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Bruna Garcia, Tarik Oussalah, Jean-Pierre Rajot, Anne-Sophie Colas. Space-time pressure distribution applied to a stiff concrete structure through a protective sand layer from full-scale experimental rock fall tests. *Journal of Geotechnical and Geoenvironmental Engineering*, 2024, 150 (4), 10.1061/JGGEFK.GTENG-11787 . hal-04419989

HAL Id: hal-04419989

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Submitted on 2 Feb 2024

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1 **SPACE-TIME PRESSURE DISTRIBUTION APPLIED TO A STIFF**
2 **CONCRETE STRUCTURE THROUGH A PROTECTIVE SAND LAYER**
3 **FROM FULL-SCALE EXPERIMENTAL ROCK FALL TESTS**

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7 **Abstract**

8 This study focuses on the characterization of low-velocity (lower than 100 km/h) rockfall impact
9 loads transferring to a thick steel-reinforced concrete (SRC) slab through a protective sand layer. A
10 full-scale experimental tests campaign was performed, each test consisting in releasing a concrete
11 block which, after a vertical free-fall, impacts a sand protective layer placed over a SRC slab, in
12 order to represent an isolated rockfall impact to which an actual SRC structure could be exposed.
13 During the impact, the vertical pressure distribution was observed using several pressure cells in-
14 stalled at the sand-slab interface. A total of 35 tests were carried out, systematically combining sand
15 layer thickness (D), block's equivalent diameter (B), and free-fall drop height (H), related to impact
16 velocity. The masses of the released blocks were in the range of 117 to 7399 kg, corresponding to
17 diameters in the range of 0.42 to 1.79 m. Five free-fall drop heights, up to 33 m, were considered,
18 to reach impact velocities up to 90 km/h, covering the range of most velocities observed in actual
19 rockfall studies. Three thicknesses of the sand layer protecting the thick SRC slab were considered:
20 1, 1.5 or 2 m. Data reduction from this full-scale impact tests program makes it possible to char-
21 acterize, for a given thickness of protective sand layer, the time-space pressure pulse distribution
22 applied to the protected structure during the impact for a large range of rock boulder masses and
23 speeds actually observed in the field.

INTRODUCTION

Among the possible rockfall protections, various types of steel meshes devices have been developed to mitigate rockfalls of low to medium impact energy (1 to 10 MJ). Rockfall shed galleries (Figure 1) or, when adapted to the site profile, reinforced soil bunds are being used for medium to large energy levels. To improve the durability and maintenance of these structures, which are often critical for infrastructure operation and rescue organization, granular soil layers may be placed on the roof of rock-shed galleries, tunnel heads or other structural elements possibly exposed to direct hit from a falling rock boulder.

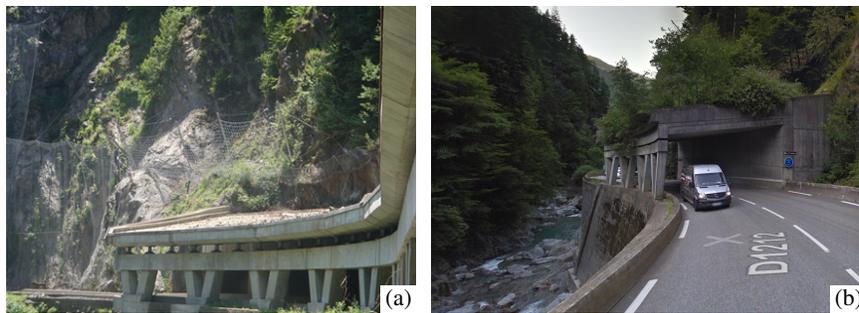


Fig. 1. Example of a rock shed gallery in Val d'Arly (Ugine, French Alps).

Granular soils are often available and their performance to protect structures from rockfall impacts, although not yet fully quantified, has been demonstrated for ages. Without a protective granular soil layer, the collision with the rock boulder produces significant damages to the steel reinforced concrete structure to dissipate a large amount of energy within a very short period of time (Durville et al. 2010). When a soil layer is protecting the structure, large deformations and displacements occur in the soil during the impact, which dissipates part of the energy. The impact load is then transmitted to a wider surface of the structure and is applied more progressively and during a longer period, resulting in a lower damage to the structure.

In fact, analysis of the dynamic penetration of a rock boulder in soils, eventually with subsequent soil-structure interaction during penetration, raises several major issues for predictive numerical modeling. As a consequence, many authors rather developed experimental approaches to investigate the physical phenomena and propose empirical relationships. In the literature, a significant number

44 of reduced-scale tests have been performed to investigate the influence of several factors, such as
45 block's mass, block's shape, impact velocity, angle of impact, protective soil grain size distribution,
46 relative density, thickness of the layer, etc. The majority of analytical or empirical expressions
47 derived from these tests give an estimate of the maximum impact force at the top of the protective
48 soil layer, but not to the force transmitted to the structure at the soil-slab interface.

49 Based on their reduced scale tests, some authors ([Yoshida et al. 1988](#); [Montani Stoffel 1998](#);
50 [Heidenreich 2004](#); [Calveti and Di Prisco 2012](#); [Schellenberg 2008](#)) proposed empirical relation-
51 ships to estimate the maximum value of the impact force and the block's penetration depth. They
52 also considered the maximum value of the forces transmitted to the protected structure and to its
53 foundation, which may differ from each other due to structural dynamic effects during impact.
54 Other research results on dynamic structural design remain confidential, due to private-company
55 led research or to their potential military use.

56 Two of the most important design guidelines for rockfall protective soil layers are the Japanese
57 Rockfall Countermeasures Handbook ([Japan Road Association 2000](#)) and the Swiss Technical
58 Guide ([ASTRA – Swiss Federal Transportation Office 2008](#)). Based on the empirical relationships
59 for the maximum value of the impact force and for the block penetration depth, these guidelines
60 suggest recommendations to define the equivalent pressure distribution transferred through the pro-
61 tective layer to be considered in quasi-static design analysis of the structure. These guidelines also
62 include requirements on the layer thickness to prevent the rock boulder from reaching the structure
63 during an impact.

64 Still, several authors ([Bhatti 2015](#); [Pichler et al. 2005](#); [Labiouse et al. 1996](#); [Schellenberg 2008](#);
65 [Calveti and Vecchiotti 2005](#); [Kishi et al. 2002](#)) pointed out the lack of full-scale tests to extrap-
66 olate these empirical expressions to actual rock block sizes and impact energies of the order of
67 those observed in the field. In fact, in dynamics, inertia forces involve both the space-scale and
68 the time-scale, which therefore does not allow to define an unique similarity relationship between
69 reduced-scale tests and the full-scale impacts in the field. Furthermore, for dynamic mechanical
70 analysis of the protected structure, not only an equivalent quasi-static maximum value of the load

71 transferred to the structure through the soil layer is needed, but the time-rate and duration of the
72 loading, as well as its spatial distribution, are of crucial importance because the inertia of the struc-
73 ture has a significant influence on the stress values actually applied to its constitutive materials
74 during impact. The main objective of the present study is to propose a method to characterize
75 the space-time pressure pulse distribution applied to a structure protected by a sand cushion layer
76 during an impact from a rock boulder. This distribution may be directly used by the structural
77 engineer for the dynamic design of the structure. For that purpose, an extensive full-scale exper-
78 imental parametric study was performed to characterize how impact loads of low-velocity (lower
79 than 100 km/h), from boulders of various sizes, are transmitted through a protective sand layer of
80 given thickness (Oussalah 2018). In those tests, the focus was therefore on the measurement of the
81 pressure at the interface between the protective sand layer and the structure. One assumption was
82 however made concerning the choice of impact condition factors to be varied in the experimental
83 program. Among the numerous factors which may affect the pressure distribution transmitted to
84 the protected structure during impact, three impact condition factors were assumed to have the most
85 significant influence on the pressure pulse: (1) The thickness of the protective soil layer (D), (2) The
86 impacting boulder size (B), assuming a spherical block of equivalent diameter related to its mass
87 (considering an average rock density for most rocks) and (3) The impact velocity (V), considering
88 a trajectory normal to the roof of protected structure. Like for the assumed large stiffness of the
89 protected structure, a normal angle of impact was considered to produce the largest pressures at
90 the soil-structure interface compared to lower impact angle values, thus safely overestimating the
91 normal pressure pulse to be considered in the dynamic structural design. The reader interested in
92 the discussion on the main impact condition factors can refer to the first chapter of Oussalah (2018).

