Assessment of Risk due to Debris Flow Events

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Abstract: The traditional approach to hydraulic engineering problems, such as the designing of dams or embankments or, specifically in the case of consideration, the designing of a settling basin for debris flows, is deterministic and uncertainties are not explicitly considered in the evaluation of the designed structure. Nowadays some effort is made to consider phenomena in a probabilistic rather than deterministic framework, in order to respond clearly to the demand for reliability. In this paper, failure, damage, and risk are exemplified for a debris-flow prone basin and considerations on the acceptable amount of risk are presented. The evaluation of debris flow hazard is carried out for a specific site (Acquabona, Italy). The standard methodology used to perform a risk assessment analysis is applied. All relevant failure modes are represented by failure functions and each of the function's variables is described by a statistical distribution; all relevant uncertainties are included in a Level II probabilistic calculation and failure probability is evaluated with a first order reliability method. Finally, the probability of failure is compared with the acceptable amount of risk.

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Introduction

The environment in which humans live, our civilization, and individuals themselves are threatened by many hazards. Hazards such as floods and earthquakes are probably as old as Earth itself; others are man-made and result from technological progress in the different branches of engineering (civil, mechanical, chemical, nuclear, and so on). Human populations try to protect themselves against these hazards when disasters occur or when the risk is felt to be too high. Protection is mainly obtained by a reduction in the frequency of damage and an increase in the ability of our defense systems to shield us in the case of hazardous events. However, when a safe level is exceeded, the consequences of natural hazards are often enhanced in developed societies, due to great background investment and confidence placed in defense mechanisms. Ruinous events become progressively more rare, but at the same time potentially more severe, by making, in any case, people's knowledge obtained through direct experience insufficient to manage the problem properly, rendering the necessity of a more rational approach. Increasing attention has been therefore paid in recent times to hazard assessment and mitigation techniques.

The problem can be divided into

- How can we evaluate risk?
- What is the acceptable risk or how safe is safe enough?
- What can we do to reduce the risk to an acceptable level?

For all of these steps, people are used to giving their subjective judgment, which is, in many cases, contradictory to statistical evidence; but even so, these judgments provide the basis for a socially accepted concept of dangerous activities or of necessary defense strategies against natural hazards. A more objective approach to the problem is highly advisable, in order to minimize risk where it is an important issue, and to avoid inconclusive discussions.

The present work deals with the risk of natural catastrophes and, in particular, debris flow events in the Alpine region.

The objective of the study is to present a methodology for assessing the risk due to natural events, based on the approach of Thoft-Christiansen and Baker (1982) and Burcharth (1992), as well as to apply this methodology to the case of debris flow. The results of the analysis, applied to a selected Italian region, i.e., the risk of living in an area subjected to debris flow, are compared with risks due to common human activities.

In the Definition of Failure and Acceptable Risk section, definitions of acceptable risk are summarized and related categories are introduced. Reference is made in this section to the definitions of individual and socially acceptable risk given by Vrijling et al. (1995, 1996) and Vrijling and van Gelder (1997).

In the Example of Specific Risk Assessment section, the risk analysis is applied to debris flow, with special attention given to a specific study site, Cortina d'Ampezzo and the Boite Valley. The site's geological, hydrogeological, and climatic conditions are described. This information is used to develop a numerical model simulating the propagation of debris flow in a prone catchment, Acquabona, Italy, for a wide set of conditions, and allows for the formulation of an empirical relationship that provides the height and volume of debris flow at critical sections in the channel as a function of input data such as rainfall and the characteristics of debris. Failure due to debris flow is identified as the arrival of debris on the national road; the process is schematized and failure probabilities are calculated for each mode. The acceptability of the calculated risk due to debris flow is then discussed and suggestions for the reduction of risks are given. In the appendix, a short description of the methodology used to estimate the prob-

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ability of failure is presented; this part may be useful in understanding the results.

Definition of Failure and Acceptable Risk

Failure and Risk

In any system or structure where damage is possible, when a certain damage threshold is exceeded, a failure is said to take place. The failure may be defined as functional or not severe, when a partial loss of the system's functionality occurs, normally requiring some maintenance work to return the system to its full functionality; an ultimate or severe (or total) failure is defined when the primitive conditions can no longer be obtained.

An example of a functional failure is a road blockage due to debris flow passing over it, which does not show any other damage; when debris is removed and perhaps minor maintenance is completed, the road returns to its initial state. An example of ultimate failure is any failure that results in casualties.

Risk is formally defined as the combination of the probability of some ruinous event and the related damage. Following the IUGS Working Group's definitions, (IUGS 1997) risk is a measure of the probability and severity of an adverse effect to health, property, or the environment; elements at risk are the population, buildings and engineering works, economic activities, and infrastructures in the area potentially affected by the natural phenomenon.

The probability is usually divided into the probability of the hazardous event (exceptional precipitation or earthquake, for instance), over which we have no influence, and the conditional probability of contact between the hazardous event and people or goods, which is possible to control.

Remedial measures act essentially on the contact probability, i.e., reducing the probability that the damaging process comes in contact with goods or humans, acting either on the process or on the goods. For instance, a settling basin, that stops the debris flow in an appropriate area, and relocation of exposed activities or the installation of a warning system reducing the probability that people may be in the wrong place at the wrong moment are possible measures to reduce contact probability.

Acceptable Risk

Acceptable risk is the risk that we are prepared to accept as it is, with no regard to its management.

Risk is normally accepted when it balances out the cost of some clearly identified benefit, but defining the proportionate cost and the benefit value may depend substantially on who is making the decisions and who is taking the risk.

The acceptable risk has, in any case, the following characteristics (Vrijling et al. 1995):

- The decision to accept risk has a cost/benefit character.
- Risk acceptance depends on the degree of willingness of persons involved.
- Acceptance of risk takes place either at a personal level or at a local, regional, or national (societal, not personal) level.

Therefore, two points of view are present when analyzing whether risk is acceptable or not—the individual point of view, typically, when a single person is choosing whether to carry out a single activity (Vrijling et al. 1995), and the societal point of view (Vrijling et al. 1995; IUGS 1997; Hughes et al. 2000), typically when many people are exposed to many hazardous activities. Since society is not normally allowed to impose extreme hazards on its members, in fair political decision making, the most stringent point of view determines the acceptability of risk (i.e., both criteria have to be satisfied). Management of risk [i.e., the complete process of risk assessment and risk control (IUGS 1997)] implicitly assumes that we can choose among different actions or activities that expose us to different levels of risk; therefore, in the following, index *i* will identify the action/activity in question, also in the personal point of view when the activity is assumed to be fixed.

