work of forces, ΔP , is defined as

$$\Delta_k^{k+1} P = -h v_{k+1/2}^\top F_{k+1/2}. \quad (2)$$

177 with h the time step and F the force vector that collects the externally applied
 178 forces and the gyroscopic effects. The notation $\Delta_k^{k+1} P$ is used to outline that the work
 179 of forces over a time interval is equal to the variation of the potential energy if the
 180 gyroscopic forces vanish.

The work associated with the normal component of a contact impulse is given by:

$$w_N^\alpha = \frac{1}{2} (u_N^{\alpha,+} + u_N^{\alpha,-}) p_N^\alpha = \frac{1}{2} (1 - e^\alpha) u_N^{\alpha,-} p_N^\alpha \leq 0 \quad (3)$$

181 since $u_N^{\alpha,-} \leq 0$ and $p_N^\alpha \geq 0$, with u the local relative velocity, p the contact impulse
 182 and e the restitution coefficient

183 The work associated with the tangential component of a contact impulse is
 184 computed as:

$$w_T^\alpha = \frac{1}{2} (u_T^{\alpha,+} + u_T^{\alpha,-}) p_T^\alpha = -\mu^\alpha \|\bar{u}_T\| p_N^\alpha \leq 0. \quad (4)$$

185 with μ the friction coefficient.

The discrete work of all contact impulses is given by:

$$W_{k+1} = \sum_{\alpha \in I} u_{k+1}^\alpha / 2 p_{k+1}^\alpha, \quad (5)$$

that be decomposed in its normal

$$W_{N,k+1} = \sum_{\alpha \in I} u_{N,k+1}^\alpha / 2 p_{N,k+1}^\alpha = \sum_{\alpha \in I} \frac{1}{2} (1 - e^\alpha) u_{N,k}^\alpha p_{N,k}^\alpha \quad (6)$$

and tangent parts

$$W_{T,k+1} = \sum_{\alpha \in I} u_{T,k+1}^\alpha / 2 p_{T,k+1}^\alpha = \sum_{\alpha \in I} -\frac{1}{2} \mu^\alpha \|u_{T,k+1}^\alpha + u_{T,k+1}^{\alpha,-}\| p_{N,k}^\alpha. \quad (7)$$

186 It is shown in [Acary and Collins-Craft \(2024\)](#), in the case of linear elasto-dynamics,
 187 that the discrete work of contact forces is non-positive and the following discrete
 188 energy balance is satisfied

$$\Delta K_k^{k+1} + \Delta_k^{k+1} P = W_{k+1}, \text{ with } W_{k+1} \leq 0. \quad (8)$$

189 where $\Delta K_k^{k+1} = K_{k+1} - K_k$. Numerical evidence shows this relation is also satisfied
 190 in the case of rigid bodies under gravity.

The energy dissipation due to the work of the tangential components of contact impulses ($W_{T,k+1}$) is directly related to frictional processes. Consequently, the cumulative energy dissipated by friction is :

$$D_f = - \sum_{k=0}^N W_{T,k+1} \geq 0. \quad (9)$$

The remaining part of the work of the contact impulses, that is the contribution of the normal components of contact impulses ($W_{N,k+1}$), is associated with energy dissipation (D_p) due to plastic strain associated with concrete blocks damage, in particular in the vicinity of the impact point. D_p is defined as

$$D_p = - \sum_{k=0}^N W_{N,k+1} \geq 0, \quad (10)$$

Over the whole time interval of simulation, we have the energy balance

$$\Delta(K + P) = -(D_p + D_f). \quad (11)$$

191 In other words, the total energy of the system decreased over time by the amount of
 192 dissipation at contacts by friction and plastic strain.

193 3.2 Application to the reference impact cases

194 The previously described method was employed for computing energy dissipation in
 195 the case of the two impact tests conducted on the real-scale structures (Furet et al,
 196 2022). The considered simulation time step was 0.25 milliseconds and the simulated
 197 impact duration was 1 second (see the video of a simulation with [this link](#)).

198 Figure 3 shows for the two impact cases the evolution with time of the kinetic
 199 energy and variation in potential energy of all the concrete blocks (K_{wall} and ΔP_{wall} ,
 200 resp.), the sum of the variation in potential energy and the kinetic energy of the
 201 projectile ($\Delta P_{proj} + K_{proj}$). K_{proj} comprises of the rotational and translational kinetic
 202 energies. The initial value of the former component is nil for these two impacts but will
 203 be varied in the following. This Figure also shows the cumulative energy dissipated by
 204 friction at all interfaces (D_f) and by plastic strain (D_p). The sum of all these energy

205 terms is also plotted (Σ). All these quantities are normalised by the projectile kinetic
206 energy at impact, $K_{proj}(t_0)$.

207 It is assumed that, at the projectile-wall contact, energy dissipation only occurs
208 in the impacted concrete block, which is consistent with the absence of projectile
209 damage observed after the experiments. In these plots, kinetic energy accounts for both
210 translational and rotational energies. For presentation clarity purposes, the interaction
211 of the projectile with the ground after it bounced away from the wall is not simulated.

212 The first observation from Figure 3 is that the sum of all these quantities remained
213 constant, with a nearly nil variation over time. This shows that the energy balance
214 equation (Eq. 8) is respected and demonstrates the soundness of the computation
215 scheme.

216 The two impact cases exhibit similar trends. The projectile total energy, ΔP_{proj}
217 + K_{proj} , sharply decreased at the very impact beginning, as a consequence of its
218 translational velocity reduction associated with the impact with the wall. Just after
219 the projectile lost contact with the wall, its velocity was small, with values of 10.7% for
220 the incident velocity for the 520kJ impact, and 5.6% for the 1020kJ one. The variation
221 in concrete blocks' potential energy, ΔP_{wall} , remained small with a maximum value
222 attained at 0.15 second approximately (amounting to less than 4% the impact energy),
223 suggesting a limited upward displacement of the concrete blocks. By contrast, the
224 concrete block kinetic energy, K_{wall} , experienced a high variation over the first tenths
225 of milliseconds, with a maximum amounting more than 20% the impact energy in
226 both cases. It took more than 0.5 seconds before the wall kinetic energy was close to
227 zero, with a slightly higher duration for the 1020kJ impact.

228 Dissipation by plastic strain, D_p , mainly occurred at the very beginning of the
229 impact. Nearly 90% of the total dissipation by plastic strain was reached less than 0.1
230 seconds after the projectile touched the wall. Dissipation by plastic strain lasted longer
231 for the 1020kJ impact case (more than 0.4 seconds). In contrast, the cumulative energy

232 dissipation by friction, D_f , increased more progressively and stopped increasing after
233 0.55 seconds approximately.

234 For both impact cases, the dominating dissipative mechanism over the whole
235 impact duration reveal to be plastic strain. In the end, energy dissipation by plastic
236 strain amounted to approximately 65% of the incident projectile kinetic energy for
237 both the 520kJ and the 1020kJ impact. The remaining was dissipated by friction.

238 These curves and the derived trends reflect the whole structure response with time
239 and space. Energy dissipation by plastic strain traduces the amplitude of the nor-
240 mal impulse between system components. Energy dissipation by friction traduces the
241 amplitude of the relative displacement in the tangential direction between system com-
242 ponents, and mainly the concrete blocks and the supporting surface. Both dissipative
243 mechanisms initiate nearby the impact location and progressively concern components
244 at a further distance, depending on the amplitude of contact force and displacement.
245 Most of the dissipation by plastic strain occurs in typically 0.2 seconds indicating a
246 rapid decrease in contact force amplitude between the blocks throughout the wall. At
247 0.2 seconds , the wall still moves and dissipation by friction lasts until sliding at its
248 base stops (typically around 0.6 seconds).

249 **3.3 Dissipation-based descriptor of the structure response**

250 This description clearly shows that quantities associated with energy dissipation in the
251 system describe the whole structure response, with time and space, in a rather clear
252 and synthetic manner. The respective contributions of the dissipative mechanisms over
253 time are highlighted.