93 **METHODOLOGY**

94 **Experimental tests**

95 *Experimental full-scale rockfall testing facility*

96 The major equipment of the Gustave Eiffel University experimental rockfall testing station is a
97 tower crane jib installed at the top of a 70 m high vertical cliff. Loads of up to 200 kN (masses of

98 about 20 tons) can be lifted and released using an electrohydraulic hook equipped with a damping
99 device. The maximum impact velocity is about 133 km/h and the maximum impact energy of the
100 order of 13.5 MJ.

101 Finally, a precast slab, named Slab 1 in Fig. 2(a), is located on the ground level platform. Slab
102 1 is composed of steel reinforced concrete (SRC), having 60 cm thick embedded in the rock sub-
103 stratum. It is 4.5 m wide and 8 m long and was used in this study to simulate a very stiff structure
104 protected by a sand layer which would be impacted by a boulder.

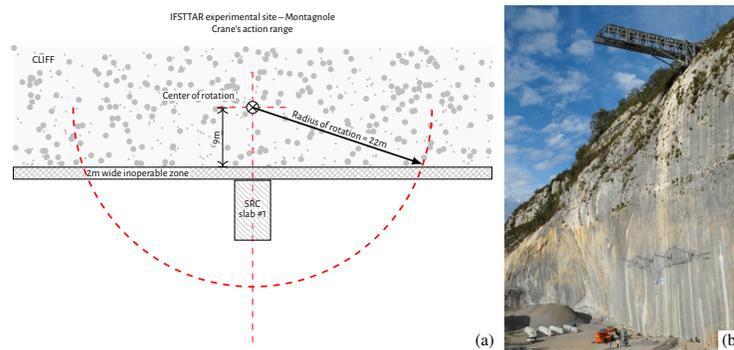


Fig. 2. Schematic plan view (a) and picture (b) of the Gustave Eiffel's full-scale rockfall experimental testing facility in Montagnole, France.

105 *Sand classification and protective soil layer construction procedure*

106 Only one type of granular protective material was considered in this experimental campaign: a
107 rolled and clean alluvial sand to guarantee that the material remains cohesionless for a long period
108 of time after its placement. Figure 3 shows the grain size distribution of the clean rolled sand used
109 in this study. Soil particle sizes range from 0 to 4 mm and the fraction passing the 80 μm sieve
110 represents 3.5% in mass.

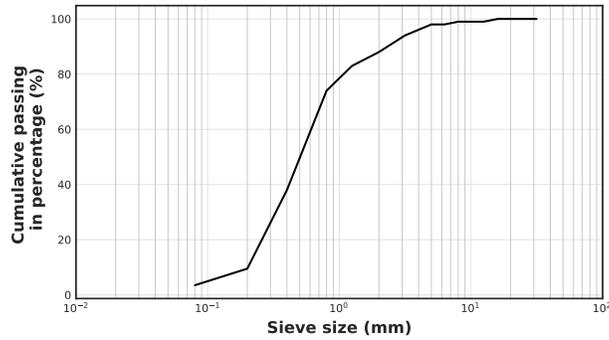


Fig. 3. Grain size distribution of the sand used in the study.

111 Figure 4 illustrates the construction of the sand cushion layer over the reinforced concrete slab.
 112 As shown in Fig. 4(a), a geotextile was first placed on the slab and surrounding ground surface. The
 113 sand cushion layer was placed in successive sub-layers, each one of 40 cm thick (b) and compacted
 114 by three passes of a vibrating plate compactor (model MVCF60 – Mikasa) at the maximum traveling
 115 speed of about 25 m/min, alternating converging and diverging spiral paths (c).



Fig. 4. (a) Soil dumping on geotextile using a backhoe; (b) Leveling of the soil sub-layers and (c) soil compaction using a vibrating plate compactor.

116 The soil's stiffness has a presumably influence on the pressure transmitted to the protected struc-
 117 ture. To reduce the scope of the parametric study to the three impact condition factors D, B and V,
 118 all the tests were performed on the sand cushion layer compacted to the same dry density of about
 119 1.53. After each test, being disturbed by the impact and penetration of the boulder, the sand was
 120 removed and the protective sand layer was constructed again, applying the same construction pro-
 121 cedure. During construction, the homogeneity of compaction was controlled with in-situ PANDA
 122 dynamic penetrometer profiles and the unit weight of the compacted sand was determined applying

123 the in-place measurement method defined in the NF P 94-061-4 standard.

124 *Instrumentation*

125 Instrumentation included two high-speed cameras (1000 images per second), a triaxial ac-
126 celerometer attached to the impacting block and seven pressure cells installed on the upper surface
127 of the horizontal SRC slab, before placing the sand layer. measurements were synchronized and
128 recorded at an acquisition frequency of 10 kHz.

129 Figure 5(a) shows one of the pressure cells used in the experimental tests (Model 3515-1 from
130 GEOKON). Strain gauge sensors are well suited for the high frequency data acquisition required in
131 this study. Depending on the cell model type, the measured pressure may range from 0 to 1.5, 3 or
132 6 MPa, with an accuracy of 0.25% of the full scale range.

133 The seven pressure cells were installed forming an “L” shape at the slab’s upper face (see Fig-
134 ure 5(b) and Figure 7). They were sealed to the slab with quick-setting cement and covered with a
135 plastic film to protect them from water infiltration during the in-situ testing period. The right angle
136 of this “L”, at the center of the slab, was the targeted impact point. The impact test conditions be-
137 ing axisymmetric, the “L” shape was devised to check for possible side effects and introduce some
138 redundancy in the data.

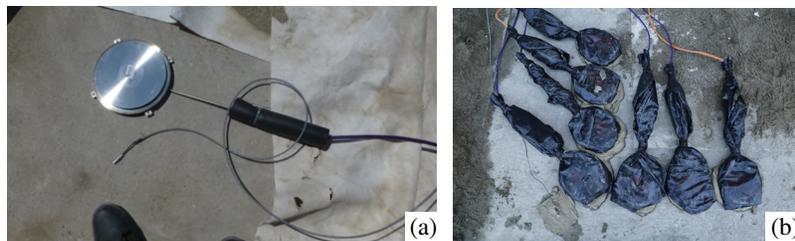


Fig. 5. Granular soil pressure cell (a), installed in an “L” shape on the slab’s upper face (b).

139 *Full-scale testing program*

140 Table 1 describes the referencing system used to identify each of the three varied impact con-
141 ditions factors D, B and V (related to the free fall height of the boulder (H)). An index from 1 to 5
142 was used to designate in each test the layer thickness, the boulder size and the impact velocity. For
143 example, test D2B2H3C2 corresponds to the test where the layer thickness D is equal to 1.5 m, the

144 equivalent block diameter B is 0.73 m and drop height is 10 meters (impact velocity (V) of 50.4
 145 km/h). C2 refers to the layer compaction procedure, the same for all the tests. Figure 6 shows the

Table 1. Tests referencing for the different impact conditions factors values.

| Index | Sand cushion layer thickness D (m) | Boulder diameter B (m) | Free-fall height H (m) | Impact speed V (m/s) | Impact speed V (km/h) |
|-------|---------------------------------------|---------------------------|---------------------------|-------------------------|--------------------------|
| 1 | 1 | 0.42 | 1 | 4.43 | 16.0 |
| 2 | 1.5 | 0.73 | 5 | 9.90 | 35.6 |
| 3 | 2 | 0.73 | 10 | 14.00 | 50.4 |
| 4 | – | 1.54 | 20 | 19.81 | 71.3 |
| 5 | – | 1.78 | 33 | 25.45 | 91.6 |

146 five different impacting blocks used in the tests. The first two blocks are spherical, composed of a
 147 steel shell filled with concrete. The three other blocks, with a rhombicuboctahedral shape, are made
 148 of steel fiber-reinforced concrete. They were conventionally designed for the full-scale rockfall tests
 required for the European Certification of Rockfall Protection Kits. Table 2 gives the characteristic

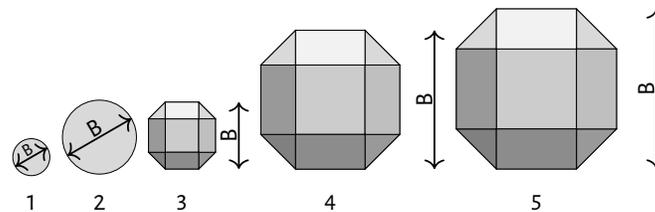


Fig. 6. Characteristic dimension of impacting blocks referenced from 1 to 5.