In most cases, damage is measured by loss of lives; its probability can be therefore compared with the probability of natural death. Statistics show that in Italy the death rate (defined as the probability of dying per unit time) due to natural causes and not including accidents, or the natural mortality rate, is 9.3×10^{-3} per year (ISTAT 1997); it decreases to 1.7×10^{-4} per year for boys aged 6–20, the group most unlikely to die in every single year. The death rate due to all causes, natural as well as accidental, is 4.1×10^{-4} for young boys and 9.7×10^{-3} for the entire population. Accidents are the cause of casualties at a rate of 2.4–4.0 $\times10^{-4}$ per year. Similar figures apply to other developed countries.

Most common everyday activities such as domestic and car accidents cause a death rate of around 2×10^{-4} per year each; with the use of public transport, the death rate from vehicle related accidents decreases to 0.5×10^{-4} per year, but the incremental hazard of using private automobiles is normally accepted.

In partial conclusion, a normally accepted order of magnitude for the hazard of death related to a particular activity is around 10^{-4} per year, of the same order of magnitude as the minimum natural mortality during a lifetime. Both are variable and probably related, decreasing when a society or personal attitude evolves from that of a pioneer toward that of a settled person. We can, however, define a reference casualty risk level χ as a proper scale for acceptable risk, being $\chi\cong10^{-4}$/year.

We wish to compare these general indications to the risk due to debris flow events.

Personal Acceptance Criterion

Vrijling et al. (1995, 1996) suggest that when the risk is small compared to the reference risk level or natural mortality, hereby stated as less than 0.10 of that accounting for all types of hazards and less than 0.01 for a single activity under average conditions, the risk is reasonably acceptable and generally accepted by the person, independent of the number of other people exposed and the consequent total number of casualties

$$P_{di}=P_{dfi}\cdot P_{fi}<\beta_{pi}\chi \Leftrightarrow \text{risk of the } i\text{th activity is acceptable for a single person} \tag{1}$$

where P_{di}=personal death hazard linked to the ith activity; P_{dfi} =conditional probability of death if the activity is chosen and failure occurs; P_{fi}=failure probability related to the activity in question; β_{pi} (Vrijling et al. 1996)=parameter that quantifies the inclination toward hazard of the person (p) for the particular activity (i) in relation to his or her deliberate choice: $\beta_{pi}=1$ represents an average value for a deliberately chosen activity (for instance, motoring); $\beta_{pi}=10$=typical value for a dangerous sport (such as mountaineering) when hazard is deliberately accepted; $\beta_{pi}=0.1$ is typical for activities when hazard is involuntary and occasionally accepted (flying); $\beta_{pi}=0.01$ when hazard is involuntary and continuously accepted; and χ=reference acceptable risk level, ranging from 1×10^{-4} to 4×10^{-4}/year (average value of 2×10^{-4}) in Occidental countries, reflecting the hazard of natural death.

The criterion for personal hazard acceptability for normal inclination toward risk is normally phrased in the following way: *The activity should not be likely to cause a hazard greater than the existing unavoidable hazard (natural mortality).*

Societal Acceptance Criterion

The previously mentioned criterion does not prevent the accumulation of risk for a single person due to the multiple hazardous activities he or she carries out, nor for the society due to the numerous persons exposed.

The socially acceptable level of risk aims to contain the accumulated risk and is related to the social process of risk appraisal. To reduce the personal involvement of political administrators, the criterion should be based on objective data such as accident statistics. As a simple model of social perception, it can be stated that every individual assesses social risk on the basis of the events occurring within his or her circle of acquaintances (Vrijling et al. 1995). The societal point of view is also related to the variety of activities a normal person undergoes, and should keep the global risk within an appropriately low level. In some situations involving the absolute value of casualties, the size of the population that is affected by societal (political) decisions (thousands or millions of people) may be relevant, but this paper does not cover the topic.

The criterion for societal risk, as defined and applied in the research by Vrijling et al. (1995), is not the same as the one defined and widely used by the IUGS Working Group (1997).

Using a circle of acquaintances of amplitude $N_c\cong100$ people, as the average range of perception to establish a norm for the acceptable risk from a societal point of view, we assume that risk due to an involuntary activity should only exceptionally cause one's death within the circle of acquaintances of any normal person.

Therefore, by rearranging these considerations, Vrijling et al. (1995) suggest the following formulas for the acceptable accidental mean death hazard P_d:

$$N_c\cdot P_d\leqslant1/L\Leftrightarrow P_d\leqslant1/(LN_c),\quad \text{accidentally}\cong\chi \tag{2}$$

where $L=$lifetime (approximately 100 years). Since $L\cdot N_c\cong10^4$ years, this criterion is not substantially different from the actual accidental death rate.

Regarding activities, we assume that a person spends 50% of his or her time at home not working, 25% at his or her workplace, 10% traveling, and 15% undergoing (voluntary) cultural, recreational, or sporting activities. During these periods, a person is exposed to some activity-related hazards (home, transport, work, or sport-related accidents), while others are continually present (for instance, exposure to earthquakes). They can all be transformed into continuous contemporary activities, by spreading the frequency of events over an uninterrupted time span, maintaining the expected number of occurrences.

Summing up the risks for all of the considered activities and introducing the societal hazard rejection/inclination factor β_s, we obtain

$$P_d=\sum_i (P_{ci}P_{fi})P_{dfi}<\beta_s\cdot\chi \tag{3}$$

where $P_{ci}=$probability that a normal person is involved in the ith activity (fraction of time spent in it), assumed to be independent from the failure probability of that activity, P_{fi}; β_s reflects the societal attitude toward hazard (Vrijling et al. 1995) and a value of 0.1 corresponds to seemingly normal moderate objection to risk.

This type of criterion for societal risk acceptability is phrased in the following way: *It is not likely that in any person's lifetime somebody among his circle of acquaintances will fall victim of an accident in any activity where risk is not voluntarily accepted.*

It is then finally suggested that the total risk due to all activities is acceptable by society if it is approximately equal to the total risk normally accepted by an ordinary person for a general, nondeliberately chosen, hazardous activity ($\beta_{pi}=0.1$). By assuming different values for the risk inclination factors β_s and β_{pi}, however one can let the criteria diverge substantially.

