FIELD MONITORING AND REAL TIME MANAGEMENT OF DEBRIS FLOWS

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Abstract

This report contains a summary of the most important characteristics of debris flows that can be measured in the field and a description of the devices that have been so far employed for this purpose throughout the world. The report has no pretense to be exhaustive about this subject but has been intended to provide a reference framework in which the improvement made during the U.E. Project "*Debris flow Risk*" in this difficult area of research could be conveniently collocated. At the end of the report a description of the main types of interventions and procedures adopted throughout the world for real time management of debris flows is also presented.

1. Introduction

Measurements of debris flows characteristics and collection of field data related to them are very important for many theoretical and practical purposes (such as the determination of the rheological behavior of the flowing mixture, the calibration of mathematical models, the development of countermeasures and warning systems etc.) all aimed to reach a better understanding of this particular kind of phenomenon and thus better protecting human settlements and infrastructures. Several are the quantities concerning debris flows that are of great interest and that have been measured by researchers and technicians who have dealt with this phenomenon; sometimes specific devices and procedures have been developed for the purpose. Among the most commonly monitored quantities there are mean flow velocity (U), surface velocity (u_s), peak flow height (h_p), flow height as a function of time ($h(t)$), peak discharge (Q_p), mean discharge as a function of time ($Q(t)$), triggering rainfalls (Tr), ground vibrations (Gv), total volume (V), specific weight or density (g or r) and impact force (If). Many of these latter parameters are very difficult to be measured and a comparison with tools and procedures developed in hydraulics to measure the same quantities for clear water might be of some help to focus the main difficulties and to identify the still unsolved problems in debris flow monitoring. This approach will therefore be adopted in the following. Indeed many of the parameters previously mentioned, such as density, are already known for water and do not need any particular monitoring, or are less interesting than they are for debris flows because information that can be derived from them can be obtained in easier ways; for instance, ground vibrations have been monitored in case of water only to investigate sediment transport (Govi et al., 1993): of course for such parameters there will be no comparison with the measurements performed in hydraulics.

2. Measurement of flow height

In hydraulics flow height is measured both manually and automatically. Water surface elevation measurements include both peak levels (flood crest elevations) and the stage as a function of time (Chow et al., 1988). The same occurs for debris flows. Measurements of peak levels and of the stage as a function of time will be analyzed separately in the following.

2.1. Measurements of peak levels

2.1.1. <u>How measurements are performed in hydraulics for water</u>

Manual observations of water level are made using *staff gages*, which are graduated boards set in the water surface and read by an operator at different times.

Automatic observations of water level are obtained through different devices and procedures. The category of devices that allows continuous measurements of the stage also allow the measurement of peak levels, of course. These devices will be treated in chapter 2.2.1. Flood crest elevations are sometimes recorded without continuous measurements through *crest stage gages*, which are devices consisting of a wooden staff gage situated inside a pipe with small holes for the entry of water. A small amount of cork is placed in the pipe, floats as the water rises and adheres to the staff at the highest water level (Chow et al., 1988). A similar device employs a water-soluble color painted over the pipe surface: the highest water level is given by the height of the color washed away.

2.1.2. <u>Measurements of debris flow peak levels</u>

Since debris flows are much less predictable and usually last much less than a water flood, manual observations through staff gages are more difficult to perform and cannot be proposed as a standard procedure. Besides, the strong erosive capacity of debris flow and the presence of large boulders in its matrix, impedes to safely set graduated boards directly into the debris flow mixture.

Debris flow crest elevations are often easily measured without any particular device, since the presence of fine materials usually leaves clear tracks on the vegetation present along the torrent or on its banks (Figure 1) and holds the role played by cork in *crest stage gages*. Particular care has to be taken to differentiate between the tracks left by the debris flow surface and the tracks left by the debris flow splashes (Aulitzky, 1989).

However when vegetation is not present and it is more difficult to detect debris flow tracks (for instance when neither lateral levees are present), a device that has been specifically employed to monitor debris flow crest elevation is a *set of wires* (Fig. 2) stretched at different levels across the valley bottom. These wires can detect the maximum depth according to the level of the highest wire that has been broken. *Contact sensors* (Okuda et al., 1980), have been also used to measure peak levels. Contact sensors are vertically hanged wires that send a signal when their tip first contact the top of the debris flow.

Figure 1 – Debris flow usually leaves clear tracks on the vegetation present along the torrent or on its banks, thus crest elevations can be easily measured without any particular device.

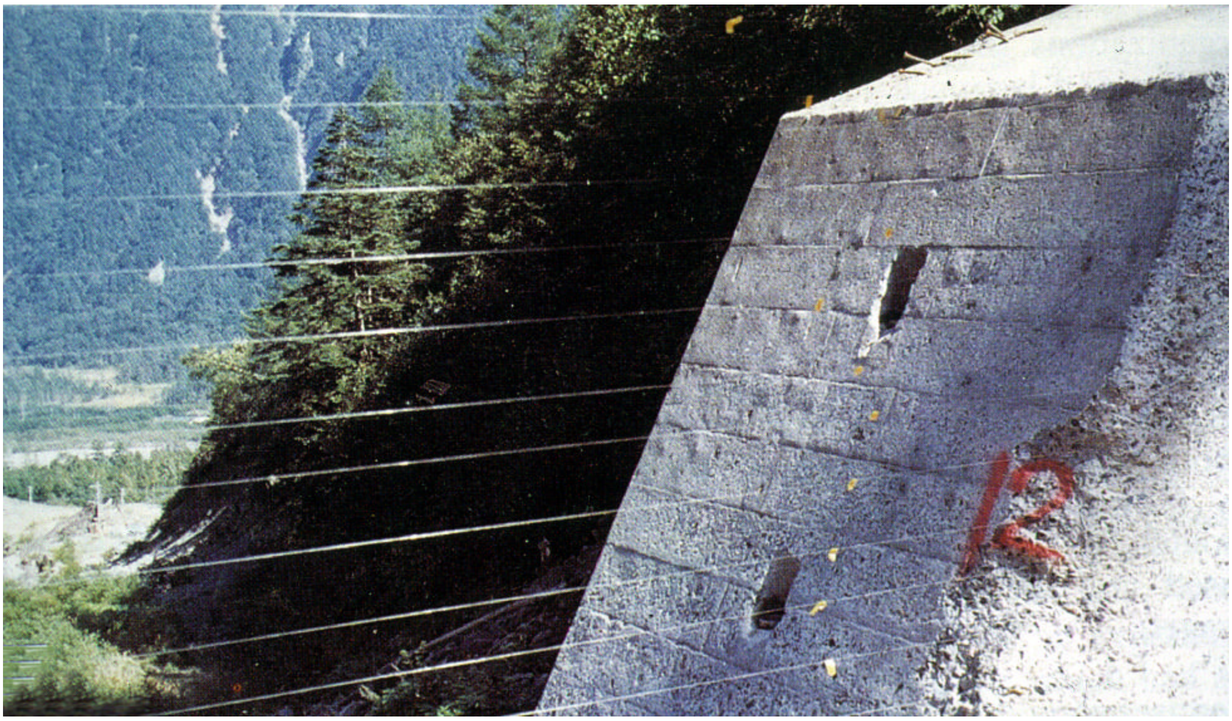

Figure 2 – Wire sensors. These sensors can detect the maximum depth according to the level of the highest wire that has been broken.