254 The predominance of plastic strain in energy dissipation after the wall is at rest
255 (i.e. after impact) is evidenced by the ratio between the cumulative values of the
256 energy dissipated by friction, D_f , and the energy dissipated by plastic strain, D_p ,
257 referred to as $R_{f/p}$. This dissipation ratio takes values of about 0.56 and 0.55 for the

258 520kJ- and 1020kJ-impacts respectively indicating that dissipation by plastic damage
259 dominates. A similar general conclusion was obtained by Furet et al (2022) based on
260 simulations with the finite volume formulation code FLAC3D. The model accounted
261 for the structure components and geometry in a very realistic way. The constitutive
262 laws accounted for plasticity, in particular for modelling damage to concrete blocks.
263 The authors concluded that plastic strain was the dominating dissipative mechanism,
264 with an average $R_{f/p}$ value of approximately 0.5 considering the same two tests.
265 Nevertheless, it was not possible for Furet et al (2022) to access all quantities associated
266 with energy, resulting in a 26% difference between the incident projectile kinetic energy
267 and the sum of all computed terms.

268 To some extent, the value of the $R_{f/p}$ ratio reflects the response of the structure,
269 in terms of displacement and contact force over the whole impact duration and whole
270 structure. A high ratio value indicates that the whole structure impact response with
271 time is characterised by significant block displacements, resulting in high dissipation by
272 friction and, vice versa, a small $R_{f/p}$ value reveals that the structure impact response
273 is characterised by large contact forces resulting in damage to the blocks. The $R_{f/p}$
274 ratio thus appears a relevant and synthetic descriptor of the whole structure response
275 and, for this reason, it will be considered in the following for discussing the variability
276 in the response of the articulated wall addressed in sections 4 and 5.

277 **4 Sensitivity of energy dissipation to model** 278 **parameters**

279 Parameters calibration is a crucial stage in the development of a numerical model,
280 which can be based on data from experiments on real structures. In this section, we
281 assess the extent to which the number of experimental data used for this calibration
282 can influence the quality of the model's predictions with regard to energy dissipation.

283 4.1 Models parameters definition

284 The parameters of the reference model which are presented in the first row of Table
285 1 were calibrated using a fine-tuned approach considering 24 measurements obtained
286 from impact experiments on real-scale structures (Section 2.3). More precisely, this set
287 of best-fit parameters was defined so that the deviation of the model predictions with
288 all these experimental data was minimised. Besides, results presented in Gupta et al
289 (2023) evidenced that decreasing the number and variety of data used for calibrating
290 the model parameters had a significant influence on the model accuracy in modelling
291 the whole structure response with time. This clearly suggests that the strategy consid-
292 ered for calibrating the model parameters may have a significant influence on energy
293 dissipation quantification by the model.

294 The dependence of energy dissipation quantification on the model parameters was
295 addressed considering different sets of model parameters that were calibrated from
296 the available experimental data set and following different calibration strategies with
297 increasing complexity (Table 2). These strategies were in particular inspired by what
298 is presented in the literature. The most simple strategy for calibrating a model consists
299 of considering the displacement measured when the structure is at rest of one point in
300 the structure. This point is generally located near the impact point. In our case, the
301 experimental measurements at this location were globally not reliable or not available
302 (Furet et al, 2022). For this reason, we considered the wall displacement after the
303 520kJ-test at the base, at the Top and at point D (see Fig. 2) which correspond to
304 calibration strategies (CS) 1 to 3 in Table 2. The other strategies consist of considering
305 displacement at different locations in the structure, different time instances (namely
306 "Rest", "Init." and "max" as defined in Gupta et al (2023)) and different impact
307 energies. These strategies were defined in a rather arbitrary manner.

308 Overall, strategies 1 to 9 consisted of calibrating the model parameters by com-
309 paring the model predictions with different selections of one to three data measured

310 during the real-scale experiments. In other words, each of these nine models was cali-
311 brated to provide the best estimate for the displacement at the considered point, time
312 instant and impact energy. This implicitly means that predictions at other points,
313 time instants and energy are not expected to be good.

314 The calibration strategies presented in Table 2 globally give priority to data mea-
315 sured during the 520kJ-test as this kinetic energy is more in accordance with the
316 kinetic energy to which this protection structure is intended. By contrast, the 1020kJ-
317 test corresponds more to an extreme situation in terms of incident projectile kinetic
318 energy, inducing severe damage to the wall. In principle, these energy levels may be
319 respectively assimilated to service and limit energy levels (SEL and MEL) considered
320 for flexible barriers (EOTA, 2018). Also, priority is given to calibration strategies con-
321 sidering measurements at rest, which is a frequent practice when calibrating models
322 on a quantitative basis.

323 For each strategy, the calibration of the model parameters followed the same scheme
324 as for the reference model, making use of the Bayesian inference accelerated with poly-
325 nomial chaos expansion (PCE) based meta-models (section 2.3). The values presented
326 in Table 1 confirm that the model parameters value vary significantly depending on
327 the way the model was calibrated. For example, the maximum relative difference in
328 parameter value with the reference model exceeds 50% (e.g., e equals 0.107 for CS8
329 vs 0.221 for the reference model).

330 The nine structure models, corresponding to these nine sets of calibrated parame-
331 ters, were employed to simulate the structure response when exposed to impacts with
332 energies of 520 and 1020kJ. The comparison between the results from the nine models
333 is based on the $R_{f/p}$ ratio, as this ratio reflects the structure response via the rela-
334 tive contribution between the two dissipative mechanisms. More precisely, the relative
335 difference in $R_{f/p}$ for a given model with that computed from simulations with the
336 reference model is presented in Figure 4.

337 4.2 Comparison of the models predictions

338 By comparison with the reference case, twelve predictions of $R_{f/p}$ out of eighteen
339 reveal rather good, with a difference less than 10% for one impact energy at least.
340 This difference is less than 5% for six predictions. Models that were developed fol-
341 lowing calibration strategies CS4 and CS8 resulted in the best predictions among all
342 nine models, with a difference of less than 5% for both impact energies. The worse
343 predictions are provided by CS2, CS3 and CS5, with at least one prediction with a
344 difference exceeding 15%.

345 The four models that were calibrated based on displacement at rest after the 520kJ-
346 test only (CS1, CS2, CS3 and CS8) all underestimate $R_{f/p}$ for the 520kJ impact energy.
347 All nine models underestimate $R_{f/p}$ for the 1020kJ impact case which is attributed
348 to the set of data chosen for the nine strategies and in particular to the fact that
349 these sets globally gave priority to data from the 520kJ impact test. A global trend
350 is observed where a larger number of input data for the calibration results in better
351 predictions. Nevertheless, the fact that differences less than 5% were obtained with
352 the CS4 model, in which calibration considered one input data only, suggests this is
353 not a strict rule.

354 Focusing on the calibration strategies resulting in the worst predictions, namely
355 CS2 and CS5, Figure 5 reveals a significant difference with the reference model in
356 terms of energy dissipation by friction and by plastic strain during the impact. For
357 the 1020kJ-impact case, the models calibrated against CS2 and CS5 underestimate
358 D_f by about 14% and 7% and consequently, both models overestimate D_p . For the
359 520kJ-impact case, D_f is overestimated by one model (CS5) and underestimated by
360 the other (CS2), with a 10% deviation approximately in both cases. The opposite
361 trend is observed focusing on D_p . Last but not least, the differences with the reference
362 model in terms of both D_f and D_p clearly appear from the early stages of the wall

363 response to impact, revealing a significant difference in terms of blocks displacement
364 with time and space.