Assuming that risk (and indirectly benefit) deriving from N different activities is approximately equally distributed for each activity [equal terms under summation in Eq. (3) or accounting for any difference through a variable coefficient (β_{si})], Eq. (3) may be rewritten for any activity as

$$N\cdot P_{ci}\cdot P_{fi}\cdot P_{dfi}<\beta_s\cdot\chi \tag{4}$$

The societal point of view may or may not be more stringent than the personal point of view, depending on how diffused the risk is [$N\cdot P_{ci}$ compared to Eq. (1)] or how reluctant the person and society are to accept the hazard involved (β_{pi} and β_s).

Eq. (4) can be easily reworked to provide the acceptable failure probability for any activity if the following information is given:

- Inclination toward hazard, β_s (normally 0.1),
- Background hazard level, χ (normally 2×10^{-4} per year),
- Classification and number of hazardous activities, N (1 for the personal point of view),
- Probability that an ordinary person is involved in the activities, P_{ci} (1 for the personal assessment; to be evaluated for each case for the societal judgement), and
- Death hazard in case of failure for persons involved, P_{dfi} (to be evaluated in any case).

Application of Criteria to Debris Flow Events

In the case of a debris flow, the example of a mountain basin may be used, where some hydrological conditions, heavy precipitation, and/or snowmelt, and/or an earthquake, acting on some steep eluvial or alluvial deposit, cause its mobilization; the mass of debris and water flows down the steep mountain channel and eventually reaches the alluvial fan, where frequently houses, infrastructures, and crops are located and where, at the same time, the channel is no longer bounded by high rock slopes and its bed slope becomes milder.

The debris flow may destroy check dams or revetments along the whole course; if it is not contained in the lower channel, it may cover crops and roads in the alluvial fan with debris and water, and potentially destroy houses. Eventually the huge amount of sediment deposited in the receiving stream may cause severe backwater effects and upstream flooding; by diverting the stream, it may cause erosion of the banks, possibly endangering roads and/or railways. In all possible cases, people's lives may be affected and at stake.

Failure in this case is defined as any event that flows out of the channel or causes the destruction of structures on banks.

Damage is not always easily commensurable. In many cases, the number of casualties acts as the measure of damage or is the most prominent damage component. In other cases, the problem may result mainly in economical damage or benefit.

In following criteria stated previously, houses should never be exposed to debris flow at any technically assessable hazard level. In fact, since the conditional death probability in this case is rather high, the acceptable hazard level from the point of view of the inhabitants would be as low as 10^{-4} per year, i.e., so low that it is assessable only with some relevant extrapolation of direct experience. For houses that are exposed to an appraisable risk, safety diversion structures should be planned so as to redirect debris and avoid contact.

In the case of transport infrastructures, individuals are exposed with only a certain probability, depending on how diffusely debris flows out of the channel (P_{dfi}; the problem is better analyzed later) and how frequently the infrastructure is used (P_{ci}). Since both of these can be of the order of magnitude of 10^{-2} or lower, assuming $\beta=0.1$, $\chi=2\times10^{-4}$, and $N=5$, as explained later, ($\beta\cdot\chi/N\cong4\times10^{-6}$), the frequency of occurrence of a general debris flow on a road can be, from the societal point of view, quite significant, i.e., on the order of 10^{-2} per year or even higher for minor roads.

Based on practical experience, these conclusions correspond to what is in reality accepted. We may conclude that the suggested criteria can be reasonably applied also to the case of debris flow risk, providing a rational approach to differentiate one case from another case.

Regional Case

Mortara et al. (1986) collected information concerning debris flow events that have taken place in the Brennero area since 1867, i.e., over a period of 120 years. The survey area in particular covers Valle Isarco and Valle Aurina in Sud Tirol, Italy; details can be found in the paper cited and related references. The considered area is not far from Cortina d'Ampezzo, a site that will later be analyzed.

Information was found in documents including telegrams from the Prefecture, reports from the *Magistrato alle acque di Venezia*, the Police, the Ministry of Public Works, and reports of *Genio Civile di Bolzano*. The documents give a description of the events, their date, their location, and the resulting damage.

The total number of considered events is 90; their damage is described in terms of destroyed roads and houses, and casualties.

The total number of victims during the events was 143. The number of casualties/year is 143/120=1.2 per year, and the population in the area was, on average, approximately 500,000 people.

The average risk for a person in each year is

$$\frac{N \text{ casualities/year}}{\text{Population}}=\frac{1.2}{500{,}000}=2.5\times10^{-6} \text{ per year} \qquad (5)$$

In this case, the risk due to debris flow events is much lower than that due to natural mortality; i.e., debris flow does not seem to be a critical risk at a regional scale unless one takes a very cautious viewpoint, in the sense that at this scale the implied risk is significantly smaller than the risk of driving a car, for instance. The conclusion may be quite different if we focus our attention on critical areas.

Example of Specific Risk Assessment

Risk analysis applied to a debris flow hazard was performed for the Acquabona catchment, on the left side of Boite Valley near

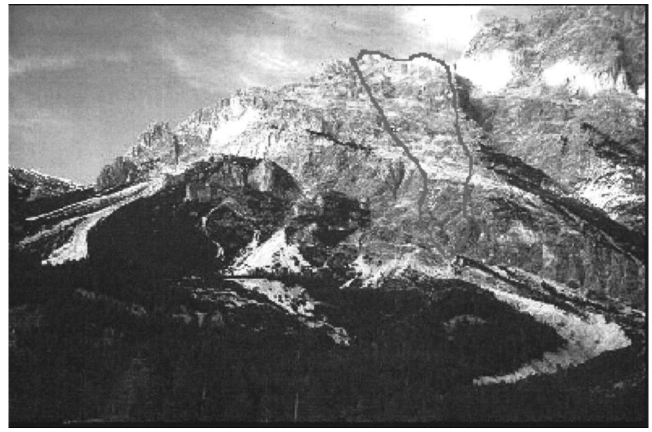

Fig. 1. General view of upper basin of Acquabona (solid line) and of channel (Berti et al. 1999)

Cortina d'Ampezzo in the Dolomitic area, where small debris flows occur almost every year. The analysis provides an exemplified methodology for risk assessment due to debris flows and suggests some guidelines for use with other sites.