149 properties of each block. In order to represent a similarity to real impacting boulders, the unit mass
 150 of all blocks was close to that of most rocks (2500 kg/m^3). For the last three impacting blocks, B
 151 takes the value of the equivalent sphere having exactly the same mass, by assuming an unit mass
 152 of 2500 kg/m^3 . It may be noted that the mass of Block 2, of spherical shape, is close to that of
 153 block 3, of rhombicuboctahedral shape. These two blocks were used to investigate the influence of
 154 the blocks shapes on the observed pressure pulse. In the range of protective layer thicknesses and
 155 impact velocities considered in this study, no significant influence of the block shape was identi-
 156 fied. Thus, as far as transmission of pressure pulse through a sand layer is concerned, blocks with
 157

Table 2. Impacting blocks characteristics and equivalent diameter (B)

| Block index | Unit Mass (kg/m ³) | Block Mass (kg) | Block diameter B (m) |
|-------------|-----------------------------------|--------------------|-------------------------|
| 1 | 2500 | 117 | 0.42 |
| 2 | 2500 | 553 | 0.73 |
| 3 | 2500 | 543 | 0.73 |
| 4 | 2500 | 4796 | 1.54 |
| 5 | 2500 | 7399 | 1.78 |

158 rhombicuboctahedral shape may reasonably be considered as spherical with equivalent diameter B,
159 for the range of impact condition factors considered in this study (see chapter 5 of [Oussalah \(2018\)](#),
160 page 161).

161 In Appendix I, for each of the 35 tests performed in this study, Table 3 indicates the impact
162 condition factors D, B and V according to the referencing convention.

163 *Experimental set-up*

164 Figure 7 is a schematic representation of the test's set-up and instrumentation plan. A coordinate
165 system was defined, where the origin is at the slab center, the positive x-axis in the direction of the
166 slab's largest dimension (towards the cliff), the positive y-axis in the direction of the slab's width
167 and the z-axis upwards vertical. The cross-section AA' includes the three impact test condition
168 factors D, B and H (the free-fall height, related to impact speed V) and their respective sets of
169 values in the experimental program.

170 For all sand cushion layer thicknesses, the extend of the protective fill at the ground level was
171 such that the top surface would be centered on the slab and no less than 7 m long (in the x-direction)
172 by 4 m wide (in the y-direction) to avoid possible boundary effects when the boulder hits the center
173 of the test's set-up. Axisymmetric mechanical conditions were checked comparing the pressure
174 measurements on the slab in both x and y directions.

175 In Figure 7(b) and (c), the two plan views refer to the two configurations of the seven pressure
176 cells locations (in red in the figure, numbered 11 to 17) which were used in the experimental pro-

177 gram, called “Config1” and “Config2” in the figure. In Figure 7(b), and for Config1, the spacing
 178 between the centers of two adjacent pressure cells (of diameter 23 cm) was the same in both the
 179 x and y directions, equal to 25 cm. In Config2 (Figure 7(c)), the spacing between the centers of
 180 two adjacent pressure cells was, in the direction of the fill length (x-direction), 40 cm and, in the
 181 direction of the fill width (y-direction), 50 cm.

182 The first configuration was used for the tests with the smallest cushion layer thickness ($D = 1$ m)
 183 while the second for the two larger thicknesses (1.5 or 2 m), to account for possible wider diffusion
 184 of the forces as the thickness of the sand cushion increases. The pressure cells were placed along
 185 two directions from the center of the slab to provide some redundancy in the measurements and to
 186 check the assumption of axisymmetric loading conditions. Finally, two high-speed cameras (C#1
 and C#2 in the figure) were installed in two horizontal directions.

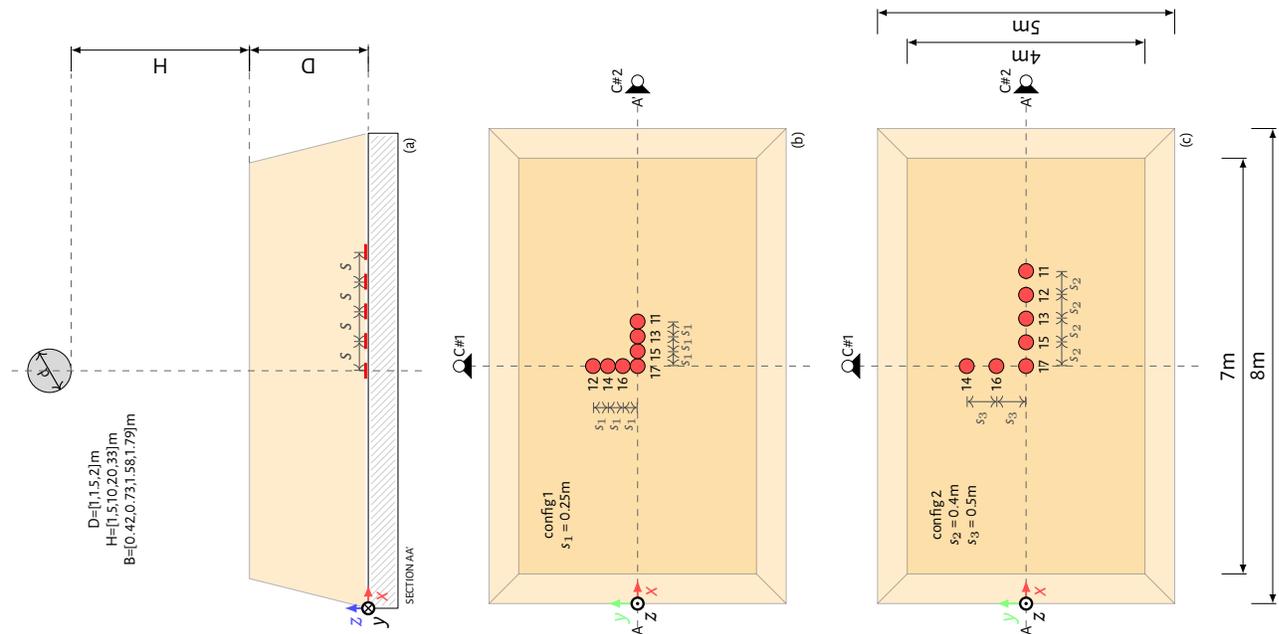


Fig. 7. Schematic representation of test setup and instrumentation plan. (a) AA' cross-section; (b) and (c) are the plan view for the two pressure cells spacing configurations (Config 1 and Config 2, respectively).

187

188 **Data reduction**

189 Corresponding to a vertical impact on a horizontal homogeneous fill protecting a concrete slab,
190 the impact test conditions were presumably axisymmetric. The pressure measurements at the top
191 of the slab were therefore analyzed in terms of time (t) and horizontal (radial) distance (r), at the
192 slab surface, from the vertical impact trajectory to the centers of the different pressure cells.

193 The block was lifted from the targeted impact point at the top surface of the fill, located just
194 above the P17 pressure cell at the right angle of the L-shaped pressure cells set-up. In fact, it
195 turned out that, due to the electrohydraulic hook dropping mechanism, during the test the actual
196 impact point observed on the high speed video recordings might be a few centimeters away from the
197 targeted impact point. In addition, although test conditions were axisymmetric by principle, a slight
198 deviation of the boulder (a few more centimeters in the horizontal direction over the penetration
199 depth) was systematically observed during its penetration in the sand fill.

200 As a consequence, for the sake of analyzing the results from a series of tests which basically
201 were axisymmetric, the location of the vertical impact trajectory was deemed to be defined by the
202 center of the boulder at the end of the test. For that purpose, the exact position of the block after
203 penetration in the sand fill was determined by triangulation using measured distances from the top
204 of the block to two referenced points sealed in the cliff. In Appendix I, Table 3 includes the values of
205 these two impact coordinates, denoted X_{impact} and Y_{impact} . Figure 8 is a schematic representation
206 of a test configuration after impact. As explained previously, in the plan view the location of the
207 free-fall impact trajectory is defined by the center of the boulder after penetration. In the horizontal
208 plane at the slab level, the radial distances of the pressure cells numbered P_{1i} , $i = 1$ to 7 , were
209 denoted $r_{(P_{1i})}$.

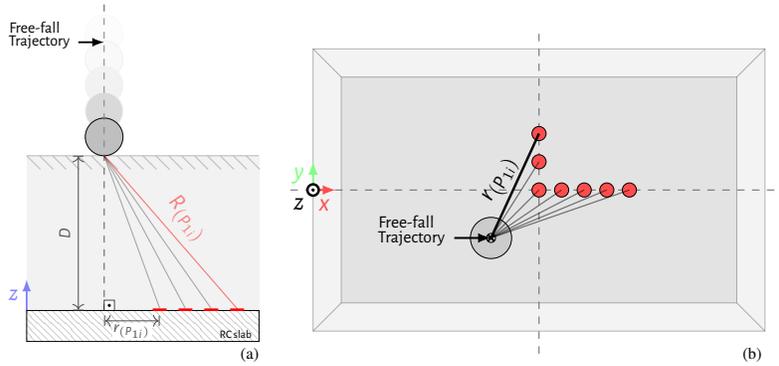


Fig. 8. Schematic representation of distances from impact trajectory to the pressure cells.