365 4.3 On the model parameters calibration

366 The results presented in the previous section evidenced that the way the model
367 parameters are calibrated may have a significant influence on the accuracy of
368 simulation-based estimation of the energy dissipative capacities of the wall. This is
369 obviously due to the fact that the model parameters govern the overall dynamic
370 response of the structure, in terms of displacement and load transfer with time and
371 space, which has consequences on energy dissipation by both friction and plastic strain.
372 The predictions of models calibrated against two or three data appeared surprisingly
373 good, some showing a difference in $R_{f/p}$ value less than 5 % with the reference model.
374 By contrast, the difference for models calibrated against one data was globally much
375 higher, with some values exceeding 15 %.

376 The general trend where a higher number of data results in better predictions is
377 not a rule, which suggests that for a model to be reliable, its parameters should be
378 calibrated against a rich set of data, meaning a set conveying information reflecting the
379 spatio-temporal structure impact response. For this structure, a data set consisting in
380 two displacement measurements (at different locations, time or for different projectile
381 kinetic energies) generally revealed sufficiently rich. It is thought that the number and
382 type of data to be used for getting a rich data set is structure-dependent meaning that
383 this conclusion should be considered with caution when dealing with other structure
384 types. Besides, getting a rich data set from real-scale experiments requires that the
385 experimental set-up was designed to get many data, as for example the displacement
386 at different locations or at different time instances.

387 Paying particular attention to the reliability of the model predictions is even more
388 necessary when energy dissipation quantification constitutes the basis of a design

389 method. This is for example the case with the analytical method proposed by [Marchelli](#)
390 [and Deangeli \(2022\)](#) to design rockfall protection embankments which is based on
391 the simulation-based estimation that 85 % of the incident projectile kinetic energy is
392 dissipated by plastic strain in the embankment.

393 It is important to remind that, as with any model, the numerical model of this
394 structure relies on different simplifications and assumptions which may have conse-
395 quences on the model predictions in terms of energy dissipation. The proposed NSCD
396 model accounts for concrete block damage in a simple way, with the advantage of a
397 reduced computation time. It has been calibrated so that displacements in time and
398 space can be predicted with good accuracy. Using this model for computing energy
399 dissipation implicitly lies on the hypothesis that all physical processes involved in
400 energy dissipation are accounted for. Demonstrating this rigorously is out of reach,
401 due to both experimental and numerical constraints and limitations. As for the for-
402 mer, this demonstration would require additional measurements that are difficult, if
403 not impossible, to make (impact strength of highly reinforced blocks, relative displace-
404 ment between blocks...). As for the latter, it would require substantial increase in the
405 model complexity that would lead to excessively long computations. This research is
406 thus based on two working hypotheses which concern the use of a simple model for
407 the blocks and the dissipative mechanisms.

408 **5 Energy dissipative capacities over a large range of** 409 **impact conditions**

410 On-site rockfall protection structures are exposed to a wide variety in impact condi-
411 tions during their normal operation. Up to now, the induced variability in response of
412 rockfall protection structures has mainly been addressed focusing on their deforma-
413 tion or deflection, load transmission and failure ([Breugnot et al, 2016](#); [Mentani et al,](#)
414 [2016](#); [Bourrier et al, 2016](#); [Toe et al, 2018](#); [Previtali et al, 2021](#); [Lambert et al, 2021](#);

415 [Douthé et al, 2022](#); [Qi et al, 2022](#); [Maheshwari et al, 2024](#)). It is here proposed to
416 address the variability in structure response in terms of energy dissipation.

417 **5.1 Impact conditions definition**

418 In the previous section, the structure response was addressed considering two impacts
419 in the centre of a 14m long wall, by a projectile with a normal-to-the-wall incident
420 trajectory. These test conditions are consistent with current practices for rockfall pro-
421 tection structures testing, such that prescribed for flexible barriers ([EOTA, 2018](#)), but
422 are not representative of field conditions where impacts may occur under very dif-
423 ferent conditions. These impact tests constitute conformance tests that may not be
424 representative of the on-site structure response. For this reason, and in a similar way
425 as previously done for flexible barriers ([Mentani et al, 2016](#); [Toe et al, 2018](#); [Previ-
426 tali et al, 2023](#)), the investigation of the zig-zag wall response was expanded varying
427 the impact point location, the translational and rotational velocities of the incident
428 projectile, the deviation of its trajectory with respect to the horizontal axis and with
429 respect to the normal to the wall longitudinal axis. Realistic ranges have been consid-
430 ered for these parameters ([Table 3](#)). The range for the impact point location along the
431 vertical axis, z , considered a minimum value equal to the projectile radius at the toe
432 of the wall and a free-board equal to the projectile diameter at its top, in accordance
433 with some design practices ([Lambert and Bourrier, 2013](#)). The impact point location
434 along the horizontal axis, y , was varied from the wall centre to a distance of 3.53m
435 aside, in accordance with the length of the zig-zag pattern of this wall. The range for
436 the translational velocity, v , corresponds to translational kinetic energies from 130 to
437 810kJ. The maximum value is about 20% less than the wall nominal capacity (con-
438 sidered to be 1020kJ based on the experiments) to limit severe damage to concrete
439 blocks. The considered ranges for the projectile rotational velocity, Ω , inclination and
440 deviation were derived from the literature ([Bourrier et al, 2012](#); [Toe et al, 2018](#); [Noël](#)

441 [et al, 2023](#)). The same projectile as in the previous section was considered. The wall
442 length was increased to 28.2m to limit boundary effects while keeping the computa-
443 tion time reasonable. The structure response description proposed hereafter is thus
444 relevant whatever the impact point location and providing that the wall extremi-
445 ties experience very limited displacement. This condition can be insured on-site with
446 ground abutments or shrouds at the wall extremities.

447 These impact conditions were also considered by the authors for conducting an
448 inverse analysis of the wall response to serve in operational contexts ([Gupta et al,](#)
449 [2024](#)).

450 A Latin hypercube sampling method ([Lataniotis et al, 2015](#)) was employed to
451 generate 300 sets of 6 input parameters from the ranges presented in [Table 3](#) for
452 running simulations with the reference NSCD model of the wall.

453 **5.2 Influence of the impact conditions on the structure** 454 **response**

455 The variability in structure response varying the impact conditions is illustrated from
456 the 300 simulations results in [Figure 6](#) focusing on the post-impact displacement at
457 the top of the wall. This figure shows the location of the extremity of the structure's
458 vertical connectors, as well as the mean position and the standard deviation of the
459 position in the X- and Y-axis directions of the connectors' extremity.

460 The cloud of points reveals that much larger displacements in the X-axis direc-
461 tion are observed at a distance from the wall centre (i.e. when Y ranges from -2 to
462 -4 m. This is also the place where larger variability in displacement with impact con-
463 ditions is observed. Also, the displacement component along the Y-axis direction is
464 much smaller at the wall centre (Y=0m) than that 2.5m aside. These differences in
465 wall displacement according to the impact location along the wall longitudinal axis
466 are attributed to the zig-zag conformation of the wall. Basically, the interconnections

467 between the blocks favour significant displacement of blocks at a distance from the
468 impact location, which number depends on the impact location. Basically, if the num-
469 ber of blocks experiencing displacement is small for a given impact location, then the
470 displacement of the impacted block is large, and vice-versa.

471 The variability in wall response with the impact conditions is also revealed by
472 the variation in $R_{f/p}$, whose value typically ranged from approximately 0.4 to 3.8
473 over the 300 simulations (Fig. 7). This figure suggests a trend concerning the impact
474 inclination angle where an increase in the impact inclination angle, α , above 0° results
475 in an increase in the minimum value of $R_{f/p}$, meaning an increase in the relative
476 contribution of friction over plastic strain in total energy dissipation. To a much lesser
477 extent, the minimum value of $R_{f/p}$ seems to slightly vary with y and β .

478 Apart from α , no clear trend for the influence of the parameters can be directly
479 derived from this simple figure.

