Objective Comparison of Rockfall Models using Real Size Experimental Data

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Abstract

Consultancies using rockfall simulation software, as well as rockfall software developers, have been invited to use their simulation tools to predict the trajectories of 100 rocks in 2D or 3D using a digital elevation model of a site in the French Alps. These data have been compared with data obtained by real size rockfall experiments carried out the same site. Additional data provided to the participants were: the geographic location of the experimental site, the form and volume of the rocks used during the experiments and the locations of two calculation screens on the main path. Characterisation of the soil had to be done by the participants. At the calculation screens, each candidate had to calculate the mean and maximum velocity, kinetic energy and jump height of each rock. In addition, the stopping points of each rock had to be calculated. Eventually, 12 out of 17 candidates from 4 different countries sent back their results. Only 3 out of 12 were capable to simulate the same rockfall kinematics and trajectories with an error of ± 20%. Seven participants were capable to simulate the observed stopping distance with an error of ± 10%. The maximum errors were in the order of 400%. Among the commercial models involved, three of them were used by multiple participants. The outcomes of the test showed that two different users can obtain invalid or very accurate results with the same model. This indicates that the role of the expert is crucial in hazard expertises that use rockfall simulation models. Since this has been the first benchmarking test of its kind, the outcomes should be used with caution, as only one test site has been used. At another test site, results could be completely different. For natural hazard modelling in general, there is a need for accurate validation data.

Keywords: benchmarking, simulation model, natural hazard zoning

Introduction

In rockfall hazard prevention the use of rockfall trajectory simulation programs is common (Tianchi, 1983; Bozzolo and Pamini, 1986; Descoudres and Zimmermann, 1987; Pfeiffer and Bowen, 1989; van Dijke and van Westen, 1990; Azzoni et al., 1995; Stevens, 1998; Keylock and Domaas, 1999; Guzzetti et al., 2002; Dorren et al., 2006). Unfortunately, a wide range of model types exists, varying from 2D to 3D, statistical to deterministic based and all with different precision of the output (Dorren, 2003). This diversity, combined with the lack of precise information on the conditions of use of the different programs available, makes that the French users of trajectory studies have difficulties to identify the most adapted product to their needs. Therefore, we realised a benchmarking test of rockfall trajectory simulation programs (Berger et al., 2004). The realisation of such a blind test requires a set of reliable data.

The direction of risk and pollution prevention of the French ministry of Ecology and Sustainable Development decided to support this first benchmarking test. The data used for this test are coming from real-size rockfall experiments carried out by the Cemagref.

Objectives and public concerned

Two kinds of public are concerned by this benchmarking test:

- Research consultancies working in the field of rockfall hazard assessment using a trajectory simulation model.
- Project managers and all the other beneficiaries of expertises made with these models.

The interest of these groups is quite different. The first one wants, if the model has already been used for hazard assessment expertises, to guarantee its functioning or, if the model is under construction and not yet operational, to test it. The second group wishes to have information on the performance of currently existing models in a specified context of use for which real and reliable field data exist. The comparison of results

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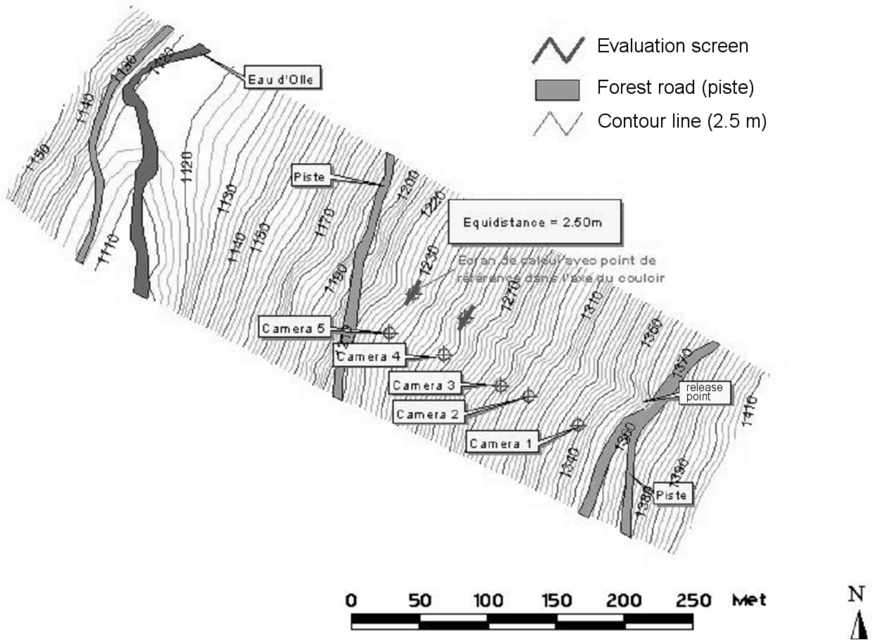