In this specific case, damage may occur when debris deposited at the base of the higher rock slopes, due to intense precipitation events, is mobilized. The mass of debris and water flows down the steep mountain channel and eventually reaches the alluvial fan, which is crossed by a national road and where houses are located near its border.

Acquabona debris flows follow a deep channel cutting the scree in the upper part where the flow path is well defined and where debris is provided up to flow competence. In the lower part, natural levees are formed and different paths may be followed; the national road crosses the flow path near the valley's bottom and was frequently covered by deposits; a debris flow settling basin was eventually built to protect the road, composed of a 12 m high artificial levee with an overflow-sill made up of rock units. Further details are given in the Acquabona Site section.

Risk is due to the possibility that the debris flow may reach the road, hitting and/or covering cars, causing damage, or taking people's lives.

The analysis is developed in the following steps:

1. Collecting geological (Genevois et al. 2000), hydrological (Orlandini and Lamberti 1999), and rheological data (Papa and Lamberti 1999), and estimating their statistical distribution,
2. Performing a large number of debris flow simulations aimed at illustrating the relationship between primary variables and the variables appearing in the failure functions,
3. Describing failure modes and failure functions,
4. Evaluating the failure probabilities based on a Level II methodology (Burcharth 1992),
5. Estimating acceptable failure probability and comparing it with results of the hazard analysis, and
6. Analyzing proposals to reduce the risk.

Acquabona Site

A general view of the basin is provided in Fig. 1. In this area, the rock cliffs and mountain summits consist of Upper Triassic to Lower Jurassic age dolomites and limestones, whereas the lower parts are predominantly underlain by marly formations from the

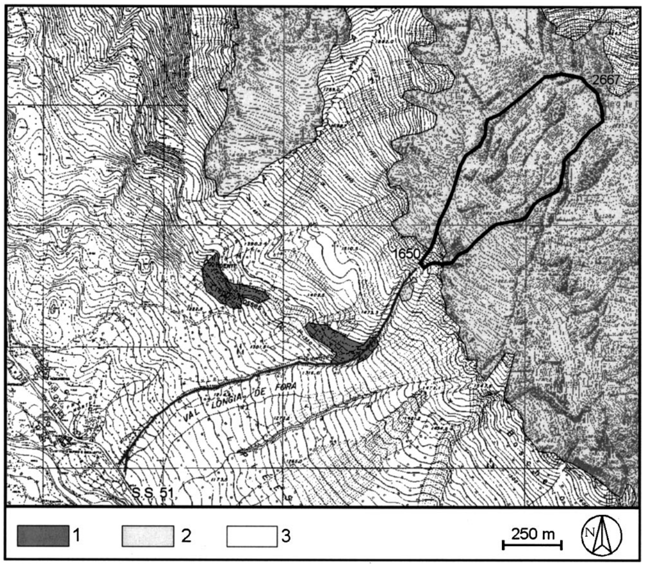

Fig. 2. Acquabona geological sketch (1 = Raibl Fm, 2 = Dolomia Principale Fm and Durrenstein Fm, 3 = quaternary deposits)

Lower-Middle Triassic age. In Fig. 2, the geological sketch of the area is shown. Peak elevations vary between 2,500 and 3,200 m above sea level (ASL), and local relief may exceed 1,500 m. Mountain slopes are widely covered by scree of relevant thickness; the intense weathering of the fractured rock cliffs favors a high debris yield. The talus slopes are formed by debris, where there are occasionally boulders of up to 3–4 m; the slope angle decreases from about 45–30° at the upper parts of the talus (in contact with the overhanging rock cliffs) to 20–10° on the lower parts of the talus slopes. In Fig. 3, a picture of the middle part of the channel is presented. The transversal section has a trapezoidal geometry. The start of the settling basin has an elevation of 1,180 m ASL; it is 30 m wide and 100 m long, with an average deposit slope angle of 7–8°.

Fig. 3. Middle part of channel, Acquabona (Berti et al. 1999)

Debris contains a 10% fine fraction (silt and clay) in the upper part of the channel, increasing to about 30% in the deposit area. The higher percentage of fine fraction present in the deposit is due to outcropping marls along the channel and to stone abrasion along the stream.

In the lowest part of the basin, flow is traversed by the national road SS 51. The occurrence of debris flow was observed for centuries and the road was blocked every second to third year for a long period, until a settling basin was constructed in 1990 just upstream of the national road in order to reduce risk.

The debris retention basin was constructed just upslope of the road, and the village of Acquabona is located just upstream along the Boite Valley, so that flow spilling over the channel levees may reach the village; the road and the village represent elements at risk from debris flow.

A detailed description of the site is given in Berti et al. (1999) and Genevois et al. (2000).

The climatic conditions in Acquabona are typical of an Alpine environment. Annual precipitation ranges roughly from 900 to 1,500 mm; precipitation occurs as snowfall from November–December to April–May. Debris flows usually occur in the summer and early autumn, and are associated with intense, concentrated rainfall events, being often related to short-duration thunderstorms.

Observations were made during the years of 1997–1998 within the European Union research project ''Debris Flow Risk,'' including

- Precipitation in the basin, wind, and precipitation at a nearby station,
- Monitoring of debris flow passage with geophones at three stations,
- Flow visualization (video recording),
- Flow height and front velocity (with three near geophones) at the downstream station,
- Deposited volume measurements,
- Debris geotechnical characterization, and
- Occasional visual records in the initiation area.

Numerical Simulations

Numerical simulations of the flow (Papa and Lamberti 1999) were performed, reproducing the roll wave formation with passable accuracy. The model used is based on the shallow-water assumption (Fraccarollo and Toro 1995; Fraccarollo 1996) with the following simplifying assumptions:

- Channel cross sections have a trapezoidal shape.
- The fluid mixture is accounted for as being homogeneous.
- The original bed of the flow domain is unerodible, but different rheologic properties are considered in the different parts of the debris flow path.
- The fluid mixture is characterized by a Bingham rheology; similar results were obtained with a different numerical model based on Herschel Bulkley rheology (Laigle and Coussot 1997; Laigle 1999).

The channel is represented by sections drawn on a 10 m scale difference in elevation.