210 The beginning of an impact was considered to be the moment when the block immediately
 211 touches the protective layer. This location of the block, at the top of the layer on the vertical impact
 212 trajectory, defines the initial distance $R_{(P_{1i})}$, $i = 1$ to 7, between the boulder and the pressure cells
 213 when the impact begins. This initial distance is related to the horizontal distances between the
 214 vertical impact trajectory and pressure cells by equation 1:

$$215 \quad R_{(P_{1i})} = \sqrt{D^2 + (r_{(P_{1i})})^2} \quad (1)$$

216 Where D is the protective layer thickness.

217 RESULTS

218 Figure 9 illustrates typical “induced pressure” versus time curves observed at the top of the
 219 SRC slab during an impact test. The term “induced pressure” designates the increment of pressure
 220 through the sand layer caused by the impact at the top of the layer, *i.e.* the total pressure observed
 221 in the pressure cells minus the sand layer’s self-weight, a constant value that was observed in the
 222 pressure cells before performing the tests. This way, the value of induced pressure is initially equal
 223 to zero and, after a certain duration, it returns to zero again.

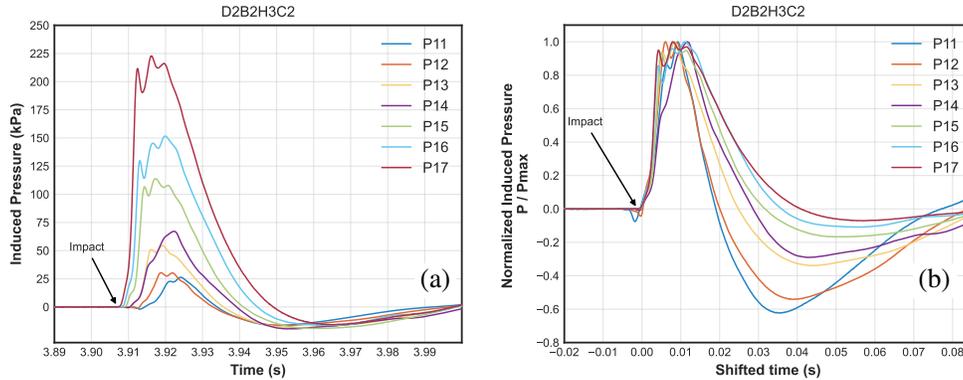


Fig. 9. Analysis of pressure cell measurements in test D2B2H3C2: (a) Induced pressure vs. time curves (a) and (b) Normalized induced pressure vs. shifted time.

224 As mentioned in the preceding, there was an offset between the targeted point at the surface
 225 of the sand layer (located above pressure cell P17) and the final position of the block. In this test
 226 (D2B2H3C2), the offset, presented in a plan view in a subsequent figure, was such that P17 was
 227 the pressure cell closest to the impact trajectory, leading to the maximum observed value of peak
 228 induced pressure in Figure 9 (a). P15 and P16 (see Figure 7 for the pressure cells numbering in the
 229 experimental setup) were located at about the same distance from the trajectory, some 50 cm farther,
 230 thus being subjected to similar but lower values of peak induced pressure. The typical results from
 231 Figure 9 (a) illustrate four aspects of the observed behavior, which will help to understand the data
 232 reduction procedure presented in the following. First, the moment where the pressure begins to rise
 233 in a pressure cell increases within the distance of the cell to the impact trajectory (in the figure,
 234 the lower the peak, the larger the distance). Second, the rate at which the pressure rises is lower
 235 for the more distant sensors. Third, in the graphs, local oscillations may be noted in the pressure
 236 measurements for all the cells. These local “high frequency” variations on the curves, of a few
 237 milliseconds period duration, were attributed to the natural vibration frequency of the pressure
 238 cells, which are protected from punching by two thick steel disks of 23 cm diameter (the first mode
 239 natural vibration frequency of a square steel plate of 20 cm long and 2.5 cm thick is about 500 Hz,
 240 *i.e.* 2 ms duration). Fourth, after a certain duration, the induced pressure may become negative
 241 before returning progressively to zero. In the D2B2H3C2 test, the sand layer thickness was 1.5 m.

242 The self-weight of the layer was of the order of 25 kPa. Therefore, the pressure applied at the top
243 of the slab decreased due to the cushion layer's self-weight but remained positive (in compression).
244 This phenomenon was related to the dynamic deflection of the slab, delayed of about 30 ms due to
245 its inertia. In all the tests, the pressure remained positive at the sand-slab interface and no effect of
246 possible subsequent vibration of the slab was observed.

247 Based on a large amount of cell pressure measurements, the purpose of the data reduction pro-
248 cedure detailed in the following is to represent, for each impact test, the space and time induced
249 pressure pulse distribution using as few characteristic properties as possible. First, the data reduc-
250 tion procedure to represent the spatial distribution at the slab's surface of the induced pressure peak
251 values is presented. Secondly, the representation of the induced pressure versus time at a specific
252 distance from the impact trajectory is considered.

253 **Spatial distribution of induced pressure peak values at the slab's surface**

254 The peak of induced pressure, at different distances from the impact trajectory, is a key aspect to
255 describe the time-space induced pressure pulse transmitted to the slab through the protective sand
256 layer. As shown in Figure 9(a) for test D2B2H3C2, a maximum value of induced pressure may be
257 observed during the impact for each pressure cell. In Figure 10(a), the maximum values of induced
258 pressure at the seven pressure cells (P11 to P17) was plotted as a function of the distance from the
259 center of the pressure cell to the impact trajectory (r_{P1i}). For test D2B2H3C2, Figure 10 (b) shows
260 the locations of the impact point and of the pressure cells setup in the XY-plane, at the top of the
261 slab. The distribution of induced pressure peak values had to be extrapolated towards the impact
262 trajectory, at a distance $r = 0$, as shown on Figure 10 (a).

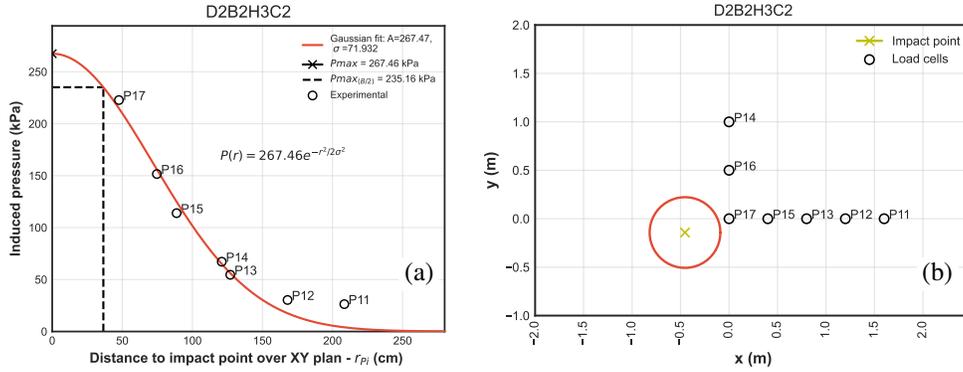


Fig. 10. (a) Induced peak pressure as a function of distance from impact point; and (b) Impact point on XY plane. (test 14, D2B2H3C2).