Fig. 1. Map showing the topography of the experimental site

proposed in our test has as objective to provide information to the different participants and not to provide a ranking of the results, the models used and even less to make a certification, or an agreement.

Since there is only one set of data representative for one specific site, the present test cannot, in any case, be used as a basis for a ranking of the different products. But the analysis of the results will permit to:

1. Understand the potential differences between the results coming from simulations and those measurement of real rockfall events
2. Realise a first critical analysis of a benchmarking test on trajectory models using well documented real size rockfall experiments
3. Provide the research consultancies and project managers with a first anonymous panorama on the products used and this in terms of software families and anonymous comparative information on the difference between simulation results and real data.

A future operation of model or program certification has to separate the quality of the model itself and the expertise of the model user. Both determine the accuracy of the model output. In this test we were aware of the fact that the trajectory simulation results are to a large extent determined by the operators. Therefore, this is another reason why this test cannot be used to certify or rank trajectory simulation models according to their quality or accuracy of their output.

General principle of the benchmarking test

Since 2001, the Cemagref carries out real size rockfall experiments at an experimental site, using high-speed digital video cameras to film trajectories of falling rocks that are released by a Caterpillar digger (Dorren et al., 2005). We released 100 rocks and mapped their trajectories, their deposit points and we measured their velocities as well as their passing heights. These data have been used to realise this benchmarking test.

Only the data on the location of the experimental site, its topography (in the form of a high resolution digital terrain model, as well as the contour lines with an equidistance of 2.5 m, see Fig. 1) and the characteristics of used rocks (number, volume, size, form, weight) were given to the participants (Berger et al., 2004).

The participants were supposed to characterise the soil and its energy dissipative capacity their selves (Azzoni and de Freitas, 1995; Chau et al., 2002; Dorren et al., 2004; Dorren et al., 2006). The rocks used during the experiments were all removed from their original deposit positions in order to prevent the candidates to realize retro calculations. The choice of the number of simulated rocks was left to them. After finalising the

Table 1. Values observed at the two evaluation screens.

	Rebound height (m)				Velocity (m/s)				Kinetic energy (kJ)			
	Max.	Min.	Mean	Std.	Max.	Min.	Mean	Std.	Max.	Min.	Mean	Std.
Screen 1	5,0	0,0	1,4	1,1	28,1	1,8	12,5	5,2	786,4	3,3	204,9	168,8
Screen 2	6,2	0,0	1,6	1,4	28,9	4,5	13,8	5,5	958,3	21,1	244,5	196,3
Measurement error	+/- 5%				+/- 5%				+/- 15%			

test, each participant received 1) a comparison of their own results with the real data and 2) an anonymous table showing the ranges of errors of the data simulated by all the participants.

The benchmark test consisted of 6 distinct steps:

1. Advertisement to participate at the benchmarking test
2. Application of the candidates
3. Receipt of the candidatures and transmission of the initial data to the candidates
4. Receipt of the data calculated by the participants
5. Comparison of the calculated data with the observed ones
6. Synthesising the results in a report and passing it to the participants for feedback as well as an agreement to publish the synthesised results to the ministry.

A steering committee was formed to assure a fair course of the test.

Required simulation results

The results we required from their simulations were the spatial distribution of the deposit points of all the simulated rocks and possibly the delimitation of the maximal rockfall runout area from the starting point, while explaining the extrapolation method used for delimiting this area. In this benchmarking test, this area is defines as the maximal rockfall envelope. The scale of the output map is 1: 2500. Other required data were the simulated translation velocities (m s−1), the vertical passing heights (m) and the kinetic energy (kJ) at two "evaluation screens". Evaluation screen 1 is located after 185m from the starting point, measured over the slope and evaluation screen 2 is located after 235 m. These data were compared to those obtained during the real sizes experiments. The results should be presented in a table giving the statistical distribution of the required variables (minimal value, maximal value, average value and the standard deviation), as well as a diagram showing the passing height and the velocity versus the mass of the rocks.