With regard to boundary conditions, the two types of flow regimes are distinguished. If the flow at the upstream boundary is subcritical, only the discharge is specified; if the flow is supercritical (as it was in this case), the discharge and the flow depth are specified; the flow depth for a given discharge was obtained assuming a uniform flow. A free exit from the basin is imposed as a downstream boundary condition.

The input water hydrograph (discharge) was provided by a distributed rainfall-runoff model (Orlandini and Lamberti 1999). To obtain the debris-flow hydrograph, the concentration of debris in the mixture has been calculated using the equation proposed by Takahashi (1991)

$$c=\frac{\tan\theta}{\Delta(\tan\varphi-\tan\theta)} \tag{6}$$

where θ = bed slope angle, referring to the part of the channel where the flow reaches an equilibrium state. In the Acquabona channel, this part is assumed to be between an elevation of 1,650 and 1,190 m; the corresponding mean slope angle is 22°; φ = internal friction angle; and $\Delta=(\rho_s-\rho)/\rho$ = relative density. Laboratory tests carried out by Genevois et al. (1999) showed that in saturated conditions, the internal friction angle is about 40°; ρ_s is the density of the particles, equal to 2,620 kg/m^3; and ρ is the density of water, equal to 1,000 kg/m^3.

Model simulations were compared with prototype debris flow behavior (Papa and Lamberti 1999; Fraccarollo and Papa 2000). The comparison of levels, flow velocity, and volume of debris arriving in the basin was encouraging.

Unfortunately, no unique calibration of the Bingham fluid was able to represent both the stream height along the channel and stream stopping in the settling basin; this can be interpreted either by a change in material characteristics along the channel, or by an inadequacy of the assumed rheological model. Therefore, the simulations were carried out for two calibrated sets of rheological parameters for the intermediate channel flow and for ceasing in the settling basin.

In summary, we believe to have reasonable models that provide flow and stop characteristics, starting from a water hydrograph at the upstream end of the channel.

The model was used in the risk analysis as a sort of black box, producing the synthetic response of the basin to rainfall events, and hence providing statistics on the relevant variables.

Empirical Relations Describing Relevant Events

Debris flows in Acquabona are triggered essentially by rainfall. Rainfall statistics are provided by Orlandini and Lamberti (1999). Consequent debris flows were simulated for various rainfall volumes and various rheological parameters; calibration of the model and example simulations are described in Papa and Lamberti (1999). The simulation results were used to describe the statistics of the relevant variables in relation to the known rainfall statistics.

Simulations were performed for different precipitation return periods (1, 2, 5, 10, 25, 50, 100, and 200 years) and durations of the triggering rainfall event (from 15 min to 24 h), providing values for the variable peak liquid discharge and water volume in a sufficiently wide set. Looking at the simulation results, it was evident that the critical section along the channel, where, with extremely intense rainfall, debris flows can overtop the embankments, is located at an elevation of 1,213 m. This is a position where the section is narrow and the embankments, around 3 m high, are not always sufficient to contain the debris flow discharge.

Results used in the subsequent analysis were flow depth at the critical section and volumes of debris arriving in the settling basin; from these results, the probabilities of failure during a span of 1, 2, 5, 10, 25, 50, 100, and 200 years were evaluated.

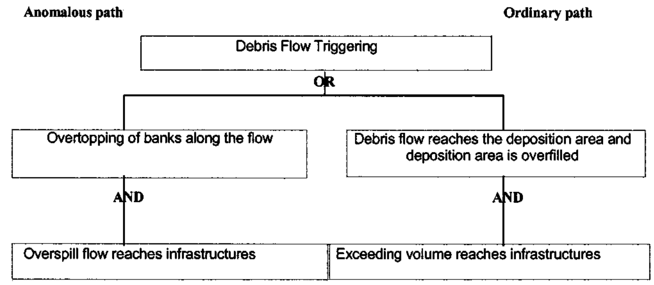

Fig. 4. Flowchart representing hazard from debris flow in Acquabona

Only rainfall events with a 25 year return period and a short duration (15–60 min), of the same magnitude of the events observed and monitored in June 1997 and August 1998, were simulated with varying rheological parameters. In particular, the yield stress τ varied from 500 to 2,000 Pa, the concentration c varied from 0.5 to 0.7, and the pseudoviscosity μ varied from 100 to 400 Pa·s.

Empirical relations were found to describe the relevant variables

- The total volume of water and debris arriving to the settling basin, V_d, and
- The maximum flow height reached in the critical section (at quota 1,213 m), H_d.

The relations are

$$V_d=39.1\cdot c^{1.97}\cdot\mu^{-.017}\cdot\tau^{-0.19}\cdot Q_p^{0.30}\cdot V_w^{0.91} \tag{7}$$

$$H_d=8.5\cdot c^{0.36}\cdot\mu^{-.0.65}\cdot\tau^{0.17}\cdot Q_p^{0.053}\cdot V_w^{0.07} \tag{8}$$

where Q_p = peak discharge; and V_w = volume of incoming water hydrograph (m^3); τ = yield stress (Pa); c = debris concentration; and μ = apparent viscosity (Pa·s).

Description of Failure Modes and Failure Functions

The hazard deriving from debris flow is the result of various elementary failure events logically combined in some manner related to the case under study.

In Acquabona, the risk is related to the possibility that debris flows reach the road or the village. The following are the two possible debris paths:

- An ordinary path. The stream follows the channel and enters the settling basin; the deposited volume fills the basin and debris overspills onto the national road just below the basin.
- An anomalous path. Debris does, in fact, spill over the embankments along the flow (in one or more sections); it follows an alternative path and reaches the national road or the village.

Elementary failure modes are

1. The deposition basin is filled up (V_d > 18,000 m^3).
2. The volume exceeding the basin capacity reaches the national road.
3. The stream spills over the banks somewhere along the channel.
4. The overspill volume flows down and reaches the national road or the village.

The system failure is represented by at least one of the following complex events:

- The ordinary path is the combination of elementary failures $1\cap 2$; the basin is filled (first failure mode) and debris reaches the national road (second failure mode).