480 The Sobol indices are much more informative and confirm the influence of α . The
481 method proposed by Sobol (1993) consists in decomposing the variance of the output
482 parameters as the sum of the contributions of the different input parameters including
483 the possible interaction between input parameters. Each contribution is characterised
484 by the ratios of the partial variance to the total variance, called Sobol sensitivity
485 indices. As for the impact location, $R_{f/p}$ is particularly dependant on the position
486 along the wall longitudinal axis, y , but not on that along the vertical axis, z . In a
487 rather counterintuitive manner, the projectile translational velocity, v , appears to have
488 a very small influence. The influence of the deviation, β , appears significant.

489 It is worth mentioning that there is a strong dependence between these parameters
490 as confirmed by the fact that the sum of the six Sobol indices significantly exceeds
491 1.0. This means that the dependence of $R_{f/p}$ on one specific parameter, is influenced
492 by the value of another parameter. For example, the influence of the deviation angle,
493 β , depends on the impact location along the wall longitudinal axis, y , due to the wall

494 zig-zag conformation. The interrelationship also explains why no strong trend can be
495 observed in Figure 7 , at the exception as for α .

496 The distribution of $R_{f/p}$ was computed from the 300 simulation results comple-
497 mented with a refined distribution obtained from a specifically developed PCE-based
498 meta-model (Fig. 9, top). This figure shows that the main dissipative mechanism is the
499 plastic strain in the block (globally, $R_{f/p} < 1$). Energy dissipation by friction appears
500 to be negligible in some impact cases with $R_{f/p}$ values much less than 0.5. On the con-
501 trary, the amount of energy dissipated by friction is more than twice that dissipated
502 by plastic strain in other impact situations. Comparison of this distribution with the
503 value of dissipation ratio $R_{f/p}$ obtained for the two impact tests against which the
504 model was calibrated (0.56 and 0.55) reveals that these test conditions favoured even
505 more dissipation by plastic strain.

506 Considering separately cases where the impact energy is higher or lower than 500kJ
507 leads to the same general conclusion (Fig. 9, bottom) meaning that the relative con-
508 tribution of friction with respect to plastic strain in energy dissipation is the same
509 whether the projectile velocity is high or low (because its mass was not varied). This
510 comment is in line with the previous one on the influence of the projectile velocity on
511 $R_{f/p}$.

512 Overall, the prevailing dissipative mechanism appears to be block plastic strain,
513 but there exists a strong dependence on the impact conditions. Besides, normal-to-
514 the-wall impacts result in $R_{f/p}$ values which do not reflect the average wall dissipative
515 capacities, meaning that the precise assessment of its on-site response in terms of
516 energy dissipation should not be extrapolated from results from such tests.

517 **5.3 Interpretation**

518 The results presented in Figures 7, 8 and 9 convey information of great value for
519 understanding the structure response and assessing its dissipative capacities.

520 The displacement of the structure and the amount of energy it dissipates by plastic
521 strain and friction depends on the energy that is transferred to the wall during the
522 impact. This amount of energy, referred to as "imparted energy", E_{impart} , is considered
523 equal to the variation in projectile total energy during the impact:

$$E_{impart} = \Delta(P_{proj} + K_{proj}) \quad (12)$$

524 The ratio between the imparted energy, E_{impart} , and the projectile kinetic energy
525 at impact, $K_{proj}(t_0)$, ranges from approximately 0.25 to 1 depending on the impact
526 conditions (Fig. 10, top). The variability in this ratio is governed by the inclination
527 angle, α , and other parameters having negligible influence (Fig. 10, bottom). Lower
528 values of this ratio are observed for high and low values of α (Fig. 10, top). This is
529 attributed to the fact that a deviation in trajectory with respect to the normal of the
530 impacted concrete block favours projectile deviation, resulting in a higher projectile
531 rebound velocity and a lower E_{impart} . Such non-normal impacts also result in lower
532 impact forces on the impacted concrete block, and thus less plastic damage to this
533 block. These two comments are thought to explain the trend for the influence of α as
534 well as for the influence of β on the minimum value of $R_{f/p}$ where a lower contribution
535 of plastic strain is observed when the deviation of the projectile trajectory with respect
536 to the normal to the impacted block is higher.

537 The virtually negligible influence of the translational velocity on the relative con-
538 tribution between the two dissipative mechanisms, i.e. $R_{f/p}$ ratio, (Fig. 8) is partially
539 attributed to the Gaussian distribution considered for this parameter which results in
540 less frequent extreme velocity values in the set of impact conditions.

541 The $R_{f/p}$ ratio refers to the relative contribution of friction over plastic strain in
542 energy dissipation but does not indicate the amount of energy that is dissipated in the
543 wall. For this reason, evaluating the criticality of an impact in terms of displacement
544 or damage requires also accounting for the amount of energy the wall dissipates during

545 impact, which equals E_{impart} . In other words, a very low, resp. high, value of $R_{f/p}$
546 will lead to high damage, resp. displacement, only if the energy that is transferred to
547 the wall during impact is high.

548 The structure efficiency analysis conducted combining $R_{f/p}$ with the imparted
549 energy, E_{impart} , reveals a certain correlation between the two variables, where lower
550 $R_{f/p}$ values are globally associated with impact conditions where E_{impart} is high, and,
551 inversely, higher $R_{f/p}$ values correspond to lower values of E_{impart} (see Fig. 11). Impact
552 situations where the projectile incident trajectory is horizontal, with α values close to
553 0° , are globally associated with higher E_{impart} values. On the contrary, extreme values
554 of inclination ($\alpha < -45^\circ$ or $\alpha > 45^\circ$ approx.) lead to E_{impart} values less than 400kJ.
555 This figure confirms that downward projectile trajectories (positive α values) tend to
556 favour dissipation by friction, with $R_{f/p}$ values most often higher than 1 while upward
557 projectile trajectories tend to favour dissipation by plastic strain, with $R_{f/p}$ values
558 most often lower than 1. These comments are in line with the previous comments on
559 the influence of α on the structure response.

560 While Figure 9 revealed that the number of impact conditions where dissipation by
561 plastic strain was statistically dominating, Figure 11 shows that the structure response
562 over this wide range of impact conditions is such that conditions where plastic strain
563 dominates are associated with a large amount of energy dissipated by the structure.
564 This leads to the conclusion that the probability of having large damage to concrete
565 blocks is high with this zig-zag conformation wall.

566 6 Perspectives

567 In this work, the dissipative capacities of the structure were addressed by varying
568 the parameters describing the impact conditions over realistic ranges and considering
569 realistic but rather arbitrary distributions (see Table 1). Important findings derived
570 from figures 9 and 11, in particular, are related to these ranges and distributions.

571 Nevertheless, these ranges and distributions are not fully representative of that derived
572 from rockfall trajectory simulations on real sites. In a very similar context, [Lambert
573 et al \(2021\)](#) have shown that the efficiency of flexible barriers in arresting rock blocks
574 was extremely sensitive to the distributions of the impact condition parameters, even
575 when the barrier was designed for the concerned site.

576 In addition, there exists some couplings between the parameters. In particular,
577 upward incident trajectories relate to cases where the rock block bounces in the ditch
578 uphill of the structure before impacting it. This bounce induces energy dissipation
579 and, for this reason, the rock block translational velocity at impact on the structure is,
580 on the average, much less than in the case of a block directly impacting the structure
581 with a downward trajectory. These couplings exist and are site-specific but were not
582 accounted for when sampling the 300 sets of input parameters.

583 These comments suggest that the structure dissipative capacity for a given site
584 may statistically differ from that derived from the results presented herein. The mean
585 value of 0.8 approx. for $R_{f/p}$ is not relevant for all sites. As a consequence, the wall
586 effective dissipative capacities for a given site should rather be quantified considering
587 the site-specific range of impact conditions which are obtained from rockfall trajectory
588 simulations ([Lambert et al, 2021](#)).