Comparison of simulated and real data

In total 22 candidates expressed their interest in the benchmarking test and finally 12 participants sent back their simulated results. In the following text, numbers will be used for the 12 participants to guarantee anonymity. These numbers correspond to the sequence of incoming results at our institute. Important information for interpreting the results of the test is that:

- Participant 9 and 13, participant 12 and 17 as well as participant 14 and 15 used the same commercial rockfall trajectory program.
- Participant 7, 9 and 15 used programs that they considered not to be operational.

Comparison at the two evaluation screens

Firstly, we compared the simulated data with the observed data presented in Table 1. The values observed are the values obtained with the real-size experiments. Secondly, we calculated a ratio that represents the difference between the simulated and observed value (Table 2). This ratio corresponds to: simulated value * 100 / observed value. A ratio higher than 100% represents overestimation, while a value lower than 100% represents underestimation.

Table 2. Comparison between observed and simulated values expressed in ratios

	Ratio Vmax Screen1	Ratio Vmax Screen 2	Ratio Hmax Screen 1	Ratio Hmax Screen 2	Ratio Emax Screen 1	Ratio Emax Screen 2
Part. 1	103	92	135	143	91	101
Part. 2	102	97	63	109	n.a.	n.a.
Part. 4	49	36	91	70	12	14
Part. 7	138	124	535	732	n.a.	n.a.
Part. 8	57	56	56	65	37	34
Part. 9	39	32	0	0	18	15
Part. 11	72	73	42	54	74	78
Part. 12	37	24	4	6	8	16
Part. 13	69	63	38	37	73	72
Part. 14	78	77	79	69	87	79
Part. 15	183	172	101	109	472	513
Part. 17	90	81	117	113	87	96

Comparison of the simulated trajectories

Fig. 2 presents a map with the deposit points of the 100 rocks. Basically, three main propagation axes were observed, which are presented in Fig. 3. Rock 41 (Dimensions : $120 \times 100 \times 70$ cm, 0,84 m^3, being 2350 kg) travelled the longest distance from the starting point: planimetric distance travelled was 391.20 m. It descended from 1365 m to 1119.85 m.

Regarding the stopping points the candidates expressed their results according to the altitudes or coordinates representative of a significant change of the propagation of the simulated rocks. The presentation of the data provided by the participants differed strongly from one candidate to another. Some participants gave theirs result even only on paper graphs. Therefore, to be able to compare the stopping points calculated by the candidates with those observed in reality, we presented our results and those of the candidates by altitude classes. We calculated the percentage of rocks reaching an altitude class. This calculation represents the first stage in the analysis of these data. The second stage consisted in expressing the altitude classes of in X-coordinates, in order to present the percentage of blocks reaching a given X-coordinate on the topographic profile. For that, we decided to calculate the planimetric travelled distances by projecting the stopping points on the propagation axis 2 in Fig. 3. This profile corresponds to the one that was mainly used by the candidates. From those data we could calculate and compare the distance classes of the stopping points (Table 3).

Discussion and conclusions

Regarding the degree of participation (12 participants from 4 countries) this first rockfall trajectory simulation program benchmarking test using data from real-size rockfall experiments can be considered as a success. It is important to repeat once more that the results of this test are only valid for the topographical conditions at our experimental site and the conditions of the terrain at the time of carrying out the experiments.

The steering committee of the test has decided, looking at the measurement error of the kinetic energy (+/− 15%), to fix the criteria of acceptance for the simulated values to correspond to the observed values as being those values with a ratio between 80% and 120%.

Table 4 presents the simulated results expressed in ratio differences. These values are calculated as follows: ratio difference = 100% — ratio of the participant (ratio between the simulated and observed value). The calculated values that are considered to correspond with observed values are those within the interval [−20%, 20%]. The negative values represent a n underestimation, the positive values an overestimation. To facilitate the reading of this table, we presented the results in decreasing order of the number of times a value did not fall in the interval [−20%, 20%]. This table does not represent a classification or ranking of the participants. It only provides information on how well the model performed at our experimental site.