Table 1. Statistics of Hydrological Parameters

Parameter	Lifetime (years) 1	2	5	10	25	50	100	200
Q (m^3/s)								
U	0.45	0.89	1.47	1.92	2.50	2.94	3.39	3.83
α	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64
Mean	0.82	1.26	1.84	2.29	2.87	3.31	3.75	4.20
Standard deviation	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82
Volume (m^3)								
U	1,800	3,195	5,038	6,433	8,277	9,671	11,066	12,461
α	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000
Mean	2,961	4,344	6,188	7,583	9,426	10,821	12,216	13,610
Standard deviation	2,581	2,556	2,556	2,556	2,556	2,556	2,556	2,556

Note: Parameters U and α are location and scale Gumbel parameters, respectively.

- The alternative path corresponds to the combination of elementary failure $3 \cap 4$.

A flowchart is given in Fig. 4. System failure is represented by the combination $(1 \cap 2) \cup (3 \cap 4)$.

The elementary failure functions may assume the following forms:

- $g_1(c, \mu, \tau, Q_p; V_w) =$ basin capacity $-$ arriving volume of water and debris,
- $g_2(c, \mu, \tau, Q_p; V_w) =$ distance to the road $-$ distance covered by the overtopping flow from the basin,
- $g_3(c, \mu, \tau, Q_p; V_w) =$ height of banks $-$ flow height, and
- $g_4(c, \mu, \tau, Q_p; V_w) =$ distance to the road $-$ distance covered by bank overfill flow.

In Acquabona, due to the road's position just downstream of the basin and to the small size of the channel passage under the road, as soon as the basin volume is filled, the road becomes damaged.

The hydrological variables Q_p and V_w are described by Gumbel distributions (Table 1), and it was supposed that rheological parameters are described by normal distributions.

In all cases, the geometry of the channel was treated as deterministic, except for the retention basin's capacity and the bank height in critical sections, which are described by normal distributions with their mean equal to the expected value and their standard deviation representing their estimated variability.

Results of Analysis

Following the described methodology, giving the mentioned distribution to the variables and considering the system failure tree (Fig. 4), a reliability analysis was performed for different lifetimes. The failure probability is summarized in Table 2.

Table 2. Acquabona, Failure Probabilities for Increasing Lifetimes

Lifetime (years)	Percentage failure mode 1	Percentage failure mode 2	Percentage failure mode 3	Percentage failure mode 4	Percentage system failure probability
1	3	100	0.5	0	3
2	6	100	1	0	6
10	32	100	3	0	32
25	52	100	5	0	52
50	72	100	8	0	72
200	88	100	15	0	88

Failure probability and sensitivity factors for each represented variable were calculated, providing, as an example, the influence of the highly uncertain rheologic parameters.

The variables that show higher sensitivity factors on Mode 1 failure probability are the capacity of the basin, the equilibrium concentration of debris, and the hydrological parameters (in particular, the rainfall volume). Therefore, the error in neglecting the variability of pseudoviscosity (uncertainty of the rheological model) is low, as could be anticipated by looking at the empirical function g_l, where, in the power law μ, it appears with a very low exponent. In fact, viscosity influences the flow velocity in the channel but not the volume entering the basin.

In the span of 25 years, Mode 1 showed an expected failure probability of 0.52, which is highly dependent on the variability of the basin capacity; the target capacity of the basin is 20,000 m^3, but due to imperfect maintenance, the average effective capacity is estimated to be around 18,000 m^3.

The variable accurately estimated in the analysis of Failure Mode 3 is the bank freeboard. The probability that the flow height exceeds the bank level in the most exposed section is 0.054.

The remaining two failure modes have the following conditional probabilities: $P(\text{failure2}) = 1$ and $P(\text{failure4}) = 0$. In fact, as debris fills the settling basin, overspilling debris reaches the road located just below. On the other hand, the quantity of debris that overtops the bank is so small (never more than 10 m^3) that it is almost sure to stop at a small distance from the bank and not reach any infrastructures. This seems to be a typical feature of channeled debris flows like Acquabona.

Failure probabilities are summarized in Table 2. Fig. 5 shows the probability of a failure occurring with respect to the basin capacity; for a reasonable capacity of the basin, the probability of failure in a 25 year lifetime (L) is approximately 0.52.

Survival for an entire lifetime requires surviving every single year during, expressed as

$$1 - P_{fL} = (1 - P_{f1})^L \tag{9}$$

It follows that, solving for P_{f1} in Eq. (9), the failure probability due to debris flow is on the order of $P_{f1} = 0.029$ for a single year.

Acceptable Failure Probability Compared with Hazard Analysis Results

In consulting a list of debris flow events in Acquabona (Genevois et al. 1999), covering only a limited number of years, it was observed that, before the construction of the basin, the road was blocked once every 2 to 3 years, but the amount of deposits and the debris flow magnitude were never so intense as to cause large-scale damage or casualties.

The hazard that a car could be caught in a debris flow is relatively low and is confirmed by the debris flow events recorded in the last 30 years in the area, where only once, in the Rudavoi basin, did a bridge collapse and a car become involved in an accident that caused one casualty. The event that occurred in 1868 in Cancia, Italy, was more severe, during which a debris flow that reached the village was responsible for 12 casualties.

Comparing the results of the risk analysis with the suggested criteria, we wish to verify if risk related to the Acquabona catchment, in particular, is acceptable and, in general, if the risk to the population living in the Cortina d'Ampezzo area due to debris flow is below the acceptance limit.

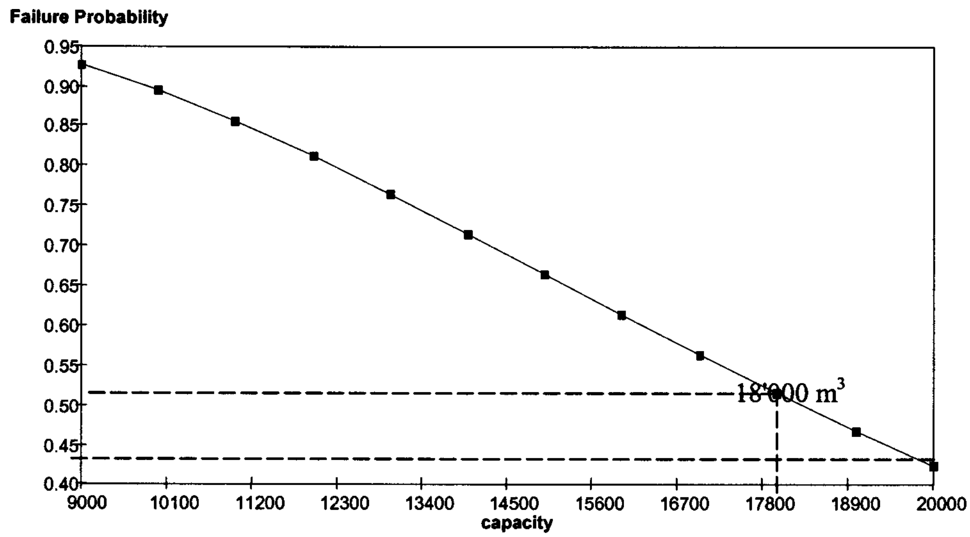

Fig. 5. Failure probability of Failure Mode 1 versus capacity of reservoir for 25 year lifetime