263 The large number of tests (35) was helpful to develop a good understanding of the shape of
 264 the induced pressure peak distribution about the impact trajectory. An axisymmetric distribution
 265 was confirmed by the measurements observed along the two lines of pressure cells, in the X and
 266 Y directions, which gave close values for cells at similar radial distances to the impact trajectory
 267 (r). The “bell-shape” of the observed peak values of induced pressure with the distance to the
 268 impact trajectory suggested to represent this spatial distribution using a normal distribution function
 269 described by Equation (2):

$$270 \quad P_{max}(r) = P_{maxx} \cdot e^{-\beta r^2} \quad (2)$$

271 In the data reduction procedure applied to each test, the two parameters in Equation 2 (P_{maxx} and
 272 β) were determined by non-linear least squares fit (Levenberg 1944; Marquardt 1963). Physically,
 273 the P_{maxx} parameter in fact is the overall maximum value of induced pressure, occurring at $r =$
 274 0, on the impact trajectory. The β parameter describes the decay of induced pressure peak values
 275 with increasing distance to the impact trajectory. Bearing in mind that the induced pressure spatial
 276 distribution might be related to the block size (thus the equivalent diameter B), it was decided to
 277 consider the peak value of induced pressure at a distance B/2 from the impact trajectory, *i.e.* right
 278 below the block’s edge in the direction of impact. The peak value of induced pressure below block’s

279 edge is thus expressed by the Equation 3:

$$280 \quad P(B/2) = P_{maxx} \cdot e^{-\beta \cdot (B/2)^2} \quad (3)$$

281 Conversely, the normal distribution decay of induced pressure peak values with the distance to the
282 impact trajectory (β) is related to the induced pressure peak value at the periphery of the block
283 throughout the following Equation 4:

$$284 \quad \beta = \frac{\ln(P_{maxx}/P_{max}(B/2))}{(B/2)^2} \quad (4)$$

285 In summary, the spatial distribution of peak values of induced pressure at the surface of the slab
286 during the impact may be represented by Equation 2. This equation is based on two physical charac-
287 teristic properties of the induced pressure pulse, P_{maxx} and β . The first one is the overall peak value
288 of induced pressure, on the impact trajectory. The second one characterizes the decay of induced
289 pressure peak values with increasing distance to the impact trajectory. This property was related
290 to the decay of induced pressure peak values from the center to the periphery of the block in the
291 direction of impact.

292 **Time distribution of the induced pressure pulse**

293 At a given distance from the impact trajectory, the induced pressure at the slab's surface during
294 an impact on the protective soil layer starts to rise at a specific moment, then rapidly increases to a
295 peak value and finally progressively returns to zero. In the following three sections, the tests results
296 are analyzed regarding these three aspects. The purpose is still to identify characteristic properties
297 which may be used to represent the time-space induced pressure pulse transmitted to the slab.

298 *Pressure pulse delay at the sand-slab surface*

299 Concerning the pressure pulse at the top of the slab during an impact, as illustrated in Fig-
300 ure 9(a), showing the induced pressure observed with the pressure cells, the time of impact does
301 not coincide with the moment when the pressure begins to rise in the pressure cells. As a matter

302 of fact, a delay is observed between the moment of impact and when pressure begins to rise in the
 303 pressure cell. It may be noted that this delay increases with the distance of the pressure cell to the
 304 impact trajectory.

305 As a consequence, the signal from each pressure cell at the beginning of impact was treated to
 306 evaluate the exact moment when the pressure begins to increase, becoming larger than the constant
 307 unit weight of the soil layer measured before impact. At each cell, the beginning of the pressure
 308 pulse was defined as the moment when the measured pressure exceeds the constant initial pressure
 309 by 2.5 times the noise of the recorded signal from the pressure cell before impact. In terms of
 310 induced pressure, which was equal to zero before the impact, this moment is when the induced
 311 pressure becomes larger than 2.5 the noise in the signal from the pressure cell before impact.

312 By reference to the propagation of mechanical waves in an elastic media, in Figure 11, the
 313 moment when pressure begins to rise in the pressure cell $P_{(1i)}$, $i = 1$ to 7 (see Figure 8), was plotted
 314 versus the distance of the pressure cell to the impact point at the top of the layer, denoted $R(P_{(1i)})$
 315 in Figure 8. Figure 11 shows that the time at which the pressure pulse begins at a pressure cell
 316 increases linearly with the distance of the pressure cell to the impact point at the top of the layer.

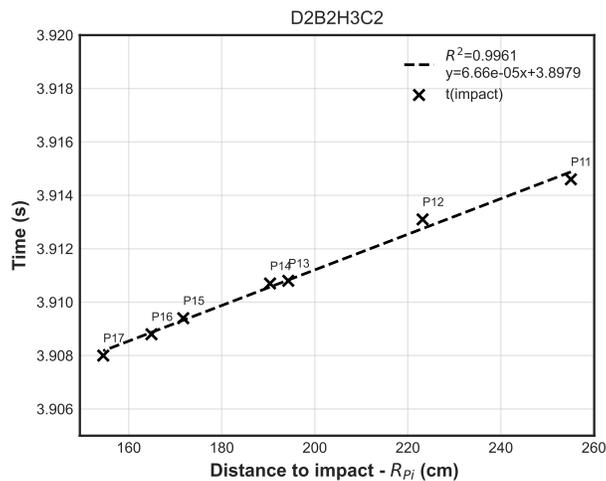


Fig. 11. Time when induced pressure pulse begins vs. distance to the impact point at the top of the protective soil layer (test D2B2H3C2).

317 The slope of this relationship may be interpreted as the stress propagation velocity through the

318 sand layer. This velocity is denoted as A_i . An important result from this study is that, in all the
 319 35 tests, the same value of the A_i velocity was found, no matter the layer thickness, block size or
 320 impact speed. For the sand compacted in all the tests to the same density (1.53), this velocity was
 321 of the order of 150 m/s. Such a value is way below the usual velocity of compression wave (V_p)
 322 from seismic refraction geophysical tests in fine dry sands, which varies from 300 to 700 m/s for
 323 loose to dense sands. In fact, the loading conditions in the sand during impact, producing plastic
 324 flow and large strains and displacements, are such that the elastic behavior assumption does not
 325 apply. However, this physical phenomenon, characterized by a constant value of the A_i velocity,
 326 independent of the impact factors D , B and V , is an useful information to represent the space-time
 327 pressure pulse at the surface of the slab during a rockfall impact. The time at which the pressure
 328 on the protected slab begins to increase at a distance r from the impact trajectory at the soil-slab's
 329 interface may be expressed by Equation 5:

$$330 \quad t_i(r) = t_i(0) + \frac{\sqrt{D^2 + r^2} - D}{A_i} \quad (5)$$

331 In which $t_i(0)$ is the “initial” moment, when the pressure at the point on the slab surface correspond-
 332 ing to the impact trajectory ($r = 0$ and $R = D$) begins to increase. During the tests, the pressure cells
 333 measurements were recorded in function of time. It may be noted that the moment corresponding
 334 to $t_i(0)$ may be defined in Figure 11 by extrapolating the linear relationship back, towards $R = D$,
 335 *i.e.* $r = 0$. This moment may be used to define a new time origin, meaning that $t_i(0) = 0$. With this
 336 convention, for the origin of time, the pressure pulse induced by the impact would begin in $r = 0$
 337 cm and at time $t = 0$ s.

338 *Induced pressure increase rate*

339 The moment at which the induced pressure reaches its peak value at a pressure cell location, at
 340 a distance r from the impact trajectory, is an important information to describe the pressure pulse
 341 caused by the impact. In fact, it governs the loading rate, which is fundamental in dynamic struc-
 342 tural design. Unfortunately, as illustrated in Figure 9 a), presenting the induced pressure observed

343 during impact in the seven pressure cells for test D2B2H3C2, the moment at which the pressure
344 pulse reaches the peak value at a pressure cell location cannot be accurately determined due to local
345 oscillations. In an attempt to estimate whether the time to peak pressure depends on the distance
346 to the impact trajectory, it was decided to plot the “normalized” induced pressure, *i.e.* the induced
347 pressure divided by its maximum value during the impact. In addition, to properly compare the
348 pressure increase duration at each pressure cell, for each normalized induced pressure curve, the
349 value of time was shifted by $t_i(r)$, the delay between the impact time and the moment where the
350 pressure begins to rise at the pressure cell. Figure 9 shows, for the test D2B2H3C2, (a) the observed
351 induced pressure versus time at the different pressure cell locations and (b) the corresponding nor-
352 malized induced pressure versus time shifted by $t_i(r)$. The larger negative values of normalized
353 induced pressure, up to -0.6 at P11 pressure cell, correspond to the farthest pressure cells, where
354 the peak values of induced pressure are the lowest, of the order of the unit weight of the protective
355 fill. As explained earlier, the negative values of induced pressure is related to the dynamic deflec-
356 tion of the thick SRC slab. From Figure 9, it clearly appears that, during pressure increase, the
357 normalized induced pressure versus shifted time curves overlap. The same physical phenomenon
358 was systematically observed in all the 35 tests: the rate of increase of normalized induced pres-
359 sure is therefore independent to the distance to the impact trajectory (r). This important physical
360 phenomenon means that the expression for the pressure on the slab induced by an impact is of the
361 general following form described by Equations 6, 7 and 8:

362 For $t \leq t_i(r)$:

$$363 \quad P(r, t) = 0 \quad (6)$$

364 For $t_i(r) \leq t < t_{max}(r)$:

$$365 \quad P(r, t) = P_{max}(r) \cdot f(t - t_i(r)) \quad (7)$$

366 and for $t \geq t_{max}(r)$:

$$367 \quad P(r, t) = P_{max}(r) \cdot g(r, t - t_{max}) \quad (8)$$

368 In which $t_{max}(r)$ is the time where the induced pressure reaches its maximum value at a distance

369 r from the impact trajectory. $P_{max}(r)$, the maximum value of induced pressure at a distance r from
370 the impact trajectory, was expressed in Equation 2 in terms of two characteristic properties of the
371 pulse of induced pressure, P_{max} (the overall maximum induced pressure, on the impact trajectory)
372 and β (defining the normal distribution of induced pressure peak values with distance to the impact
373 trajectory). While the induced pressure increases to its peak value (Equation 7), the normalized
374 induced pressure is only a function of time (function f in Equation 7). However, while the pressure
375 decreases, the normalized induced pressure is a function of both time and distance to the impact
376 trajectory (function g in Equation 8).