According to this table, the general conclusions of this benchmarking test are (Berger et al., 2004):

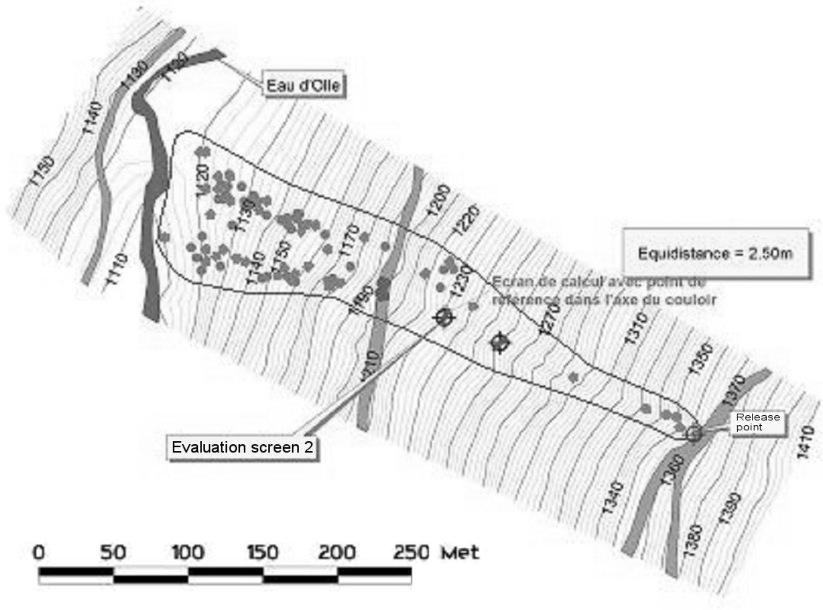

Fig. 2. Map showing the stopping points of the 100 released rocks.

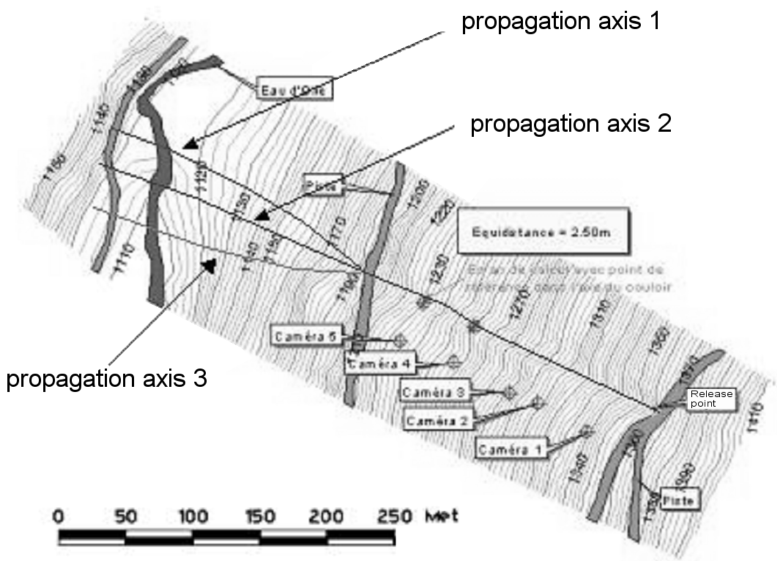

Fig. 3. Map showing the three general rockfall propagation axes.

- Concerning the calculation of rockfall kinematics: the results vary significantly. There is a global tendency to underestimate the passing height, the translational velocity and the translational kinetic energy. Regarding a rockfall protection scenario, i.e. using the data for dimensioning protective structures, only 3 participants out of the 12 have results that correspond to the experimental data (+/− 20%).
- Concerning the propagation calculation: 7 participants out of the 12 have obtained stopping distance corresponding at least to the observed one. Taking into account the protection scenario, these participants are able to propose a zoning including at least the maximal stopping distance observed.
- If we combine the kinematics and propagation calculations (disregarding the participant 2 for whom we don't have results on the energy), it appears that:
  - The participants who obtained a stopping distance in adequacy with the observed one (reaching but not over-passing the distance class of 385–400 m), have kinematic results that differ from the

Table 3. Results obtained by the participants regarding the maximal stopping point.