589 For the considered wall, with a zig-zag conformation, the main dissipative mecha-
590 nism was associated with concrete block damage. The dissipation ratio $R_{f/p}$ had an
591 average value of 0.8, meaning that 55% of energy dissipation was due to plastic strain.
592 Depending on the impact conditions, the contribution of plastic strain on total energy
593 dissipation varied between 20% and 70% approx., corresponding to the highest and
594 lowest observed $R_{f/p}$ values respectively (3.8 and 0.4). Taking advantage of the ver-
595 satility of this structure type, its design could be improved, in particular considering
596 other conformations. This design optimisation could be based on the $R_{f/p}$ ratio follow-
597 ing different strategies in terms of functional requirements. One optimisation strategy

598 could consist of preventing both large damage to the concrete blocks and large wall dis-
599 placement whatever the impact conditions. In such an approach, the optimum design
600 would be such that the ratio $R_{f/p}$ remains within a limited range such that friction
601 and plastic strain rather equally contribute to energy dissipation in any case. Another
602 strategy could consist of designing a wall favouring displacement, to prevent damage
603 to concrete blocks, as damage to concrete blocks requires work for their replacement.
604 In such a purpose, the wall pattern could be modified so that the probability of having
605 a low $R_{f/p}$ value is lower than that for the zig-zag pattern. Whatever the goal of the
606 design optimisation, the value of the ratio should always be complemented with the
607 imparted energy, E_{impart} , as large damage or displacement requires that the amount
608 of energy transferred to the wall is also sufficiently high.

609 From a methodological point of view, conducting such design improvements would
610 require performing a large number of NSCD simulations (typically 300) for each design,
611 from which a meta-model would be developed for supplying the $R_{f/p}$ values.

612 **7 Conclusions**

613 The efficiency of protection structures exposed to impact, among which passive rockfall
614 protection structures, largely depends on their energy dissipative capacities. This work
615 addressed the impact response of such structures in terms of energy dissipation, and
616 highlighted the potential of an accurate energy dissipation quantification. It was based
617 on the example of a rockfall protection wall made of interconnected concrete blocks for
618 which a numerical model developed under the NSCD framework and calibrated from
619 real-scale impact experiments was available. Under the assumption that the concrete
620 block and dissipation mechanisms are reasonably well modelled with respect to the
621 addressed topic, the conclusions are:

- 622 • the method proposed to derive the energy dissipated by both friction and plastic
623 strain from NSCD simulation results was demonstrated to ensure energy conserva-
624 tion in the system throughout the simulation, whose feature results from the fact
625 that the numerical scheme respects the discrete energy/work balance.
- 626 • for the NSCD model of this structure to provide a reliable quantification of the
627 dissipative energy terms, the calibration of its five parameters should be based on
628 at least two measures obtained from real-scale impact experiments.
- 629 • the ratio between the cumulative contribution to energy dissipation of friction and
630 plastic strain, $R_{f/p}$, is proposed as a descriptor of the whole structure impact
631 response with time and to assess its energy dissipative capacities.
- 632 • the combination of the $R_{f/p}$ value with the energy imparted to this wall, E_{impart} ,
633 revealed that damage to concrete blocks was the dominating dissipative mechanism
634 when considering a wide range of realistic impact conditions.
- 635 • the response of this wall, in particular in terms of $R_{f/p}$ value, is primarily governed
636 by the incident projectile trajectory inclination angle, which also governs E_{impart} .

637 Focus was placed on a particular type of passive protection structure but the gen-
638 eral principle of addressing its response based on energy dissipation quantification
639 could be applied to any type of structure exposed to impact in which energy is dissi-
640 pated by two mechanisms mainly, and in particular rockfall protective structures such
641 as flexible barriers or rockfall protection embankments.

642 As a perspective, the general approach will be considered for improving the design
643 of articulated walls when considering site-specific impact conditions, for example in
644 view of optimising the wall conformation based on the $R_{f/p}$ ratio.

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784 A Computation scheme

785 In our context of 3D rigid bodies, the equation of motion with contact and Coulomb
786 friction is given by:

$$\left. \begin{cases} \dot{q} = T(q)v, \\ M\dot{v} = F(t, q, v) + G^\top(q)r, \\ u^\alpha = G^\alpha(q)v \\ r^\alpha = 0, & \text{if } g_N^\alpha(q) > 0, \\ K^{\alpha,*} \ni \hat{u}^\alpha \perp r^\alpha \in K^\alpha, & \text{if } g_N^\alpha(q) = 0, \\ u_N^{\alpha,+} = -e^\alpha u_N^{\alpha,-}, & \text{if } g_N^\alpha(q) = 0 \text{ and } u_N^{\alpha,-} \leq 0 \end{cases} \right\} \alpha \in \mathcal{I},$$

787

788

789 The vector q is the configuration vector which combines the position of the centre
790 of mass and the parameterisation of the rotation with quaternions for each body. The
791 generalised velocity vector v contains the centre of mass velocities and the angular
792 velocities expressed in the body frame. The $x \perp y$ symbol means that $y^\top x = 0$. The
793 matrix $T(q)$ relates the time derivative of q to v . \mathcal{I} is the set of potential contacts
794 and $g_N^\alpha(q)$ is the gap function associated to the distance between bodies potentially
795 in contact. The matrix M is the mass matrix, the vector F is the force vector that
796 collects the external applied forces and the gyroscopic effects. For the contact point
797 $\alpha \in \mathcal{I}$, the matrix $G^\alpha(q)$ is the contact configuration matrix, which expresses the local
798 relative contact velocity u in terms of the generalised velocities v . The matrix $G(q)$
799 collects the matrices $G^\alpha(q)$ for $\alpha \in \mathcal{I}$.

800 The reaction forces r^α and the velocities u^α are decomposed into their normal and
801 tangent parts, denoted r_N, r_T and u_N, u_T , respectively.

802 Using the modified relative contact velocity \widehat{u}^α , such that $\widehat{u}_N^\alpha = u_N^\alpha + \mu^\alpha \|u_T^\alpha\|$, \widehat{u}_T^α
803 $= u_T^\alpha$, the Coulomb friction with unilateral contact is expressed as (see [Acary et al](#)
804 [\(2018\)](#) for details) :

$$K^{\alpha,*} \ni \widehat{u}^\alpha \perp r^\alpha \in K^\alpha, \quad (13)$$

805 The cone $K = \{r \in \mathbb{R}^3, \|r_T\| \leq \mu r_N\}$ is the usual Coulomb friction cone and
806 $K^* = \{z \in \mathbb{R}^3 \mid z^T x \geq 0 \text{ for all } x \in K\}$ its dual.

807 The formulation is completely equivalent to the standard Coulomb friction model
808 with contact as shown in ([Acary and Collins-Craft, 2024](#)). The relation $u_N^{\alpha,+} =$
809 $-e^\alpha u_N^{\alpha,-}$ is the Newton impact law for the contact α .

In order to take into account the impact phenomenon in case of a jump in velocity,
in a way that is consistent with the energy dissipation, the contact law is written with
the help of Frémond's approach ([Frémond, 2017](#); [Frémond, 2002](#)) as

$$K^{\alpha,*} \ni \begin{bmatrix} \bar{u}_N + \frac{1}{2} e u_N^- + \mu^\alpha \|\bar{u}_T\| \\ \bar{u}_T \end{bmatrix} \perp p^\alpha \in K^\alpha, \quad (14)$$

810 where $\bar{u} = \frac{1}{2}(u^{\alpha,+} + u^{\alpha,-})$ is the average of the pre- and post-impact velocities, and
811 p^α the contact impulse.