377 Unfortunately, it may also be pointed out from Figure 9 that, due to the local oscillations in the
378 pressure cells measurements, such a representation of the test's results does not help to determine
379 the time at which the peak of pressure occurs at the different pressure cell locations. As a con-
380 sequence, to represent the induced pressure pulse prior to its peak value at a distance r from the
381 impact trajectory (i.e. to define the f function in Equation 7), the most reliable approach was to
382 consider the time-rate increase of normalized induced pressure, which is the same at any point on
383 the slab. In each test, only a few pressure cells measurements were affected by local oscillations
384 during pressure increase, like P14 in test D2B2H3C2 (see Figure 9). In the data reduction process,
385 the measurements from these pressure cells produced results which were obviously inconsistent
386 with others.

387 The time-rate increase of normalized induced pressure, prior to peak value, was therefore as-
388 sumed to be characterized by the slope of the normalized induced pressure versus shifted time curve
389 at 50% of the peak value, denoted p_{50} . As may be noticed in Figure 12, the value of this slope p_{50} ,
390 away from the start of the curve at $t - t_i$ and from the oscillations near the peak, is a reliable char-
391 acteristic property of all the curves. It is a representative property of the rate of loading on the
392 protected slab during the impact.

393 In Figure 9 (b), the shape of the curves prior to peak led to represent the normalized induced
394 pressure versus shifted time (the f function) with a parabolic relationship based on three properties
395 of the curves: (i) Its value is zero at time t_i , (ii) Slope is p_{50} when the value is 0.5 and (iii) Slope

396 is zero at the top, where the value is 1 (at the peak). Such a parabolic f function is represented in
 397 Figure 12.

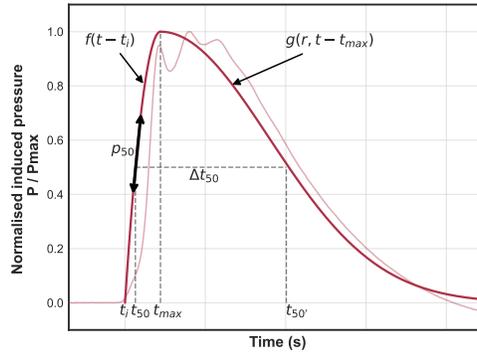


Fig. 12. Representation of the normalized induced pressure vs. time.

398 The parabolic function representing the relationship between normalized induced pressure vs.
 399 time before peak pressure is given by the following Equation 9:

$$400 \quad f(t - t_i(r)) = -\frac{(p_{50})^2}{2} \cdot (t - t_i(r))^2 + \sqrt{2} \cdot (p_{50}) \cdot (t - t_i(r)) \quad (9)$$

401 For each impact test the characteristic property p_{50} was obtained from the data reduction procedure
 402 applied to the pressure cells measurements. The value of $t_i(r)$, the time at which the pressure starts
 403 to increase at a distance r from the impact trajectory on the slab was given by Equation 5 in the
 404 preceding.

405 The previous equation may be used to calculate the time t_{max} at which the induced pressure
 406 reaches its maximum at a distance r from the impact trajectory (Equation 10):

$$407 \quad t_{max}(r) = \frac{\sqrt{2}}{p_{50}(r)} + t_i(r) \quad (10)$$

408 Similarly, the time t_{50} at which 50% of the maximum induced pressure occurs (corresponding to
 409 the point where the slope p_{50} is determined), is given by the following Equation 11:

$$410 \quad t_{50}(r) = \frac{\sqrt{2} - 1}{p_{50}} + t_i(r) \quad (11)$$

411 *Pulse duration and induced pressure unloading rate*

412 To complete the description of the pressure pulse at a distance r from the impact trajectory, the
413 decrease of normalized induced pressure versus time after the peak, *i.e.* the g function in Equation 8,
414 has to be characterized. In fact, for dynamic structural design, the unloading rate is as important as
415 the loading rate. Considering the pressure measurements, defining the duration of unloading after
416 the peak of pressure did not appear to be the most effective approach to characterize the unloading
417 rate, since the induced pressure rapidly drops after the peak and very progressively returns to zero
418 (see Figure 9(a)). Besides, the dynamic behavior of the slab impaired the measurements for the
419 larger times after impact (larger than about 30 ms after impact). In addition, as explained in the
420 preceding, the local oscillations in the pressure measurements did not allow to precisely identify
421 the time at which the induced pressure reaches its maximum at a distance r from the impact tra-
422 jectory ($t_{max}(r)$). Therefore, the most effective approach to evaluate the unloading rate appeared
423 to be relying on the time during which the pressure is greater than 50% of its peak value (or nor-
424 malized induced pressure greater than 0.5). This duration, represented in Figure 12, was denoted
425 Δt_{50} . The local oscillations in the measurements while pressure is initially rising and after peak
426 decreasing may introduce some uncertainties in the determination of Δt_{50} for some of the pressure
427 cells. However, this data reduction process turned out to produce consistent and reliable values of
428 Δt_{50} .

429 As illustrated by the graph in Figure 9(b), the duration of the normalized induced pressure pulse
430 depends on the distance to the impact trajectory. The closer to the impact trajectory (pressure cell
431 P17), the longer the pulse duration. To investigate this relationship, the values of Δt_{50} from the
432 seven pressure cells were plotted versus the distance to the impact trajectory (r). Figure 13 shows
433 this graph for test D2B2H3C2.

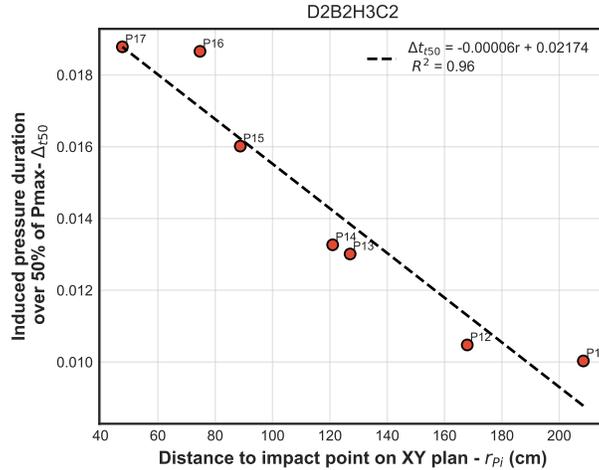


Fig. 13. Time duration on which the pressure is greater than 50% of peak value in the pressure cells at different distances to the impact trajectory (test D2B2H3C2).

Such a linear relationship was consistently observed in all the 35 impact tests. Thus the value of Δt_{50} at a distance r from the impact trajectory may be expressed as follows (Equation 12):

$$\Delta t_{50} = \Delta t_{50}(r = 0) - \frac{r}{A_{50}} \quad (12)$$

Where $\Delta t_{50}(0)$ represents the time during which the induced pressure, on the impact trajectory, remains larger than 50% of its peak value. A_{50} is the inverse value of the slope of the linear relationship of the graph in Figure 13. It has the dimension of a velocity.

For each impact test, the y-intercept $\Delta t_{50}(0)$ and the slope inverse A_{50} are two characteristic properties of the space-time pressure pulse transmitted to the structure during the impact on the protective soil layer. The results of the linear regression at the top of the graph in Figure 13 indicate that, for test D2B2H3C2, $\Delta t_{50}(0)$ was 21.74 ms and A_{50} about 165 m/s.