2.2. Measurements of the stage as a function of time

2.2.1. How measurements are performed in hydraulics for water

Paper chart recorders attached to a float, *bubble gage recorders* and *ultrasonic sensors* suspended above the water surface are tools commonly used to automatically and continuously measure water level variations (Chow et al. 1988). Paper chart recorders attached to a float are based on the recording of the rises and falls of a float immersed in the water, the movements of which are reproduced by a pen over a strip of paper continuously moved at a slow rate, thereby allowing the pen to trace out a record of water level against time on the chart. Other types of recorders can also be employed to keep track of the movements of the float. Bubble gage recorders, which are the sensors most widely used in the U.S.A., sense the water level by bubbling a continuous stream of gas into the water. The pressure required to continuously push the gas stream out beneath the water surface is a measure of the depth of the water over the nozzle of the bubble stream. This pressure is measured by a manometer. *Ultrasonic sensors* are acoustic rangefinders that are suspended over the channel, usually on a cableway. They emit high-frequency sound pulses and time the echoes. Microprocessor circuitry converts the timing of the echo to a distance and filters out background noise. The digital signal is usually converted to an analog voltage and is carried by wire to a recorder located in an instrument hut nearby.

2.2.2. Measurements of the debris flow stage as a function of time

The first two of the previously mentioned tools are again not apt to measure level variations of debris flows since they require a direct contact with the fluid to be measured. Because of the huge destructive power of debris flows only remote sensors, such as ultrasonic gages, are suitable to measure variations in stage and the ultrasonic gages are in fact the most commonly used device for monitoring debris flow level variations (Fig. 3) (Pierson, 1986; Takahashi, 1991; Arattano et al., 1997) together with visual data obtained from video-cameras (Suwa et al., 1993). In addition to recording a stage hydrograph, it is important to notice that the *ultrasonic sensors* provide a way to measure the amount of channel downcutting or aggradation (UPD, vol. 2, 5).

Figure 3 – Ultrasonic gages are the most commonly used device for monitoring debris flow level variations

3. Measurement of flow velocity and discharge

In hydraulics several methods have been developed and used to measure flow velocities and discharges in natural channels. These methods are both direct, such as measurements through the use of floating objects thrown in the water, or indirect, such as measurements through the use of *current meters* (both of the propeller, Fig. 4a, or electromagnetic type), methods that appeal to the principle of critical flow (*weirs, Venturi flumes, Parshall flumes* etc., Fig. 4b and 4c), that make use of *chemical tracers* or that are based on the surveying of the tracks left in the channel after the occurrence of a flood event (slope area method, superelevation formula) (Chow et al., 1988; Bos et al., 1984).

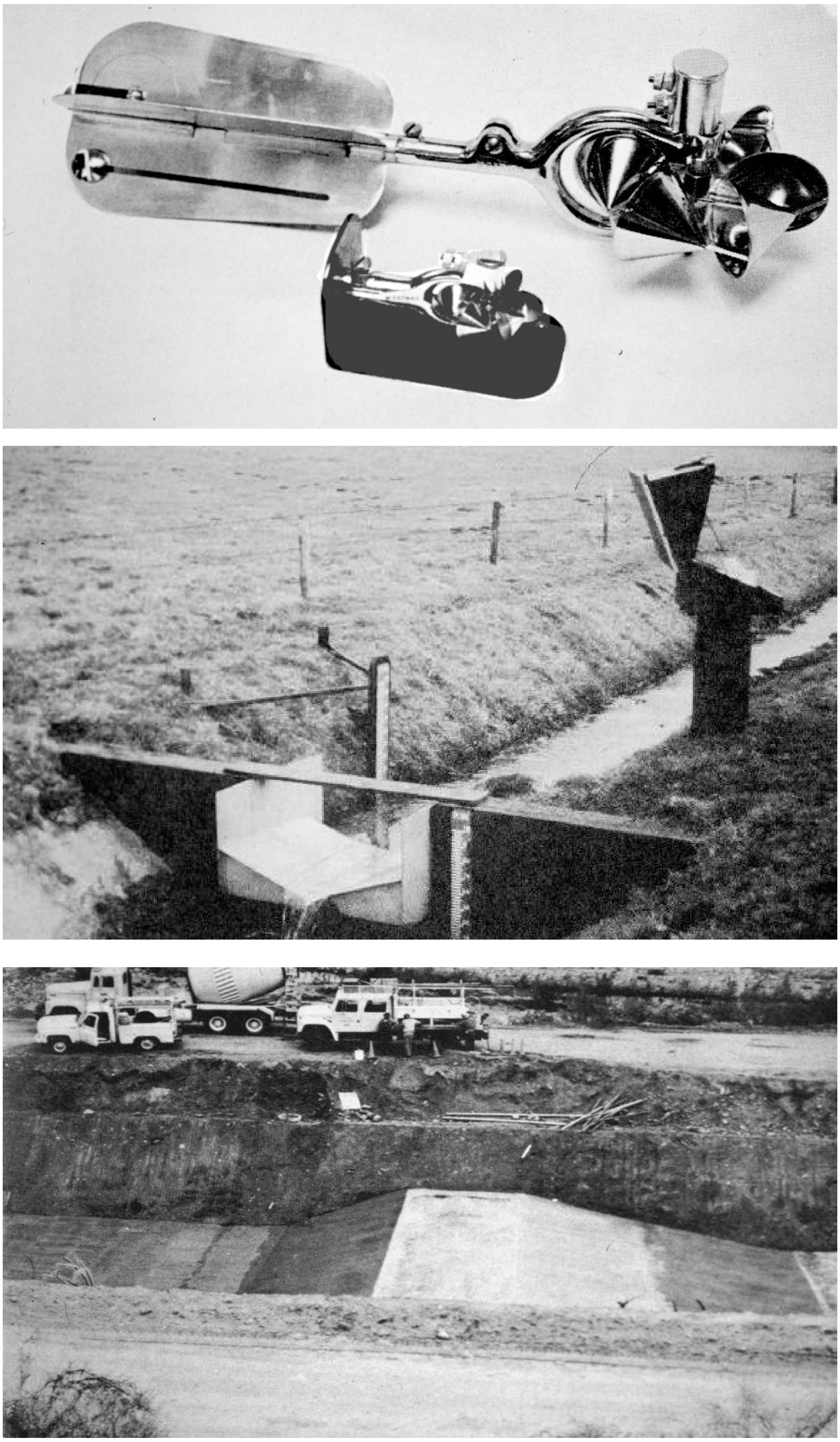

Figure 4 – Examples of methods developed and used in hydraulics to measure flow velocities in natural channels are a) current meters (after Chow et al., 1988) and the ample class of methods that appeal to the principle of critical flow, such as b) weirs (p. 119) and c) flumes (p. 141) (after Bos et al., 1984).

The presence of boulders and smaller fragments within the moving mass of a debris flow together with the difficulties in predicting its magnitude and occurrence, impedes the use of current meters, chemical tracers, weirs and flumes (Fig. 5a and 5b). Moreover the difficulties in performing good rheological measurements of these flows makes also uncertain the use of methods based on the surveying of the tracks left after the occurrence of the events.