With the Frémond's approach, the Moreau–Jean scheme (with $\theta = 1/2$) for the
system, for a time discretization $t_0 < \dots < t_k < t_{k+1} < \dots < t_n$ with a time step

$h = t_{k+1} - t_k$, is adapted as follows

$$\left\{ \begin{array}{l} q_{k+1} = q_k + hT(q_{k+1/2})v_{k+1/2} \\ M(v_{k+1} - v_k) - hF_{k+1/2} = G^\top(q_k)p_{k+1}, \\ u_{k+1/2} = G(q_k)v_{k+1/2}, \\ p_{k+1}^\alpha = 0, \\ K^{\alpha,*} \ni \tilde{u}_{k+1/2}^\alpha \perp p_{k+1}^\alpha \in K^\alpha \end{array} \right. \quad \left. \begin{array}{l} \alpha \notin \mathcal{I}_k \\ \alpha \in \mathcal{I}_k. \end{array} \right. \quad (15)$$

with

$$\tilde{u}_{k+1/2} = \left[\begin{array}{c} u_{N,k+1/2} + \frac{1}{2}(e-1)u_{N,k} + \mu^\alpha \|u_{T,k+1/2}^\alpha\| \\ \bar{u}_{T,k+1/2} \end{array} \right] \quad (16)$$

to be consistent with Equation (14). The standard notation $x_{k+1/2} = 1/2(x_k + x_{k+1})$ is used. The set \mathcal{I}_k is the set of contacts activated at the velocity level:

$$\mathcal{I}_k = \left\{ \alpha \in I \mid g_{N,k}^\alpha + \frac{1}{2}u_{N,k}^\alpha \leq 0, \text{ and } u_{N,k}^\alpha \leq 0 \right\} \quad (17)$$

Table 1 Parameters value of the different models employed in this study

Model	d_z (cm)	v_p (cm)	μ_{cc} (-)	μ_{cs} (-)	e (-)
Reference	7.3	6.7	0.313	0.310	0.221
CS1	9.4	7.1	0.392	0.307	0.135
CS2	9.8	3.7	0.277	0.417	0.018
CS3	6.0	7.6	0.289	0.427	0.284
CS4	9.0	5.0	0.309	0.344	0.296
CS5	7.0	8.7	0.251	0.315	0.291
CS6	6.9	9.9	0.542	0.301	0.288
CS7	6.7	9.0	0.253	0.322	0.296
CS8	8.9	3.9	0.389	0.305	0.107
CS9	5.1	9.7	0.257	0.308	0.209

Table 2 Alternative calibration strategies and origin of the calibration data.

Id.	Considered point(s)	Considered time(s)	Considered energy(ies)	Numb. of calib. data
CS1	Base	Rest	520kJ	1
CS2	Top	Rest	520kJ	1
CS3	D	Rest	520kJ	1
CS4	Top	Max.	520kJ	1
CS5	D	Rest	1020kJ	1
CS6	D	Init. + max. + rest	520kJ	3
CS7	D	Rest	520 + 1020kJ	2
CS8	Base + D	Rest	520kJ	2
CS9	Base + D	Rest	1020kJ	2

Table 3 Model parameters with their respective ranges

Param.	Range	Distribution	Unit
Translational velocity (v)	10 - 25	Gaussian	m/s
Rotational velocity (Ω)	0.0 - 5.6	Uniform	rot/s
Impact pos. - along length (y)	0.0 - -3.53	Uniform	m
Impact pos. - along wall height (z)	0.55 - 2.10	Uniform	m
Impact inclination (α)	-60 - +60	Uniform	°
Impact deviation (β)	-45 - +45	Gaussian	°

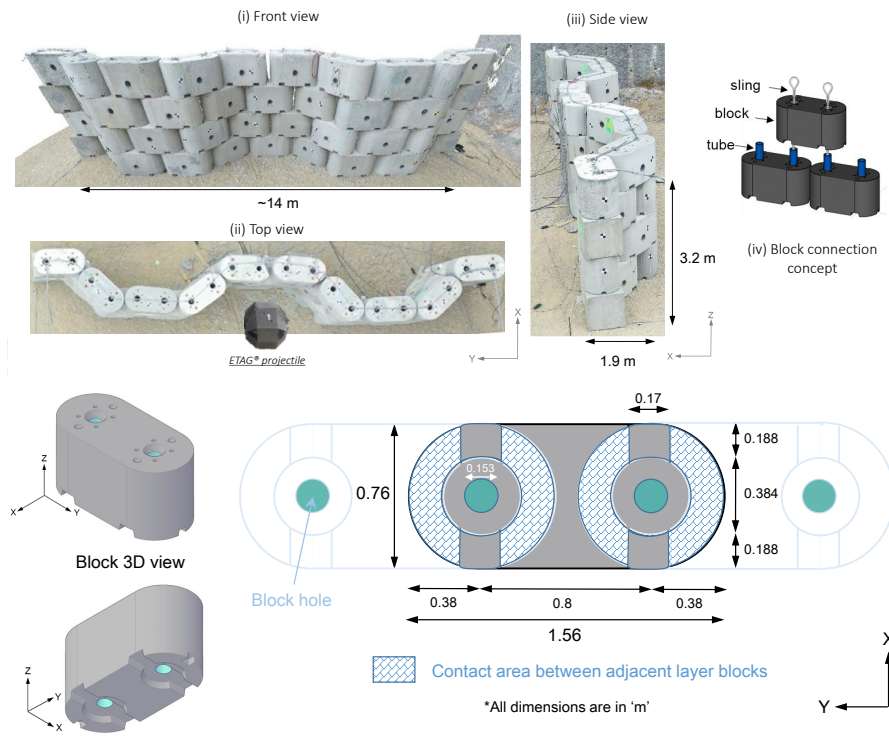


Fig. 1 (a) Experimental full-scale structure and (b) concrete block geometry and dimensions

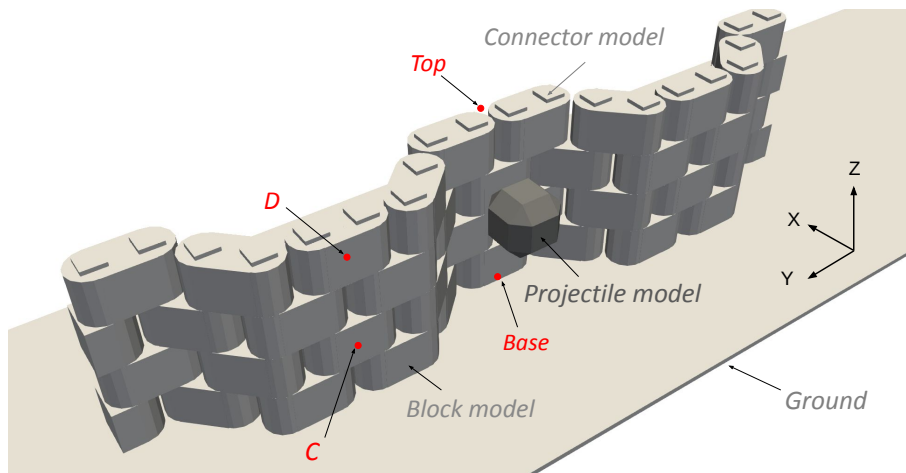


Fig. 2 The NSCD model of the articulated structure and its components, taken from (Gupta et al, 2023). Location of points where data were collected during the real-scale experiments ('Base', 'Top', 'C' and 'D').