The populations exposed to risk are thought to be the municipalities of Cortina, San Vito, and Borca; during the summer period N_s = approximately 50,000 people (in winter, the area is covered by snow and no debris flow was ever triggered).

Houses are not present and apparently not built (and should not be) in the debris flow prone areas. Therefore, it is at least assumed that people are exposed to risk only while driving through these areas.

The considered activity is driving on major roads in the Cortina area, without any special attention to weather or to dangerous road stretches, i.e., exposed to debris flow. The total length of major roads in the area is approximately 80 km. It is further assumed that the average number of casualties that would arise in the case of a car being caught by a debris flow would be one (two persons in the car and 50% hazard each are likely figures); i.e., the same probability applies to casualties and to cars caught by the flow.

In the case of failure in Acquabona, i.e., if a debris flow reaches the road, a car is considered to be caught by the flow if it is along the path of the flow (about 40 m) or cannot stop before it (about 40 m). The probability that a car or person driving in the considered area and having no better warning information than ‘‘debris may be everywhere with the same likelihood’’ is caught on the road by a debris flow at Acquabona is approximately 80 m per 80 km; $P_{dfi}=0.001$.

Six sites equivalent to Acquabona, i.e., presenting a similar hazard since the time when a retention basin was constructed (Fiames, Rio Gere, Rudavoi, and so forth), do exist in the area. Therefore, a car driven on major roadways has a probability of $P_{dfi}=0.006$ of being caught by a debris flow (flowing out of the channel).

Individual Point of View

From the individual point of view (a person with a moderate attitude of objection toward risk should decide whether to drive, not expressly across Acquabona), the individual acceptable failure probability is provided by Eq. (1) with $\beta_i=0.1$; in 1 year the failure probability due to debris flow in Acquabona should be less than 0.01–0.04 and in general the failure probability due to debris flow in the studied area should be less than 0.0017–0.0067 per year, for $1\times10^{-4}<\chi<4\times10^{-4}$ per year, in order to be acceptable ($P_{fi}<\beta_i\cdot\chi/P_{dfi}$). Pressure to construct a retention basin where the frequency is once every few years is therefore comprehensible.

After the basin was constructed, and, according to our estimates (results in Table 2), the hazard conditions were equalized at different sites around the level of 0.03 per year; the hazard (being$=6\times0.03=0.18$ per year) remains, however, well above the acceptability level. The risk can be controlled by persons paying attention to the weather (during which hazardous events occur) and to dangerous spots on the roadway; if they do not, they show a less than moderate objection to risk.

Societal Point of View

This is, for instance, the point of view of the mayor of Cortina when questioning the seriousness of debris flow risk for his municipality or deciding whether he should resist further pressure to undergo defense work for debris flow in the municipality. Results can be applied to similar areas in the Dolomite region, where the frequency of events in space and time is fairly equal to that of the area under examination.

This analysis differs from the previous one because the previous analysis applies to a person deciding to drive and does not account for the number of persons doing that nor for the time spent driving; i.e., it does not account for the societal relevance of the driving activity. The crucial point is the estimate of the repetition factor—how many similar activities are carried out by any one person, and how many people are actually exposed.

We assume that any one person lives at home, works, and, finally, drives his or her car for an average of 2 h per day, with half of this driving time being spent on major roads. We can assume that the probability of being exposed to risk caused by driving is 1 in 24 ($P_{ci}=0.04$). The number of activities equivalent to driving is around 5 (driving, playing sports, working, taking care of the home, and others); the repeated exposure factor N should therefore be assumed as 5.

The social acceptable failure probability may be provided by Eq. (4) with $\beta_s=0.1$, $N=5$, and $P_{dfi}=0.006$, as established before. Rearranging Eq. (4), the acceptability criterion is

$$P_{fi}<\beta_s\cdot\chi/(NP_{dfi}P_{ci})$$

Failure probability P_{fi} therefore should be less than

0.008–0.033 per year. The individual criterion is more severe than the societal criterion, requiring personal attention. The estimated failure probability is 0.029 per year, near the upper acceptability level; something should probably be done to reduce the probability—for instance, a warning system (information/alerting or a light).

How to Reduce Risk

To reduce the risk, several forms of action can be taken.

The local government could prepare a hazard management plan composed of a risk map that shows the possibility of occurrence of a debris flow and the degree of vulnerability of the area, and an information/alerting plan. Debris flows are mainly related to heavy summer thunderstorms and can reach roads in well-delimited areas. Inhabitants can be informed/instructed to avoid hazardous conditions, i.e., not to be in the wrong place at the wrong time.

In the specific case of Acquabona, where the main hazard is due to the basin overfilling, protective measures are

- Regular dredging of the basin to 20,000 m^3, in order to keep this capacity at the maximum level and to reduce the probability of failure (from the analysis and results in Fig. 5, $P_{f25} = 0.42$) resulting from the application of the Eq. (9) $P_{f1} = 0.021$ in 1 year, and/or
- Redesigning the outflow weir and channel in order to evacuate in safe conditions at least part of the flow excess,
- Stopping traffic during spilling events, and
- Recommending, in any case, that no housing should be allowed to be built within reach of the overtopping flow.

Just after hazard assessment was completed, after one event the basin was not cleaned and the following year a spilling event took place; fortunately, failure was not severe (there were no casualties).

Conclusions

A methodology for the assessment of risk due to natural catastrophes with specific application to debris flow events is presented.

In general, the risk acceptability criterion leads to the conclusion that the following rules should exist:

- Houses cannot be exposed to any appraisable hazard.
- Roads can be exposed provided that the failure probability remains below a certain limit, depending on contact probability.