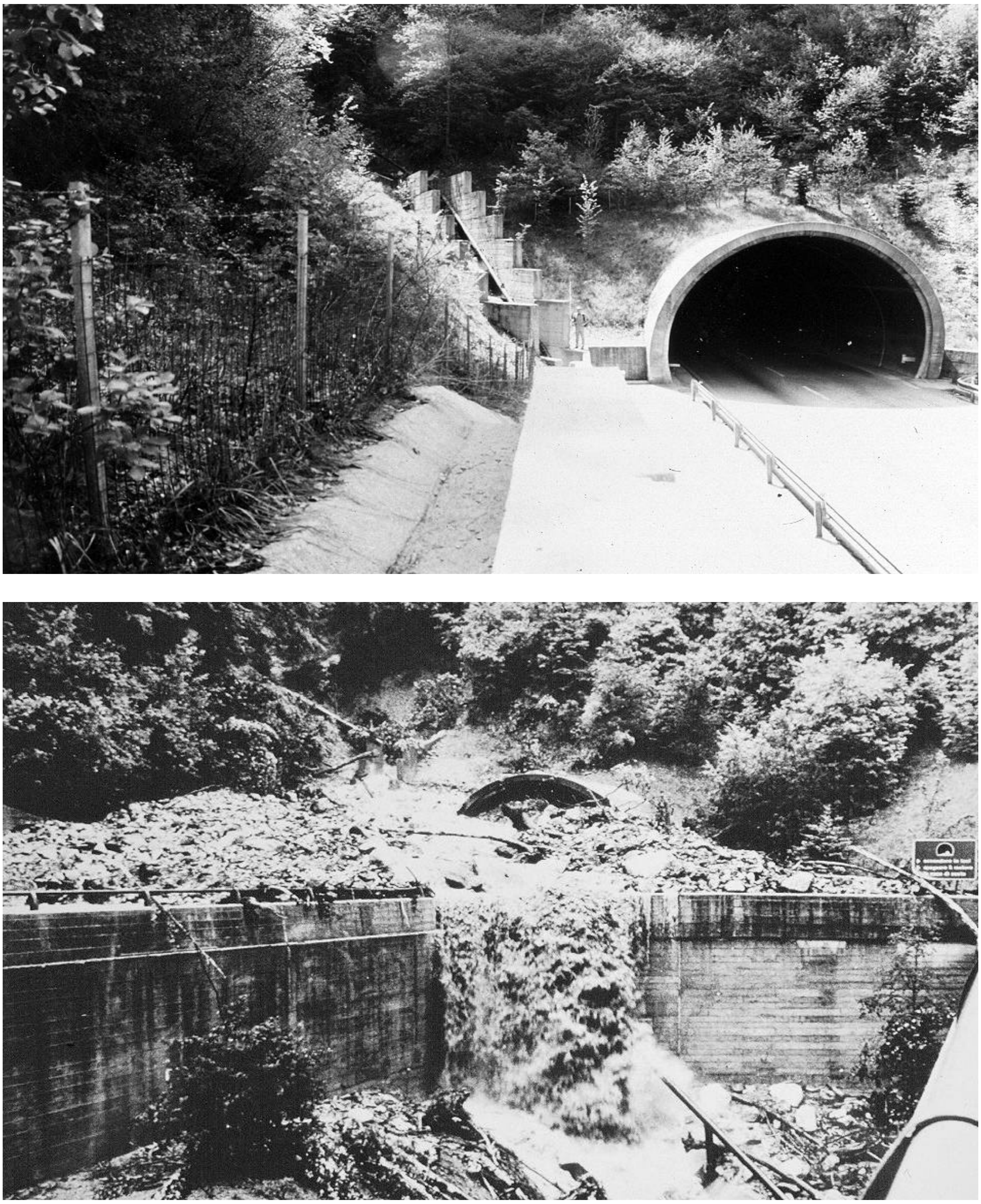

Figure 5 –A small debris flow creek that periodically causes damages to an Italian motorway (Arattano et al., 1991): a) before and b) after a debris flow occurrence. The presence of large boulders and smaller fragments within the moving mass of a debris flow, together with the difficulties in predicting the maximum magnitudes, impedes the use of current meters, weirs, flumes and other methods commonly used to measure velocity for clear water.

3.1. Measurement of mean flow velocity

3.1.1. How measurements are performed in hydraulics for water.

In hydraulics measurements of mean velocity as a function of time are usually performed through weirs and flumes (Fig. 4b, 4c) or through the use of chemical tracers. Mean velocity can be easily obtained also from point velocity measurements, as obtained through the use of current meters (Fig. 4a), calculating an integral over the cross section area. When expedite measures are needed an approximated value of mean velocity can be also obtained from surface velocity measurements, as obtained through a float thrown in the water, multiplying them for a convenient constant (usually ranging between 0.84 and 0.9 and commonly adopted equal to 0.85 (Becchi et al., 1994).

3.1.2. Measurements of mean front velocity of debris flows.

For debris flow is very difficult to measure mean flow velocity as a function of time: only surface velocity measurements as a function of time are in fact possible through particular monitoring devices and mean velocity can be only measured for the main front of debris flow surges. No tools have been developed to measure point velocity. Surface velocity measurements as a function of time will be examined in chapter 3.2.

Mean velocity of the main front of a debris flow surge can be measured using two or more ultrasonic gages placed at a known distance along a torrent reach. Debris flows generally have a steep and very well defined front that can be easily identified in the hydrographs. Mean front velocity can be thus determined as the ratio of the distance between the gaging sites to the interval of time between the appearance of the front at the gaging stations. This characteristics of debris flow to present a well defined front can be revealed also by the use of seismic devices (Okuda et al., 1980; Arattano, 1997, 1999; Arattano and Moia, 1998, Fig. 6) and this has allowed the use of these devices also for mean velocity measurements (Arattano, 1997, 1999; UPD, vol. 2, 5; CNR-IRPI, vol. 2). These two tools can be also used together, placing seismic sensor in less accessible locations and ultrasonic sensors where they can be easily hanged over the torrent.

Trip wires or "*wire sensors*" (Okuda et al., 1980), that is set of electrified wires broken by the passing flow, may also allow mean front velocity measurements if installed at successive downstream sites. However these devices cannot provide information, after they have been broken, about the velocity and height of further surges superimposed to the main one (Johnson and Rodine, 1984) or about subsequent debris flows: they need to be reset each time a flow passes. Contact sensors (Okuda et al., 1980), that are vertically hanged wires that send a signal when their tip first contact the top of the debris flow, have been also used to measure mean front velocity.

Pendulums can also be used, other than as warning devices, as tools for mean velocity measurements (Fig. 7).