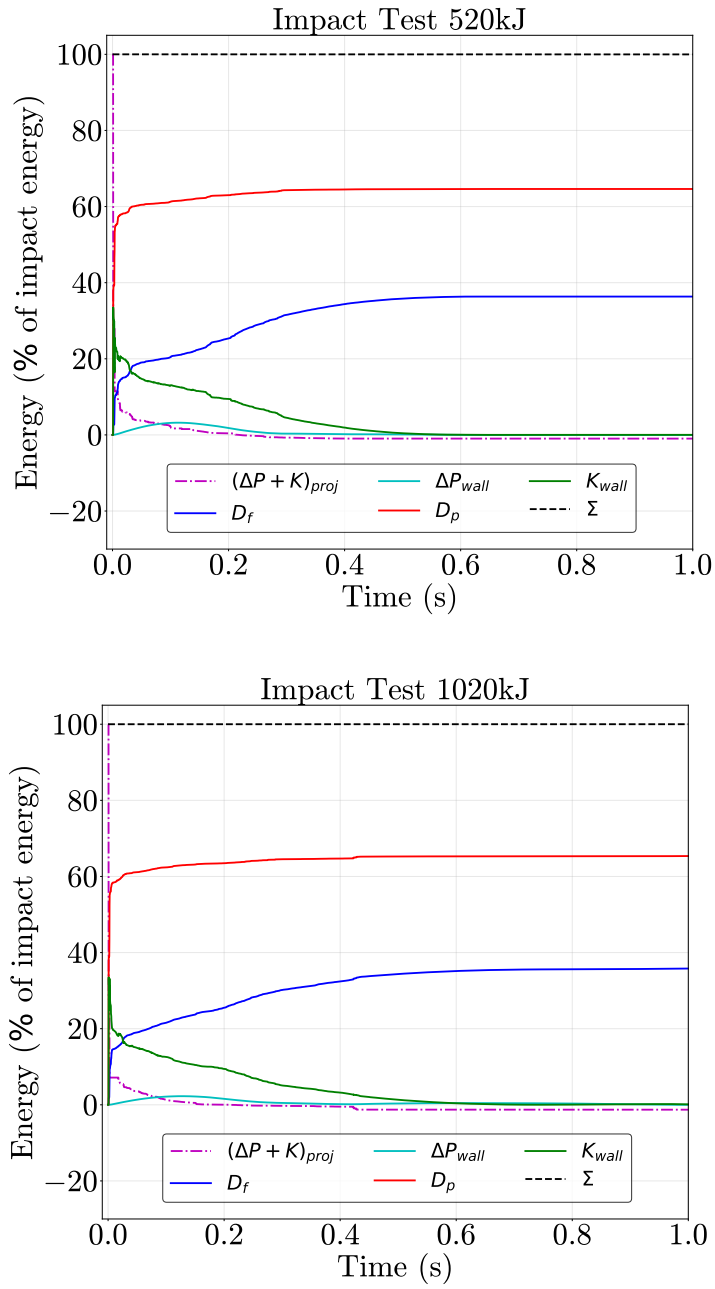


Fig. 3 Energy in the system obtained from the simulation of the structure response to 520- and 1020kJ-energy impacts.

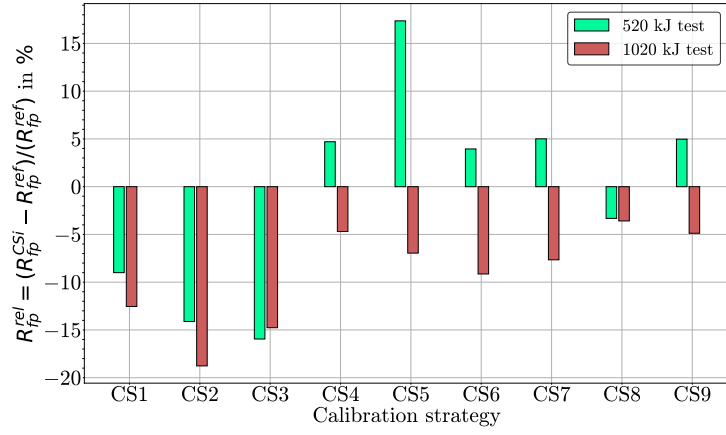


Fig. 4 Relative difference in the ratio of energy dissipated by friction to energy dissipated by plastic strain obtained with the models calibrated against the various strategies listed in Table 2 with respect to the ratio value obtained with the reference model.

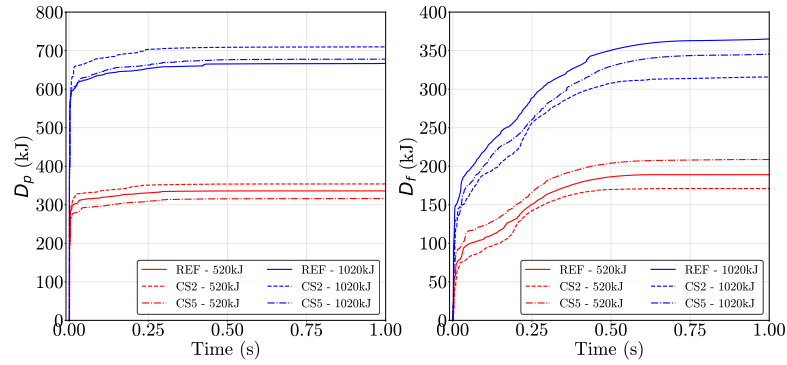


Fig. 5 Energy dissipated in the wall based on simulation results with models calibrated following strategies CS2 and CS5 compared with the reference model: energy dissipated by plastic strain, D_p (left) and energy dissipated by friction, D_f (right).

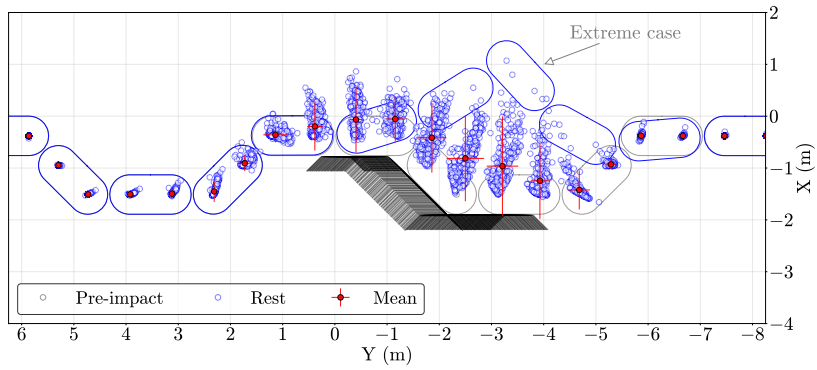


Fig. 6 Displacement at the top of the wall after impacts under different conditions. The dark area shows the range of the impact point location. Axis are defined in Figure 2.

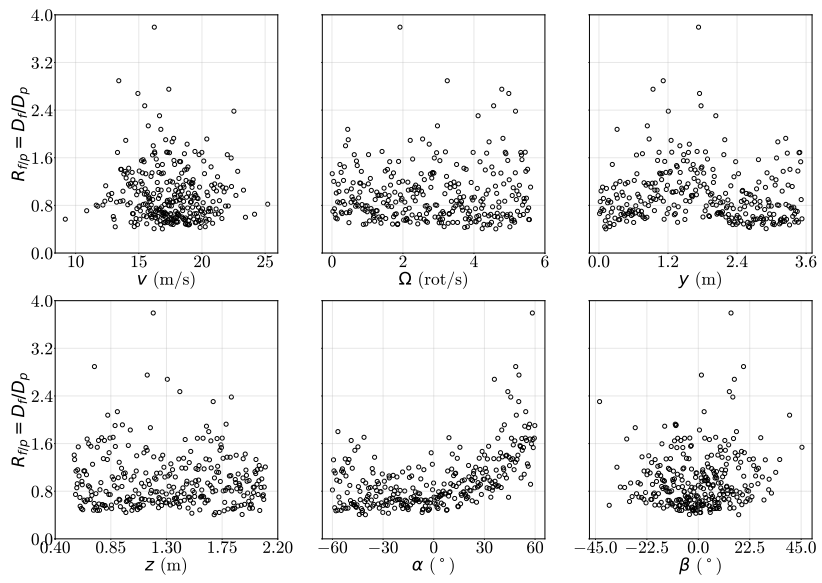


Fig. 7 Dissipation ratio ($R_{f/p}$) vs. each of the six parameters describing the impact conditions for all 300 simulations.