	Observed value		Part. 2	Part. 4	Part. 7	Part. 8	Part. 9	Part. 11	Part. 12	Part. 13	Part. 14	Part. 15	Part. 17
Max. reached distance	390		385	360	355	395	355	365	395	275	390	400	430
Simulated ñ observed distance	0		-5	-30	-35	5	-35	-25	5	-115	0	10	40
Distance Ratio (simulated/ observed	100%		99%	92%	91%	101%	91%	94%	101%	71%	100%	103%	110%
Probability of reaching 385-400 m (%)	4				0	7	0	0	20	0	2	100	11
Probability of depassing 385-400 m (%)	0	1				0			0		0	0	7
Probability ratio (simulated/ observed)	100%				0%	175%	0%	0%	500%	0%	50%	2500%	275%

ones observed. This accounts for 5 participants out of the 12.

– The opposite, i.e. propagation result different than the one observed and adequate kinematics is not verified.

  ∗ Only, the participants having obtained a stopping distance longer than the one observed, have kinematics results that correspond most to the observed ones. This accounts for 2 participants out of the 12.

  ∗ The participants having obtained a stopping distance shorter than the one observed (5 participants out of the 12), under-estimated the rockfall kinematics.

- Only 1 participant obtained results within the accuracy interval of −20%–20%, for the 6 kinematics parameters.
- The participants using the same commercial software obtain very different results. Consequently, we conclude that "human" expertise of the user/operator plays a substantial role.

For the 12 candidates, it showed that the trajectographic assessment performed within this test is most accurate for the calculation of the rockfall runout zone (7 participants out of 12) than for the calculation of the rockfall kinematics (3 participants out of 12).

Taking into account the dispersion of the results obtained, it's necessary that the results obtained within trajectographic studies are careful and clearly presented as only one of the elements intervening in the chain of decision-making of the expert.

This test has also allowed us to identify the weak points of the procedure that was initially established. Due to the choice to realise a blind test, the participants could not collect the whole set of the data required for a retro calculation of their trajectory simulation models. Thus, the participants were confronted with the most unfavourable situation that one could meet in reality. This underlines the difficulty of the exercise. In the future we would probably consider not carrying out the test completely blind, e.g., by leaving behind some witnesses (rock impacts, rocks at their original stopping point).

Table 4. Synthesis of the simulated results of all participants.

	ratio differences vmax Ecran1	ratio differences Vmax Ecran2	ratio differences Hmax Ecran 1	ratio differences Hmax Ecran 2	ratio differences Ecmax Ecran1	ratio differences Ecmax Ecran2	ratio differences sur la distance	Probability of reaching 385-400m	Depassing 385-400m
Part. 17	-10%	-19%	17%	13%	-13%	-4%	10%	Yes	Yes
Part. 1	3%	-8%	35%	43%	-9%	1%	4%	Yes	Yes
Part. 2	2%	-3%	-37%	9%			-1%	Yes	No
Part. 15	83%	72%	1%	9%	372%	413%	3%	Yes	No
Part. 14	-22%	-23%	-21%	-31%	-13%	-21%	0%	Yes	No
Part. 8	-43%	-44%	-44%	-35%	-63%	-66%	1%	Yes	No
Part. 12	-63%	-76%	-96%	-94%	-92%	-84%	1%	Yes	No
Part. 4	-51%	-64%	-9%	-30%	-88%	-86%	-8%	No	
Part. 11	-27%	-28%	-58%	-46%	-26%	-22%	-6%	No	
Part. 7	38%	24%	435%	632%			-9%	No	
Part. 9	-61%	-68%	-100%	-100%	-82%	-85%	-9%	No	
Part. 13	-31%	-37%	-62%	-63%	-27%	-28%	-29%	No	

Ratio difference between -20% and 20%

Ratio difference not in the interval -20% - 20%

Data not provided by the participant

If such an operation should be repeated, it will be necessary that the participants can have access to the site before and after the experiments. Consequently, the call for participation should be carried out before the realisation of the real sizes experiments.

Moreover, a preliminary meeting, associating both financiers and the participants, will be necessary to determine the protocol that has to be employed. Especially, the following should be defined:

- the data to be calculated
- the parameters describing the rocks
- the data formats
- the presentation of the results
- whether an anonymous procedure is required
- the final presentation of the outcomes of the benchmark test

This last point will optimize the phase of examination and analysis of the results.

In the future, the optimization of such operations and know-how in this field will require the (international) creation of a working group, network or association of the technical community, potential clients and scientists. This will enable exchanging data, sharing know-how and formalising technical needs, as well as scientific ones. Before doing this, we should investigate if there is a real need and willingness for such a working group, a network or association.

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