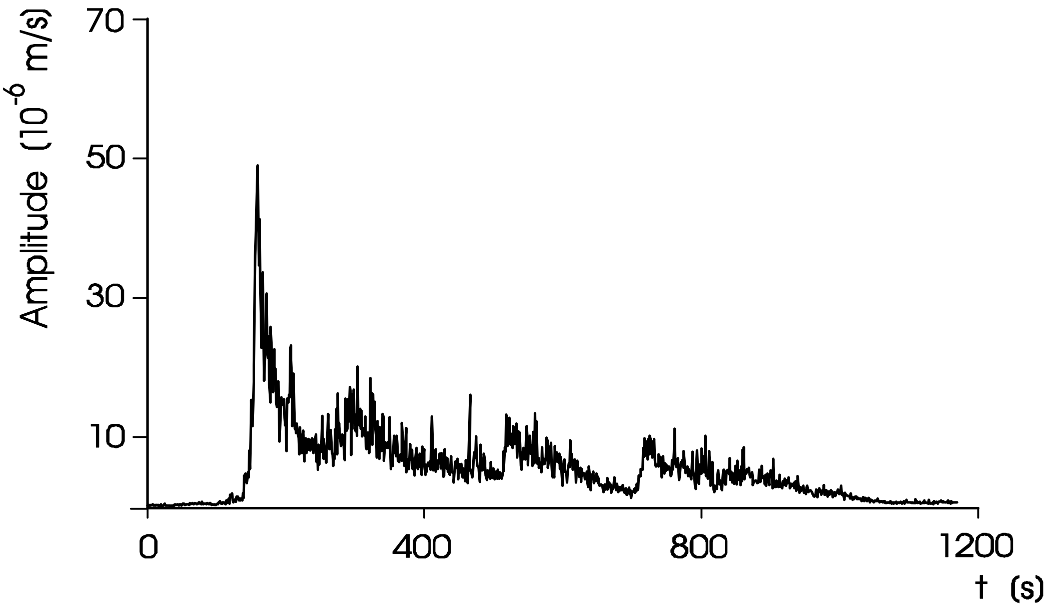

Figure 6 – The characteristics of debris flow to present a well defined front can be revealed also by the use of seismic devices: the mean velocity of ground vibration produced by a debris flow presents a very well defined peak at the passage of the front (after Arattano, 1997).

Figure 7 – *Pendulums* can also be used, other than as warning devices, as tools for mean velocity measurements. In this figure: a set of pendulums have been hanged over the creek and connected to a radio transmitter to warn of the occurrence of a debris flow (S. Bernard catchment, Maurienne Valley, France).

3.1.3. Measurements of mean velocity of characteristic features along the debris flow wave

The main front of a typical debris flow is usually followed by superimposed, smaller waves having lower front heights (Johnson and Rodine, 1984). These smaller waves are particular features that can be revealed through the use of ultrasonic sensors and can be easily spotted in the hydrographs. In these case their mean velocities can be determined in the same manner as mean velocity of the main front.

This characteristics of debris flow to present smaller waves behind the main front can be revealed also by the use of seismic sensors and their velocity can be also determined through the use of this type of device (Arattano, 1997; CNR-IRPI, vol. 2).

3.1.4. Advantages and shortcomings of devices used for mean velocity measurements of debris flows.

It must be noticed that the different tools previously mentioned present each advantages and shortcomings that may suggest which is better to use in different situations. Trip wires and contact sensors are certainly less expensive than the others devices, even though they need each time to be reset after they have been broken. Ultrasonic sensors can provide more information than mean velocities, since they also allow to monitor variations in stage with time and the amount of channel downcutting or aggradation. However they need to be hanged over the channel bed and this may result difficult for valley slopes are often very steep and unstable and do not provide safe places to dig stakes or other structures to sustain the sensors; this is particularly true as one proceeds upstream along the torrent. Seismic sensors present less problems from this point of view: in fact they are more easily installed since they simply require to be dug into the ground. However they provide a poorer information than ultrasonic sensors, since they do not allow to monitor variations in stage unless a good calibration is performed.

3.2. Measurements of surface velocity of debris flows

Time-lapse photography, speed sensors based on spatial filtering velocimetry and electromagnetic laser-doppler speedometers have been used in the past as methods for continuous surface velocity measurements of debris flows. A modified version of the Spatio Temporal Derivative Space Method (STDSM) (Ando, 1986) has been developed and applied by Inaba et al. (1997) to measure the velocity vector field of debris flows occurred at Mt. Yakedake. The automated shooting of videos of debris flows and the subsequent use of image processing techniques may provide another solution to the problem of measuring superficial velocities of debris flows (Arattano et al., 1998).

As stated before the presence of boulders and smaller fragments within the moving mass of a debris flow impedes in fact the use of current meters for measurements of point velocity within the mixture and only remote sensors that do not require a direct contact with the fluid can be employed. Therefore only surface velocity can be measured. Electromagnetic doppler speedometers have been also used for water, but in that case the newtonian behavior of water and the better understanding of turbulent motion allows to obtain the value of mean velocity from the knowledge of surface velocity (Becchi et al., 1994). Suwa et al. (1993) use a coefficient of 3/5 for the ratio between mean velocity and surface velocity but this coefficient, holding for a dilatant type of mixture (Takahashi, 1978), is very uncertain.

3.2.1. Continuous measurements

Pierson (1986), positioning above a bedrock reach of a debris flow torrent a time lapse system, consisting of a 35-mm camera with a wide angle lens, an hour-minute-second digital data back, a motor drive and an infrared pulse transmitter and receiver for wireless remote control, determined average surface velocities and horizontal velocity profiles for ten debris flows occurred between 1981 and 1983 on Mount St. Helens. When a debris flow passed beneath the camera an operator used an infrared remote control to take periodic sets of exposures at a rate of 3.1 frames per second. The velocity data were obtained scaling off the sequential photographs the distance traveled by individual cobbles and boulders. A shortcoming of this method is the need of an operator; this problem might be solved triggering the system through a set of wires, an ultrasonic sensor or other type of devices.

A speed sensor based on spatial filtering velocimetry was used by Itakura et al. (1985) and Itakura and Suwa (1989) to obtain surface velocity measurements of debris flows. The working principle of this sensor, shown in figure 8, is based on the assumption that the flow-surface pattern of a debris flows remains unchanged in the short time interval in which it sweeps over the view-field of the sensor (Itakura et al., 1985). In this case, if the number of slits of the parallel-slit reticle shown in figure 8 is sufficiently large and they also have a large length, the time-varying output signal of the differential operational amplifier is sinusoidal and its central frequency f_0, measurable through the use of a frequency-extraction method, can be linked to the debris flow surface velocity V_S through the following expression:

$$V_S = a \cdot f_0 \cdot H$$

where:

H distance between the flow-surface and the sensor
a width of the slit (normalized by the focal lenght)

There are three different frequency-extraction methods indicated by Itakura et al. (1985). The two most commonly employed are: zero-crossing frequency discrimination ZCFD and maximum entropy method MEM.

An electromagnetic doppler speedometer has been used by Suwa et al. (1993) to measure surface velocity of debris flows in Japan. The operating principle of the Doppler speedometer is based on the characteristic of radio waves to travel in a straight line. If they strike an object a portion of the waves is absorbed and a portion reflects off. If the object is moving, by measuring the frequency of the reflected waves, the speed of the object can be determined. The object can be the snout of the debris flow, a surface wave, a piece of floating vegetation or a coarse particle moving on the surface of the debris flow.

Supposing that the transmitter is placed in a fixed position above a torrent with the path of the emitted radio waves forming an angle q with the moving surface, then the surface velocity V_S is given by:

$$V_S = \frac{c \cdot f_d}{2 f_0 \cos q}$$

where:

c is the radio wave propagation speed, f_d is Doppler frequency, f_0 is the transmission frequency, q is the angle of depression, f_r is the receiving frequency, $f_d = f_r - f_0$

A modified version of the Spatio Temporal Derivative Space Method (STDSM) (Ando, 1986) has been developed and applied by Inaba et al. (1997) to measure the velocity vector field of debris flow occurred at Mt. Yakedake. The method makes use of a video tape of natural debris flow to perform the measurements. The method considers the luminance of a pixel as a function f of its coordinates (x, y) at a time t and derives the velocity vector field $u\,(x, y)$, $v(x, y)$ as a function of the partial derivatives of f with respect to x, y and t. The accuracy of the measurement performance has been studied by Inaba et al. (1997) with a computer simulation.