The shape of the normalized induced pressure curve after the peak and its progressive decrease to zero suggest to consider for the g function a Gaussian function, centered at the peak, where $t = t_{max}$. At this point, the derivatives of both expressions for the pressure pulse, before the peak (function f) and after the peak (function g), are zero. Consequently, the g function was given the following form (Equation 13):

449 For $t \geq t_{max}(r)$:

$$450 \quad g_{(r,t)} = e^{-\gamma(r) \cdot (t-t_{max}(r))^2} \quad (13)$$

451 In which $\gamma(r)$ is the normalized induced pressure decay rate beyond the peak, which depends on the
452 distance r to the impact trajectory.

453 At a distance r from the impact trajectory, the decay of normalized induced pressure beyond the
454 peak ($\gamma(r)$) is in fact related to the duration of the pressure pulse, which may be represented by the
455 duration $\Delta t_{50}(r)$. Noting that the g function in Equation 13 equals 1/2 when time is equal to $t_{50}(r)$
456 plus $\Delta t_{50}(r)$, and substituting $t_{max}(r)$ by its expression in Equation 10 and $t_{50}(r)$ in Equation 11,
457 the following expression for $\gamma(r)$ may be derived on Equation 14:

$$458 \quad \gamma(r) = \frac{\ln(2) \cdot p_{50}^2}{(p_{50} \cdot \Delta t_{50}(r) - 1)^2} \quad (14)$$

459 Where p_{50} , the rate of increase of the normalized induced pressure before peak, was defined in the
460 preceding and $\Delta t_{50}(r)$, the duration of the pressure pulse above 50% of its maximum, is given by
461 Equation 12. p_{50} is a characteristic property of the induced pressure pulse, as well as $\Delta t_{50}(0)$ and
462 A_{50} in Equation 12.

463 CONCLUSION

464 A total of 35 instrumented tests were performed, with sand layer up to 2 m thick, rock boulder
465 size up to 1.78 m (mass 7399 kg) and impact velocity up to 91 km/h. The sand layer construction
466 procedure was the same for all the tests and the sand's dry density was 1.53. The pressure transmit-
467 ted through the protective sand layer during the impact was observed using pressure cells located
468 on the structure at several distances from the impact trajectory. The analysis of tests results allowed
469 to observe several physical phenomena, which were then employed to identify characteristic prop-
470 erties defining the space-time pressure pulse at the surface of the structure induced by the impact
471 on the sand layer.

472 Physical phenomena may be observed. First, the time at which the pressure induced by the
473 impact at the surface of the structure begins to rise, denoted $t_i(r)$, increases linearly with the distance

474 to the impact point at the top of the protective layer (R), defining an “initial propagation velocity”
475 of the induced pressure. The same value of initial propagation velocity (A_i) was observed in all the
476 tests. This characteristic property was thus found independent of D, B and V. It may however pertain
477 to the sand’s grain size distribution and dry density, which were constant in all tests.

478 Second, the time-rate increase of the normalized induced pressure (the pressure divided by
479 its maximum value during impact) was observed to be independent of the distance to the impact
480 trajectory. This physical phenomenon implies that, during pressure increase, the space and time
481 variables may be separated in the expression for $p(r,t)$, as represented by Equation 7.

482 The maximum induced pressure value ($P_{max}(r)$) was represented by a Gaussian distribution,
483 centered on the impact trajectory ($r = 0$). The distribution was then defined by the two follow-
484 ing characteristic properties: the maximum induced pressure on the impact trajectory (P_{maxx}) and
485 the decay rate β , which was related the maximum induced pressure value observed at the block’s
486 periphery: $P_{max}(r = B/2)$.

487 Two functions, f and g , were defined to represent the normalized induced pressure as func-
488 tion of time, respectively during pressure increase and decrease. The function f does not depend
489 on the distance to the impact trajectory. These two functions were defined using three additional
490 characteristic properties of the normalized induced pressure pulse:

- 491 1. p_{50} : The time-rate of increase of normalized induced pressure when the pressure reaches
492 50% of its peak value, which was found to be independent of r .
- 493 2. $\Delta t_{50}(0)$: The duration of time while the induced pressure on the impact trajectory remains
494 larger than 50% of its peak value.
- 495 3. A_{50} : A velocity which describes the linear decrease of $\Delta t_{50}(r)$ with the distance to the
496 impact trajectory (r). In other words, the decrease of the duration of the normalized induced
497 pressure pulse with the distance to impact trajectory. This velocity was related to the value
498 $\Delta t_{50}(B/2)$.

499 The values of the five characteristic properties of the induced pressure pulse (P_{maxx} , β , p_{50} , $\Delta t_{50}(0)$)

500 and A_{50}) for the 35 impact tests have been gathered in Appendix I, Table 3. For each impact test
501 condition D, B and V, the induced pressure pulse at the slab surface during the impact may be
502 represented using the expressions for $P_{max}(r)$, f and g and computed with the corresponding
503 characteristic properties in Appendix I, Table 4. In practice, considering a rockfall hazard defined
504 as a block of equivalent diameter B and an impact velocity V, and assuming a protective sand
505 layer of thickness D, an approximate induced space-time pressure pulse distribution $p(r,t)$ at the
506 surface of the protected structure may already be estimated selecting the appropriate properties
507 values in Table 4. The structure subjected to such a space-time pressure pulse may then be designed
508 in dynamic conditions as explained for example by [Kappos \(2002\)](#).

509 It may be assumed that the approach presented in this study to define the space-time pressure
510 pulse distribution overestimates the actual pressure pulse for two reasons. First, the tests were
511 performed on a very stiff structure (a concrete slab 60 cm thick cast in place on a rock substratum).
512 Should a more flexible structure be considered, lower induced pressure values would have been
513 observed. Second, in this study, the impact was perpendicular to the protected structure. For a
514 lower impact angle, the induced pressure values would probably be lower, since a larger mass of
515 the soil layer would be displaced. However, it must be emphasized that this approach does not apply
516 for any block shape. For an elongated block shape, the impact on a sharp edge or the smallest side
517 will lead to deeper penetration, larger peak and narrower spatial distribution of induced pressure.

518 NOTATION

519 *The following symbols are used in this paper:*

D = Sand cushion layer thickness (m);

B = Block's diameter (m);

H = Release Height (m) ;

520 V = Impact Speed (m/s);

d = Block's characteristic dimension (m) ;

w = Steel-reinforced concrete slab thickness (m);

Appendix I. EXPERIMENTAL TEST REFERENCING

Table 3. Experimental tests referencing for given impact coordinates (x and y)

| Test (ref) | D (ref) | B (ref) | H (ref) | X_{impact} (cm) | Y_{impact} (cm) |
|------------|---------|---------|---------|-------------------|-------------------|
| 1 | 1 | 1 | 1 | -16.22 | 5.92 |
| 2 | 1 | 1 | 2 | -42.01 | 27.50 |
| 3 | 1 | 1 | 3 | -52.31 | -9.99 |
| 4 | 1 | 1 | 4 | -68.52 | -9.51 |
| 5 | 1 | 2 | 1 | -6.45 | -3.30 |
| 6 | 1 | 2 | 2 | -10.96 | 0.57 |
| 7 | 1 | 2 | 3 | -11.49 | 3.59 |
| 8 | 1 | 2 | 4 | -19.89 | 8.46 |
| 9 | 2 | 1 | 1 | -25.27 | -12.20 |
| 10 | 2 | 1 | 2 | -23.43 | -13.47 |
| 11 | 2 | 1 | 3 | -43.14 | -17.05 |
| 12 | 2 | 1 | 4 | -32.77 | -15.16 |
| 13 | 2 | 2 | 1 | -25.17 | -18.58 |
| 14 | 2 | 2 | 2 | -45.58 | -5.99 |
| 15 | 2 | 2 | 3 | -45.78 | -14.23 |
| 16 | 2 | 2 | 4 | -45.78 | -14.23 |
| 17 | 2 | 4 | 1 | -22.99 | 18.05 |
| 18 | 2 | 4 | 2 | -44.52 | 0.70 |
| 19 | 2 | 4 | 3 | -16.70 | -9.10 |
| 20 | 2 | 4 | 4 | -12.52 | -2.14 |
| 21 | 2 | 5 | 1 | -69.94 | 0.17 |
| 22 | 2 | 5 | 2 | -44.01 | 20.14 |
| 23 | 2 | 5 | 3 | -32.07 | -3.78 |
| 24 | 2 | 5 | 4 | -24.92 | -42.87 |
| 25 | 1 | 4 | 1 | -21.23 | 20.72 |
| 26 | 3 | 5 | 4 | -10.87 | -4.04 |
| 27 | 3 | 5 | 3 | -19.50 | 16.83 |
| 28 | 3 | 1 | 1 | -34.97 | 6.75 |
| 29 | 3 | 1 | 2 | -33.88 | 23.05 |
| 30 | 3 | 1 | 3 | -42.70 | 15.51 |
| 31 | 3 | 1 | 4 | -38.80 | 59.41 |
| 32 | 3 | 2 | 1 | -23.63 | 0.33 |
| 33 | 3 | 2 | 2 | -20.68 | -13.69 |
| 34 | 3 | 4 | 5 | -25.76 | 0.01 |
| 35 | 3 | 3 | 3 | -7.92 | 12.08 |