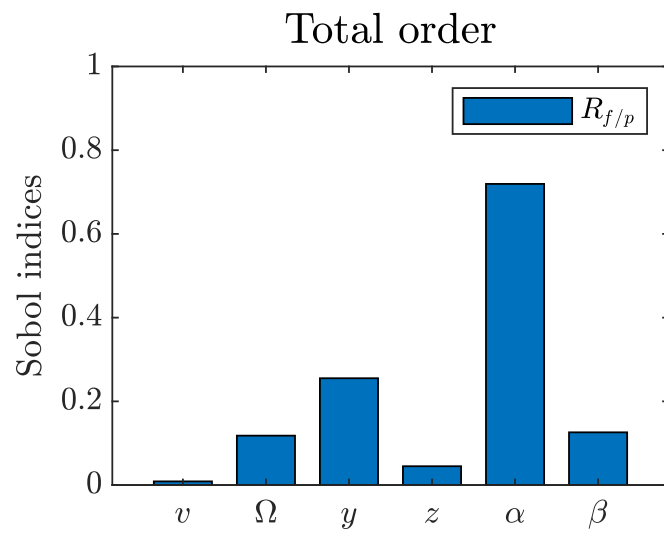


Fig. 8 Total Sobol indices for the dissipation ratio.

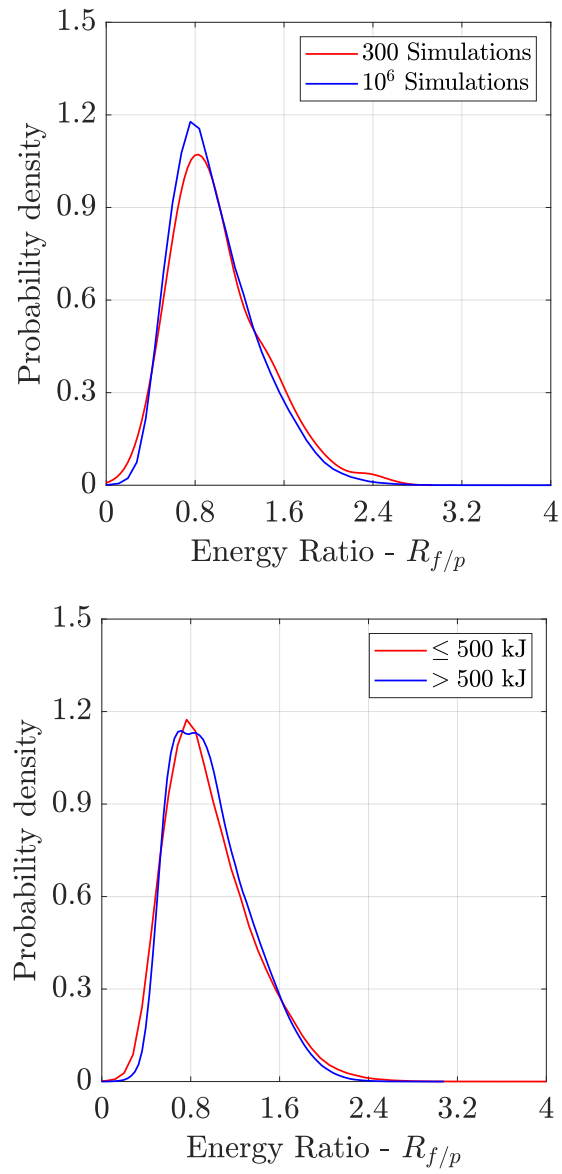


Fig. 9 Distribution of $R_{f/p}$ varying the impact conditions (top) for different numbers of simulations and (bottom) for different ranges of incident projectile kinetic energy.

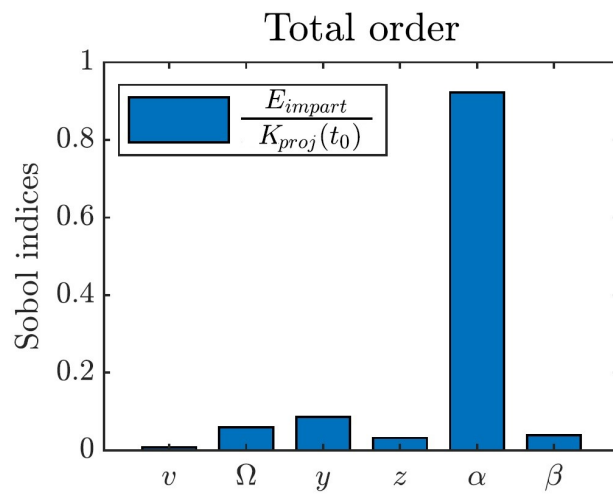
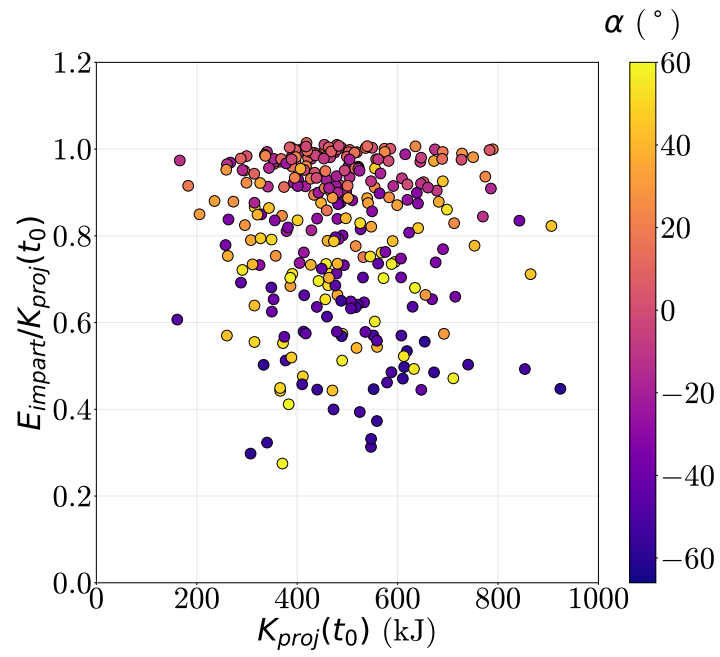


Fig. 10 Ratio of energy imparted to the wall (E_{impart}) to the projectile kinetic energy at impact (top), and the total Sobol indices of ICPs for this ratio (bottom). Computed from the 300 NSCD model simulations.

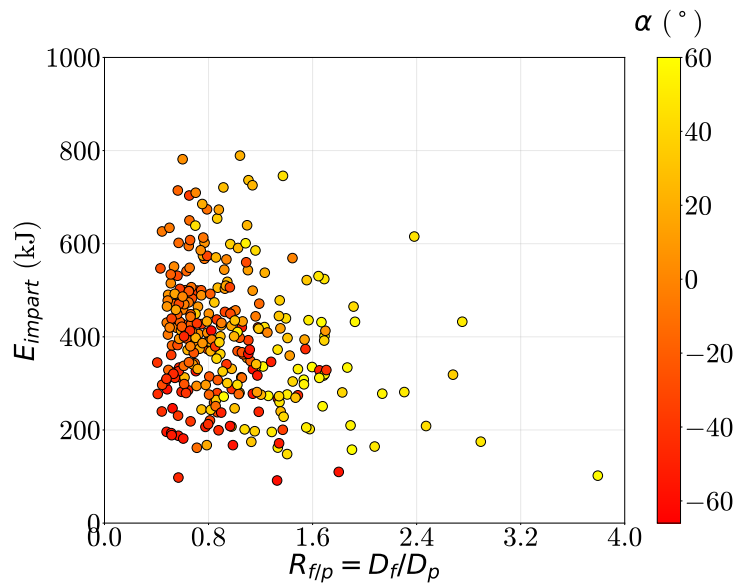


Fig. 11 Energy transferred to the wall and ratio between energy dissipated by friction and energy dissipated by plastic strain ($R_{f/p}$). Results from the set of 300 simulations varying the impact conditions.