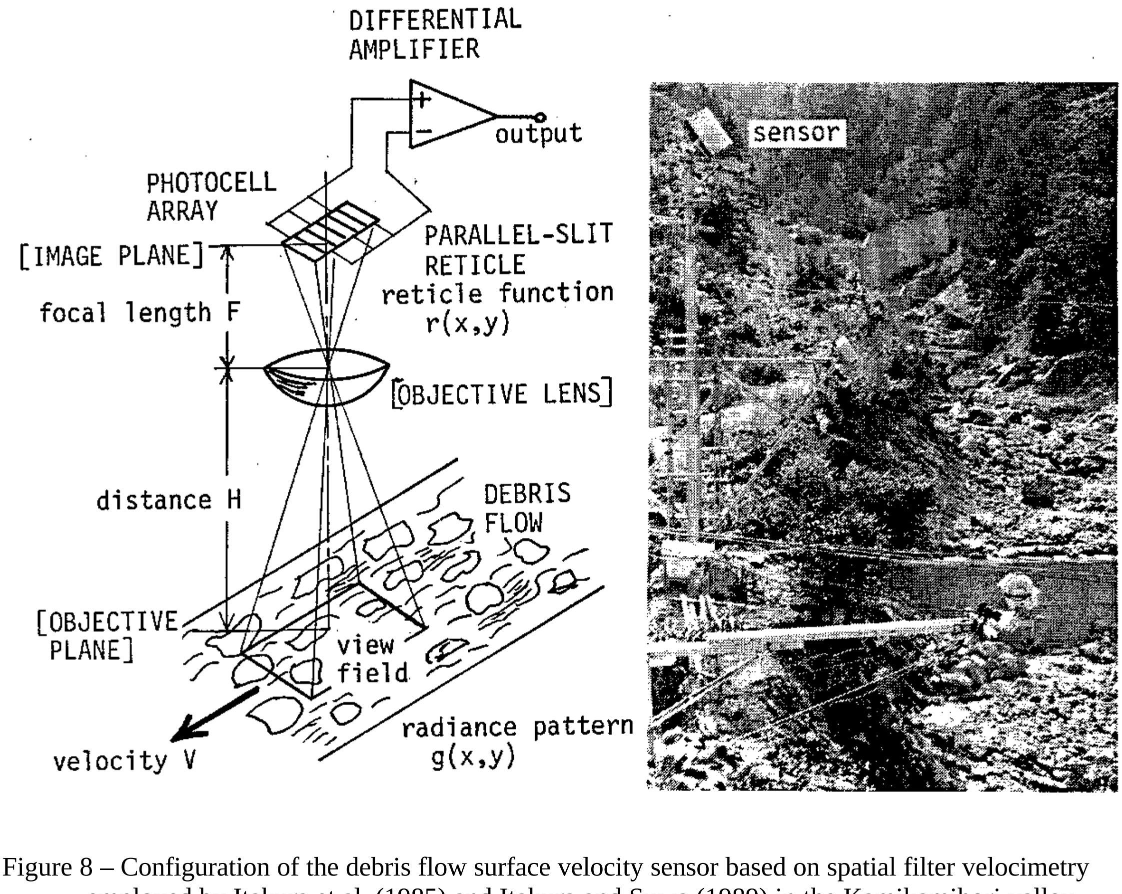

Figure 8 – Configuration of the debris flow surface velocity sensor based on spatial filter velocimetry employed by Itakura et al. (1985) and Itakura and Suwa (1989) in the Kamikamihori valley.

3.2.2. Discontinuous measurements

The shooting of videos of debris flows may be also employed in a simpler way than that used by Inaba et al. (1997) to obtain superficial velocities of the flowing mass through the use of image processing techniques. Topographical surveys need to be carried out to provide the data for the calibration of the camera and of the scene to be used in the processing of the recorded images. The measurements can be performed using a simple method, based on the direct computation of the mapping between 2D image points and points in the 3D space.

This method was tested using the video images of the two debris flow events recorded in the Moscardo Torrent (Friuli Venezia Giulia Region, Eastern Italian Alps) in 1996. Several superficial velocities were measured at different times along the two debris flow waves. Sequences of frames containing clear images of features suitable for velocity estimation (e.g. the front of the surge, a floating log, etc.) were selected. Surface velocities were computed spotting the same feature in two different frames, determining the distance travelled by the feature and computing the ratio between this distance and the time interval elapsed between the shooting of the two frames (Arattano et al., 1998; CNR-IRPI, vol. 2).

In Acquabona debris flow basin (Eastern Italian Alps) a video camera installed perpendicularly above the channel provided images which were used to measure surface velocity profiles (UPD, vol. 2, 5).

3.3. Measurements of discharge

Knowing mean velocity and surveying the cross section where the measurement has been made it is possible to compute the peak discharge at that section as the product of mean velocity and cross section area. In hydraulics usually a *rating curve* is developed, using a set of measurements of discharge and gage height, that allows to only record water level and obtain discharge indirectly.

For debris flows it is more difficult to establish a definite relationship between discharge and flow height (Takahashi, 1991). Therefore in order to know discharge velocity and flow height measurements are always both needed and need both to be performed.

4. Measurements of triggering rainfalls

Debris flow triggering rainfalls are measured through common rain-gauges. Several authors have collected rainfall data and proposed thresholds for the triggering of debris flows (Caine, 1980; Cannon & Ellen, 1985; Wieczorek, 1987; UPD, vol. 2, 7.1).

For a comparison of the rainfall data collected in a particular basin with other geographical regions the well-known relationship proposed by Caine (1980) may be used:

$$I = 14.82 \cdot D^{-0.39}$$

In this formula, based on a number of cases coming from all over the world, D represents the duration of the event in hours and I the rainfall intensity in millimetres per hour. Average rainfall intensities that caused debris flows in the Moscardo Torrent are plotted in figure 9 versus rainfall duration for comparison (Arattano et al. 1997). In this case they often fall below the threshold identified by Caine (1980). This could be a consequence of local conditions of the Moscardo basin (slope steepness and poor mechanical characteristics of materials). However the space scale of the investigation and the criteria for the inclusion of debris flows may also affect the identification of the threshold (Johnson and Sitar 1990). A rainfall intensity-duration relationship based on individual failures in a spatially-limited area (Wieczorek, 1987) is also shown in figure 9 and fits better the threshold values observed in the Moscardo basin.