Table 4. Summary of the characteristic properties of the space-time induced pressure pulse distribution for the 35 tests.

| Test (ref) | D (cm) | B (m) | B/D | H (m) | Impact Speed (m/s) | Impact Speed (km/h) | P_{maxx} (kPa) | β | $p50$ (s^{-1}) | $\Delta t_{50}(0)$ (ms) | A_{50} (m/s) | $P_{(B/2)}$ (kPa) | $\Delta t_{50}(B/2)$ (ms) |
|------------|--------|-------|------|-------|--------------------|---------------------|------------------|-----------------------|--------------------|-------------------------|----------------|-------------------|---------------------------|
| 1 | 100 | 0.42 | 0.42 | 1 | 4.43 | 15.95 | 22.09 | 1.15×10^{-4} | 729.29 | 23.80 | 46.87 | 21.00 | 19.30 |
| 2 | 100 | 0.42 | 0.42 | 5 | 9.90 | 35.66 | 48.37 | 1.52×10^{-4} | 804.31 | 29.30 | 58.86 | 45.23 | 25.70 |
| 3 | 100 | 0.42 | 0.42 | 10 | 14.01 | 50.43 | 74.32 | 1.31×10^{-4} | 253.76 | 17.90 | 184.64 | 70.13 | 16.80 |
| 4 | 100 | 0.42 | 0.42 | 20 | 19.81 | 71.31 | 176.36 | 1.16×10^{-4} | 671.37 | 10.20 | 1130.59 | 167.58 | 10.00 |
| 5 | 100 | 0.73 | 0.73 | 1 | 4.43 | 15.95 | 77.81 | 2.62×10^{-4} | 95.12 | 37.40 | 76.83 | 54.89 | 32.60 |
| 6 | 100 | 0.73 | 0.73 | 5 | 9.90 | 35.66 | 217.17 | 1.97×10^{-4} | 480.34 | 27.90 | 91.72 | 166.93 | 23.90 |
| 7 | 100 | 0.73 | 0.73 | 10 | 14.01 | 50.43 | 348.49 | 2.05×10^{-4} | 455.38 | 22.80 | 83.87 | 265.19 | 18.40 |
| 8 | 100 | 0.73 | 0.73 | 20 | 19.81 | 71.31 | 705.07 | 1.96×10^{-4} | 741.09 | 21.30 | 83.23 | 542.91 | 16.90 |
| 9 | 150 | 0.42 | 0.28 | 1 | 4.43 | 15.95 | 8.51 | 7.04×10^{-5} | 541.78 | 23.20 | 146.15 | 8.25 | 21.80 |
| 10 | 150 | 0.42 | 0.28 | 5 | 9.90 | 35.66 | 32.28 | 5.86×10^{-5} | 752.03 | 20.40 | 119.68 | 31.46 | 18.60 |
| 11 | 150 | 0.42 | 0.28 | 10 | 14.01 | 50.43 | 46.79 | 5.12×10^{-5} | 284.74 | 19.30 | 162.84 | 45.75 | 18.00 |
| 12 | 150 | 0.42 | 0.28 | 20 | 19.81 | 71.31 | 82.86 | 6.55×10^{-5} | 274.45 | 13.40 | 318.87 | 80.50 | 12.70 |
| 13 | 150 | 0.73 | 0.49 | 1 | 4.43 | 15.95 | 39.76 | 1.06×10^{-4} | 570.87 | 38.90 | 69.11 | 34.52 | 33.60 |
| 14 | 150 | 0.73 | 0.49 | 5 | 9.90 | 35.66 | 104.26 | 7.98×10^{-5} | 364.88 | 30.70 | 97.50 | 93.74 | 26.90 |
| 15 | 150 | 0.73 | 0.49 | 10 | 14.01 | 50.43 | 267.47 | 9.66×10^{-5} | 320.71 | 21.70 | 160.79 | 235.16 | 19.50 |
| 16 | 150 | 0.73 | 0.49 | 20 | 19.81 | 71.31 | 341.45 | 7.70×10^{-5} | 574.15 | 20.30 | 153.76 | 308.17 | 17.90 |
| 17 | 150 | 1.58 | 1.05 | 1 | 4.43 | 15.95 | 288.61 | 1.42×10^{-4} | 294.51 | 53.70 | 40.06 | 118.97 | 34.00 |
| 18 | 150 | 1.58 | 1.05 | 5 | 9.90 | 35.66 | 757.12 | 1.04×10^{-4} | 743.89 | 39.60 | 111.36 | 394.95 | 32.50 |
| 19 | 150 | 1.58 | 1.05 | 10 | 14.01 | 50.43 | 944.76 | 1.04×10^{-4} | 89.63 | 36.40 | 112.24 | 492.34 | 29.40 |
| 20 | 150 | 1.58 | 1.05 | 20 | 19.81 | 71.31 | 2127.05 | 1.17×10^{-4} | 149.66 | 30.40 | 108.41 | 1021.69 | 23.10 |
| 21 | 150 | 1.79 | 1.19 | 1 | 4.43 | 15.95 | 401.00 | 9.24×10^{-5} | 106.85 | 58.70 | 52.39 | 191.32 | 41.60 |
| 22 | 150 | 1.79 | 1.19 | 5 | 9.90 | 35.66 | 1041.78 | 1.19×10^{-4} | 212.84 | 41.10 | 109.33 | 401.03 | 32.90 |
| 23 | 150 | 1.79 | 1.19 | 10 | 14.01 | 50.43 | 1203.58 | 9.19×10^{-5} | 170.08 | 45.00 | 82.61 | 576.37 | 34.20 |
| 24 | 150 | 1.79 | 1.19 | 20 | 19.81 | 71.31 | 3006.73 | 1.11×10^{-4} | 451.01 | 39.10 | 71.35 | 1236.87 | 26.50 |
| 25 | 100 | 1.58 | 1.58 | 1 | 4.43 | 15.95 | 553.83 | 2.34×10^{-4} | 318.49 | 47.80 | 47.65 | 128.81 | 31.20 |
| 26 | 200 | 1.79 | 0.90 | 20 | 19.81 | 71.31 | 1259.98 | 6.06×10^{-5} | 370.58 | 38.40 | 113.92 | 775.18 | 30.60 |
| 27 | 200 | 1.79 | 0.90 | 10 | 14.01 | 50.43 | 968.65 | 4.61×10^{-5} | 362.37 | 39.20 | 103.59 | 669.62 | 30.60 |
| 28 | 200 | 0.42 | 0.21 | 1 | 4.43 | 15.95 | 8.17 | 3.25×10^{-5} | 558.66 | 11.90 | 2575.99 | 8.06 | 12.00 |
| 29 | 200 | 0.42 | 0.21 | 5 | 9.90 | 35.66 | 28.21 | 4.11×10^{-5} | 526.32 | 15.00 | 437.80 | 27.70 | 14.50 |
| 30 | 200 | 0.42 | 0.21 | 10 | 14.01 | 50.43 | 49.84 | 4.60×10^{-5} | 284.94 | 14.10 | 491.81 | 48.84 | 13.60 |
| 31 | 200 | 0.42 | 0.21 | 20 | 19.81 | 71.31 | 74.67 | 3.75×10^{-5} | 422.05 | 12.80 | 526.68 | 73.44 | 12.40 |
| 32 | 200 | 0.73 | 0.37 | 1 | 4.43 | 15.95 | 20.53 | 3.75×10^{-5} | 159.43 | 39.30 | 72.11 | 19.53 | 34.20 |
| 33 | 200 | 0.73 | 0.37 | 5 | 9.90 | 35.66 | 86.49 | 4.89×10^{-5} | 303.21 | 20.40 | 233.79 | 81.04 | 18.90 |
| 34 | 200 | 1.58 | 0.79 | 33 | 25.45 | 91.60 | 2165.61 | 6.87×10^{-5} | 494.10 | 37.60 | 84.04 | 1410.47 | 28.20 |
| 35 | 200 | 0.73 | 0.37 | 10 | 14.01 | 50.43 | 641.00 | 6.10×10^{-5} | 140.45 | 38.00 | 90.31 | 590.98 | 34.00 |

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