These rules conform to the common practice followed in the reduction of risk due to debris flow. The criterion therefore can be interpreted as a rationalization of good practices in use.

Following the methodology, failure probability functions and system fault trees have been determined; all variables entering in the failure functions have been described by their statistical distribution and the risk analysis based on a FORM method has been carried out. The example of risk assessment presented shows the remarkable importance of some variable factors (precipitation, sediment/water concentration, basin capacity, bank elevation) and the minor importance of debris rheology. The conclusion relates to the specific conditions of the analyzed case; the flow is channeled down to the basin and roll waves are formed, weakly depending on debris rheology.

For the Acquabona site, the probability that a debris flow will-reach some infrastructures is on the order of 0.03 for a single year, greater than what would correspond to the individual and societal acceptable failure probability, if people drive on major roads without any care as to weather and places at risk.

From the individual point of view, attention should be paid to this high probability.

The example shows that even the case of a small settling basin with other forms of defense, such as traffic control, is able to provide an effective solution to hazard reduction, bringing the risk to a socially acceptable level.

Acknowledgments

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Appendix. Methodology to Estimate Failure Probabilities

In each failure mode, it is generally possible to recognize load variables and resistance variables. If a larger value of the variable results in a safer system, it is a resistance parameter; otherwise, it is a load parameter. For example, if the failure mode is described by the debris volume that overfills the basin, the load variable is the quantity of debris volume arriving in the basin and the resistance variable is the capacity of the basin.

Normally, a failure function is formulated as

$$g = R - L \tag{10}$$

where R = resistance; and L = load. Usually, R and L are functions of many random variables

$$R = R(X_{1\text{res}}, X_{2\text{res}}, \ldots, X_{m\text{res}})$$

and

$$L = L(X_{m+1\text{load}}, X_{m+2\text{load}}, \ldots, X_{n\text{load}}) \tag{11}$$

All of the variables X_i are involved to describe the failure function $g(X)$, which is, by definition, positive in the safe region and negative in the failure region, and defines the so-called failure surface $g(X) = 0$, which separates the two regions.

The probability of failure or hazard, during any reference period lasting T years, is then given by $P_f = \text{Prob}[g \leqslant 0]$ at least once in T years, and the reliability is defined as $1 - P_f$.

There are different methods to perform a single failure mode probability analysis (Hallam et al. 1977; Thoft-Christiansen and Baker 1982; Burcharth 1992). Level II methods, applied in the following analysis, are based on normal variable distributions. The methods are used in the following analysis and the basic concepts are hereby described in brief.

If we assume L and R to be independent, normally distributed variables with known means and standard deviations, then the linear failure function of Eq. (9) is normally distributed with a mean value of $\mu_g = \mu_r - \mu_l$ and a standard deviation of $\sigma_g = (\sigma_r^2 + \sigma_l^2)^{0.5}$.

The quantity $(g - \mu_g)/\sigma_g$ will be the unit standard normal variable, and consequently

$$P_f = \text{prob}[g \leqslant 0] = \int_{-\infty}^{0} f_g(x)\,dx = \Phi\left(\frac{0-\mu_g}{\sigma_g}\right) = \Phi(-\gamma). \tag{12}$$

where $\gamma = \mu_g/\sigma_g$ = indirect measure of the probability of failure, and is denoted as the *reliability index*.

With geometrical considerations, it can be shown that the shortest distance from the origin to the linear failure surface is equal to $\gamma = \mu_g/\sigma_g = (\mu_r - \mu_l)/(\sigma_r^2 + \sigma_l^2)^{0.5}$. The coordinates of the design point (the nearest point of the failure surface) in the original x-coordinate system are the most probable values of the variables X at failure. Indication of the relative importance of the reliability index γ of the random variable X_i uncertainty is given by the sensitivity parameters (or factors) α_i, defined as

$$\alpha_i = \frac{-\dfrac{\partial g}{\partial z_i}}{K} \qquad K = \left[\sum_{i=1}^{n} \left(\frac{\partial g}{\partial z_i}\right)^2\right]^{1/2} \tag{13}$$

If α is small, it might be considered to model X_i as a deterministic quantity equal to the median value of X_i.

The failure event can be regarded as the result of a system of components that can either fail or function. Due to interaction between the components, failure of one component may impose failure of another component, and may even lead to failure of the system. A so-called fault tree is often used to clarify the relationships between the failure modes.

The fault tree is a simplification and a systematization of the more complete so-called cause consequence diagram, which indicates the causes of partial failures as well as the interactions between the failure modes.

The computation of the probability of the union and intersection of failures is the key to the system reliability analysis.

Failure modes can quite often be mutually correlated because some common random variables are active in both and the correlation coefficient is not always known. However, it is possible to calculate upper and lower bounds for the failure probability of the system.

A system can be composed of two types of fundamental elementary systems—namely, a series system and a parallel system.

In a *series system*, failure occurs if any of the elements $i = 1,2,3,\ldots,n$, fails; an example is the probability that debris flow reaching the road can occur following the first ordinary path or the alternative path.

The OR gates in a fault tree correspond to series components.

In a *parallel system*, the system fails only if all of the elements fail. The AND gates in a fault tree correspond to parallel components.

It is convenient to decompose the original system into a simple series of parallel systems, the so-called minimal cut-set representation.

Notation

The following symbols are used in this paper:

c = concentration;
g = failure function;
H_d = maximum flow height reached in critical section;
L = lifetime;
L = load;
N = classification or number of hazardous activities (1 for single personal choice);
P = probability;
P_c = fraction of people involved in activity;
P_{df} = death hazard in event of failure for persons involved;
P_{dfi} = conditional probability of death if failure occurs and activity is chosen;
P_{di} = personal death hazard linked to ith activity;
P_{fi} = failure probability of activity in question;
Q_p = peak discharge of incoming water;
R = resistance;
V_d = total volume of water and debris reaching settling basin;
V_w = volume of incoming water;
α = sensitivity parameter;
β = inclination toward hazard;
γ = reliability index;
Δ = relative density;
θ = bed slope angle;
μ = mean, viscosity;
ρ = density of water;
ρ_s = density of debris flow particles;
σ = standard deviation;
τ = yield stress;
φ = inertial friction angle; and
χ = background hazard level (normally 2).

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