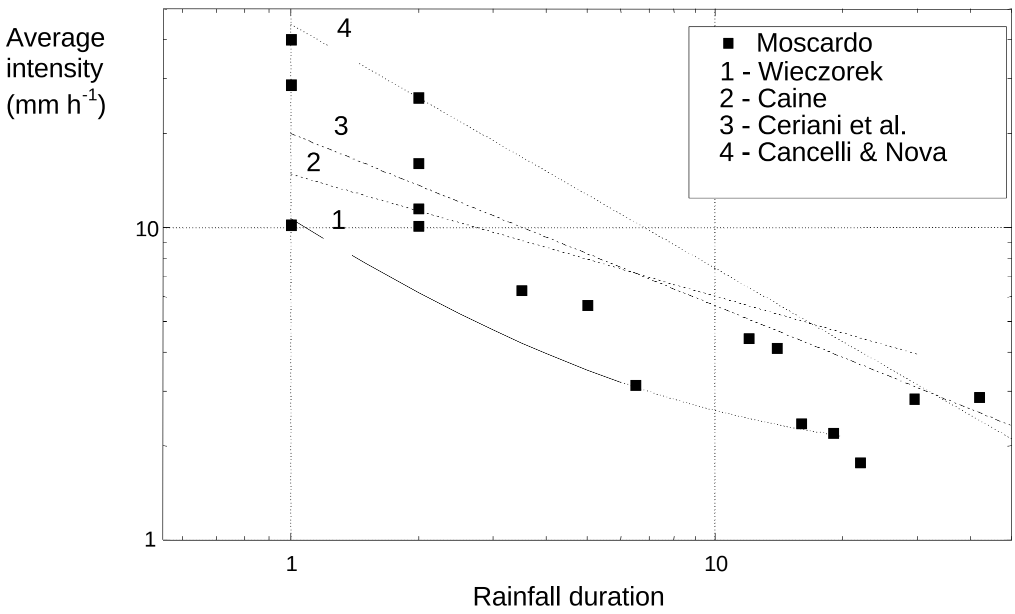

Figure 9 - Relation among rainfall intensity and duration for debris flow - triggering storms in the Moscardo basin.

5. Measurements of debris flow total volume

The measurement of total volume discharged by debris flows is usually not among the main objectives of debris flow monitoring in instrumented areas. In fact, measurements of deposited volume of debris can easily be performed, through topographic surveys, as part of just-post-eventum data collection also in non instrumented torrents. It should be reminded, however, that pore fluids escape rapidly from debris flows during deposition, so that the measurement of debris flow deposits is not homogeneous with those of total flowing material, that includes solids, water and air.

Collecting data on debris flow magnitude (total volume of debris material transported to the deposition area in the course of a single event) at a regional scale makes it possible to develop formulas or guidelines for the estimation of design debris flow (e.g. Kronfellner-Kraus, 1984, 1985, Hungr et al., 1984, Ikeya, 1989, Rickenmann & Zimmermann, 1993, Marchi & Tecca, 1996, D’Agostino et al., 1996). In a recent paper, Davies (1997) discusses suitability and shortcomings of data on debris flow magnitude and frequency for hazard attenuation and concludes that there are good reasons for collecting such data “if only to build up a qualitative idea of the order of magnitude of possible events”.

In several papers presenting direct observations of debris flow characteristics (i.e. density, particle size, velocity, etc.) data on total deposited sediment are also referred, together with other basic information, to provide an idea of overall event characteristics. For instance, an approximate estimate of the total volume of a large mud flow observed in early May 1941 in southern California is provided by Sharp & Nobles (1953). More recently, Pierson (1980, 1985) reports the total deposited volume for debris flows studied in the field in April 1978 at Mt. Thomas (North Canterbury, New Zealand) and in spring 1983 in the Rudd Canyon (Utah, USA). Assessing spatial distribution of eroded and deposited debris is an important refinement to total volume measurement. Debris flow deposit volumes and longitudinal pattern of erosion and deposition along the channel were surveyed in the field by Jakob et al. (1997) for two large debris flows in British Columbia. Digital terrain models based on pre- and post-storm stereo photos were used by Coe at al. (1997) for the volumetric characterization of a hill-slope debris flow near Yucca Mountain (Nevada, USA).

Monitoring of debris flow stage and velocity is a suitable base for estimating debris flows total volume. In the Moscardo Torrent debris flow hydrograph is monitored using ultrasonic gauges installed in mid-fan area (Arattano et al., 1997). The time lag between the recordings of the front of the wave (corresponding to the hydrograph peak) at the gauging stations allows an estimation of mean flow velocity (paragraph 3.1.2). The channel cross section area is obtained from stage measurement and topographic survey of channel geometry. Total discharged volume is then computed by integrating debris flow discharge on the recorded hydrograph. When analyzing the downstream development of a debris flow, variations of total volume discharged at different gauging stations are a suitable indicator of erosion or deposition phenomena. For instance, a strong decrease in debris flow volume from the upstream to the downstream gauging stations for a large debris flow in July 1996 has been referred to debris deposition in overbank areas along the instrumented channel reach (Arattano & Marchi, 1998).

An approach that is similar to the one adopted in the Moscardo Torrent, is referred by Tsuchiya et al. (1996) for a study site (Ohya Collapse) in the Southern Alps of Japan. In the area instrumented by Tsuchiya et al. (1996), debris flow hydrograph are recorded using a pressure gauge installed on channel bottom and flow velocity is estimated by the Manning equation. A linear relationship was found between total volume of debris flow and peak discharge; a similar relationship resulted from a previous work by Suwa (1992).

6. Measurements of ground vibrations.

It is well known that a strong ground vibration propagates from the head of a debris flow and that sometimes people living at the lower reaches of debris flow prone torrents can detect the occurrence of such phenomena before their arrival by the vibrations they produce (Okuda et al. 1980). According to Okuda et al. (1980) the strong ground vibrations promote the fluidization of debris deposit by decreasing the internal friction and cohesion in the deposit bed, thus they suggest to record these vibrations for investigating both fluidizing mechanisms and the possibility of using them as warning signals. They set a pair of simple vibration gauges along the Kamikamihori Valley on the eastern slope of Mt. Yakedake in Japan and collected a vibration record during the August 14, 1976 event (Okuda et al., 1980). In 1980 they set two seismometers near the valley for a more exact recording of ground vibrations (Suwa & Okuda, 1985).

Different types of ground vibration detectors (accelerometers, velocimeters, groundophones) have been used by other researchers around the world to monitor the passage of debris flows (Zhang, 1993; Lahusen, 1996; Arattano, 1997). However few field data have been collected so far on the vibrations induced by these natural phenomena and on the best methods to record them.

Zhang (1993) calls geosound the vibrational waves produced by debris flows. Through the analysis of a large amount of geosound data collected in China since 1982, including data of 18 occurrences at the Jiangjia Gully, he identifies the predominant frequency of the signal to be 50 Hz. Zhang (1993) finds out that the wave of geosound rapidly decreases with an increase of distance, which is in agreement with the data collected in the Moscardo Torrent (Arattano, 1997).

As previously mentioned the passage of a debris flow can be clearly identified through the use of seismic devices placed at a safe distance from the channel bed. Through a convenient processing of the recorded data, velocity estimations of the flowing mass are also possible (Arattano, 1997; UPD, vol. 2, 5).

7. Measurements of specific weight or density.

Bulk density of debris flow flowing material is a key-parameter controlling the general rheologic behaviour of water and sediment flows. With increasing sediment concentrations, flow and fluid properties gradually begin to change, fall velocity of particles decreases and fluid density increases. The water bulk densities in normal flood flows (Costa, 1988) generally range between 1.01 and 1.33 g/cm^3 while in hyperconcentrated flows bulk densities are in the general range of 1.33-1.80 g/cm^3; in debris flows, solids may constitute 70-90% by weight (47-77% by volume) of the flow mass and bulk densities generally are 1.80-2.30 g/cm^3 for typical poorly sorted sediments.

Measurements of density of debris flow material at rest in the deposition or in the source area usually do not present particular difficulties and can be performed through the collection of undisturbed samples by pushing a lubricated tube into the soil (e.g., Anderson & Sitar, 1995). Difficulties may derive from the abundance of big clasts (having diameter more than 5-10 cm) or from the presence of a metastable soil structure: in this case, the in-situ density can be estimated weighting materials dug-out from a hole and measuring the hole volume by standard methods (AASHTO T 91, 1986; UPD, vol. 2, 4).

Measurements of density of flowing debris is extremely difficult; ordinary samplers are easily crushed and washed away with only a hit of a running debris flow head. Moreover the presence of large boulders requires large samplers, increasing the probability of damaging the sampler. Due to these difficulties, very few instrumented basins have special sampler for flowing materials and published data on fluid bulk density are very scanty.

One of these basins is the well-know instrumented catchment in the Kamikamihori Valley on the eastern slope of Mt. Yakedake (Japan). Two kinds of debris samplers have been there installed (Okuda et al., 1980): one is a sampling cylinder (15 cm depth x 12 cm diameter), which is set at the top or side wall of a control dam in order to catch smaller fragments from overflowing water above the dam; the other is a larger sampling box (30 x 30 x 60 cm) which is set near the edge of the floor of the passing section of a dam and after it catches the debris fragments flowing into it from upstream entrance, it is pushed down by the flow and is kept hanging in the air at the lower side of the dam. Other special mechanical equipment for sampling flowing debris are installed along the Jiangjia Ravine, Yunnan Province, China (Zhang & Xiong, 1997) and at Sakurajima Volcano, Japan (Takahashi, 1991).

A very simple method for debris sampling is to insert a jar into the flow and to pull it out quickly, reducing in that way the probability of sampler crushing. This simple method has been used at Mt. Thomas (New Zealand) for sampling extremely poorly sorted flowing debris (Pierson, 1980): samples of just two liters in volume were collected by inserting wide-mouth (9 cm diameter) plastic jars into the flow; one six-litre sample was obtained with a bucket. Obviously, particles coarser than a few centimeters would have trouble entering the sample jars and the coarser fraction is usually not completely represented.

However, even the bulk density values obtained from material sampled in a running debris flow could be considered scarcely representative of the real fluid density; the debris filling the sampler is in fact in a static condition and is build up by particles settling following the depletion of the dynamic agitation. An indirect way to estimate the average “real” bulk density of a flowing debris could be through the measurements of flow height and load. These quantities can be measured installing a load cell at the channel bottom and an hanging ultrasonic sensor in a certain point along the debris flow channel: dividing the total load by the flow height it would be possible to evaluate the mean bulk density of the moving debris flow and, depending to the sampling time, its variation with time (UPD, vol. 2, 5 and 6). Ultrasonic sensors have been installed in many instrumented basins (e.g., Okuda et al., 1980; Arattano et al., 1997) and also pressure gauges (Tsuchiya et al., 1996) but no data have been published so far on bulk density estimated in that way.

8. Measurements of impact force

Debris flows exert enormous impact forces on obstacles in their path, such as bridge piles, defensive walls, buildings and so on. Estimation of the range of impact force is necessary for reasonable planning of structures against debris flows (Okuda et al, 1980).

The impact force of debris flows consist of two parts: the dynamic pressure of fluid and the collisional force of single boulders (Zhang, 1993). This latter often causes damages to engineering structures. Several devices have been developed by different researchers to measure the impact force of debris flows (Okuda et al., 1980; Zhang, 1993). All these devices operate automatically. Some of them only record the maximum impact force, such as the *pressure mark gages* employed by Okuda et al. (1980) on Mt. Yakedake. This gages were set on dam walls or large stones. They consist of an aluminium plate and a steel cone attached to a steel plate. By impact on the steel plate the sharp apex of the cone penetrates in the aluminium plate and the size of the mark engraved on the plate depends on the impact force. Of course this type of gage needs to be reset each time a flow passes. Both Okuda et al. (1980) and Zhang (1993) used strain gages and recorders to measure impact forces. The Mechanics Institute of the Chinese Academy of Sciences has also developed a specifically designed piezoelectrical sensor which is connected to a microcomputer to collect and process the data (Zhang, 1993).

Zhang (1993) reports to have collected more than 70 impact force graphs since 1982, finding fluid dynamic pressures as great as $5 \cdot 10^6$ Pa and impulse forces of individual boulders as large as 3120 KN.

9. Measurements of soil saturation and pore pressure in the triggering zone

It is widely recognized that a critical combination of hydrologic factors and material characteristics is required for debris flow initiation to occur. The hydrologic factors include antecedent moisture conditions and a triggering event (e.g., rainstorm, or snowmelt) which elevates pore pressures. Thus, a measurement of the variation of antecedent soil moisture before failure and pore pressure growth at failure is necessary to understand the debris flow failure mechanisms.

Despite its primary importance, little attention has been addressed in the literature to perform quantitative measurements of soil moisture for the purpose of evaluating debris flow susceptibility. Most of the published data derive from field studies on debris flow initiation and mobilization in hillslope regions characterized by residual fine-grained soils laying on steep slopes affected by widespread debris flows activity following intense storms. In these areas, most debris flows initiated as thin slabs of soils (0.5 to 2 m thick) sliding along planar surfaces: the measurement of soil moisture and pore water pressure can be easily done using the classical devices employed in geotechnics.

Harp et al. (1990) used electronic piezometers to record positive pore pressure response during failure of soils in three instrumented sites (two in Utah, one in California, USA): detailed records were obtained using pressure transducers (9 sensors in each of the two sites in Utah, 10 in California site) with a resolution of 0.6 mm and accuracy of ± 1.3 mm head. Nine piezometers equipped with electronic pressure transducers have been also installed in two monitored sites near La Honda (California, USA) in order to study the relation between heavy rainfalls, shallow positive pore pressure and slope stability in hillslopes susceptible to debris flow (Wilson & Wieczorek, 1995); data recorded were transmitted by radio and signals were decoded and stored on a remote computer. Similar devices have been also used for debris flow hazard assessment in British Columbia (Fannin et al., 1997), were a network of 32 piezometers were installed in shallow colluvia soils and data were collected near-continuous for approximately eight years.

Pore pressure response to rain storms were studied using both automatic and manual piezometers by other authors (e.g. Pierson, 1980; Keefer & Johnson, 1983; Wieczorek, 1987; Wieczorek & Sarmiento, 1988;) always in areas characterized by landslide-induced debris flows.

The study of dynamic response of subsurface waters in relation to storm runoff processes in drainage basins has been performed by many authors (e.g., Anderson & Burt, 1977; Tanaka et al., 1989; Anderson & Thallapally., 1996) using piezometers and tensiometers (UPD, vol. 2, 5 and 7).

For the purpose of evaluating the importance of antecedent soil moisture conditions on debris flow initiation, Johnson & Sitar (1990) installed, in a small area located in the

Briones Hills (California, USA), an instrumentation capable of measuring pore pressures under saturated and unsaturated conditions. Instrumentation consisted of five tensiometers-piezometers equipped with electronic pressure transducers calibrated for a range of ± 100 kPa; prior to installation, tensiometer have to be filled with de-aired water and the porous ceramic tip has to be saturated. Unfortunately, the tensiometers require careful maintenance after installation (they have to be flushed with de-aired water as need, about once every 7-10 days depending on the soil saturation) and this can be a serious problem if the monitored area is hardly accessible.

The in-situ soil saturation can be indirectly evaluated relating the measured negative pore pressures in the field with the moisture-retention curve of the soil determined on undisturbed samples; serious problems in using this method can arise if it is difficult to collect undisturbed soil samples or if it is hard to reach the monitored area for tensiometers maintenance. A special device used to determine volumetric soil moisture content is the Time Domain Reflectometry (TDR), that is based on the measurement of radar velocity and permit the automatic recording of moisture data. This kind of devices has been used in some experiments conducted in a USGS debris flow flume (Reid et al., 1997), where TDR probes were sampled every 3-4 minutes by a proper data-acquisition system; in our knowledge, however, TDR sensors have not been never tested in the field.

10. The Acquabona monitoring system

10.1. Overall view of the monitoring system

As an example of application of different monitoring devices in a catchment the instrumented basin of Acquabona is here described. The monitoring system operating at Acquabona is constituted by three on-site stations located along the debris flow channel (Fig. 10). Each station is equipped with various sensors measuring quantities of interest and radio-transmits, at established intervals, sets of data at the base station where they are stored in a PC. The base station is remotely controllable and data can be retrieved through the phone line by modem connection.

The system is capable of automatically discriminate the condition of occurrence of a debris flow. This feature is required since, during an event, data have to be acquired and stored much faster than radio transmissions permit and video systems (cameras + VCRs) have to be switched on and off. Functioning in “event mode”, hence, implies the powering of the video systems, the fast data acquisition (5 Hz) and storage on a physical memory support present in each station.

The “event mode” triggering condition is crucial for the good and profitable functioning of the monitoring system. At Acquabona a double check triggering condition based on debris flow induced ground vibrations and rainfalls gave good results in the period of functioning since it guaranteed reliability and a very limited number of false alarms.

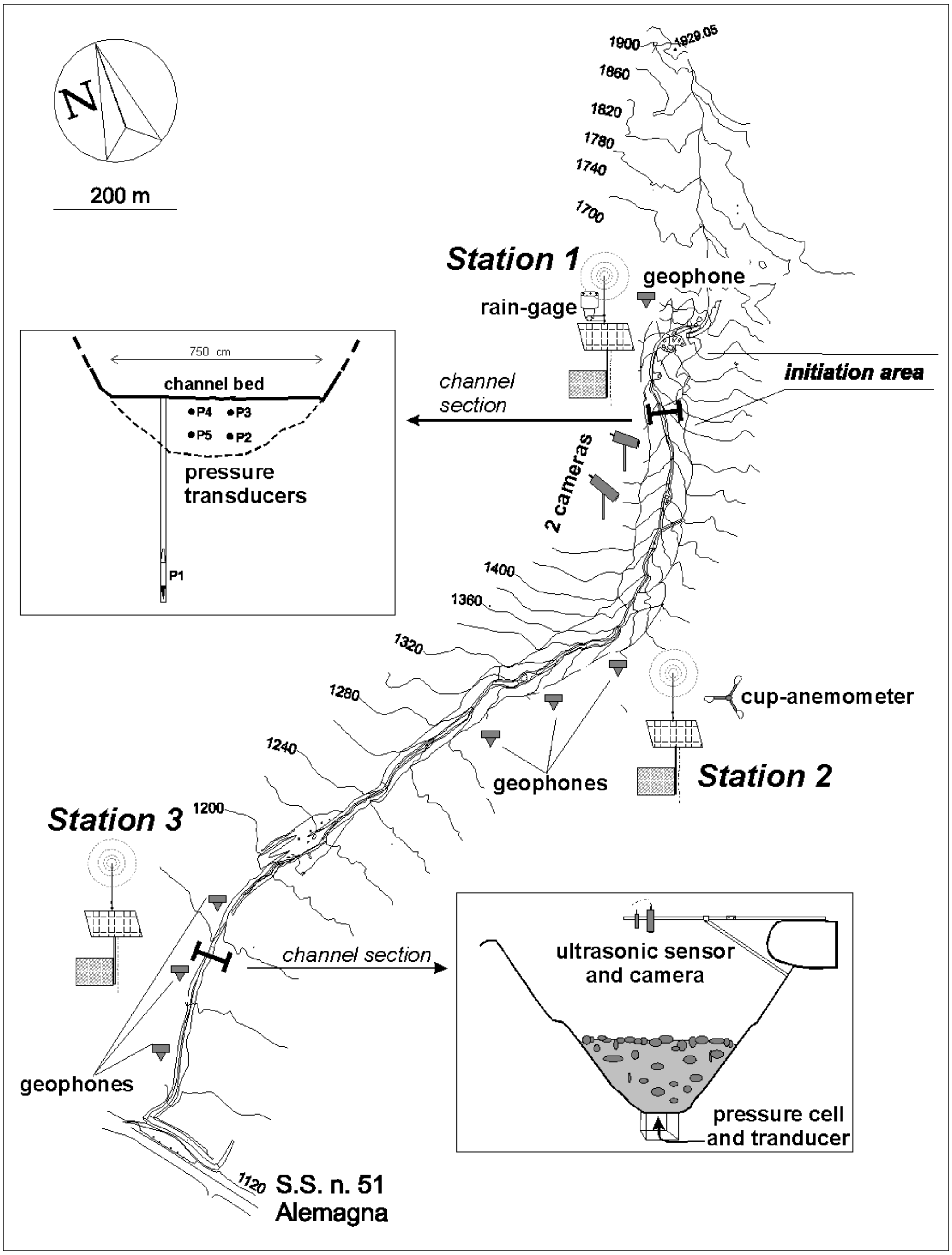

Figure 10 – The Acquabona monitoring system. Locations of the 3 monitoring stations are shown together with the operating measuring sensors.

10.2. Monitoring stations and measurable debris flow characteristics

Each monitoring station located along the flow channel has the same basic characteristics. The powering is provided by a 12 V battery recharged during daylight hours by a solar panel. An 8 channels data logger manage the data measured by the sensors, a microprocessor constantly check the triggering threshold and “decide” the operating mode. The equipment of each station includes also a transceiver radio and a 2 MB physical memory support.

The monitoring system design has addressed two main issues: the debris flow initiation processes and the characteristics of the mature flow. For this reason, besides traditionally monitored aspects like the measurement of triggering rainfalls (rain-gage - st.1) and of the mean debris flow front velocity along the channel (7 geophones located along the channel – st.1, st.2, st.3) particular attention has been devoted to the development of methods of monitoring the initial stages of the flow and of measurement methods of physical characteristics helpful in the identification of the rheological behavior of the flow.

Station 1 (initiation area, upper part of the flow channel) is equipped with 5 pressure sensors whose aim is the detection of eventual groundwater contributions to the initiation process (1 deep pressure transducer) and the measurement of the pore pressures present before and during the early stages of mobilization inside the channel bed material (4 shallow pressure transducers). A geophone measuring induced ground vibrations and a rain-gage complete the list of sensors connected to Station 1. Two cameras provide images of the initiation process which are decisive in the correct interpretation of the measured data and in the identification of the main dynamics operating during the development of the debris flow.

Station 2 (intermediate part of the channel) is equipped with 3 geophones located along the channel 100 m far from each other and measuring induced ground vibration. A cup-anemometer completes the sensors equipment.

Station 3 (lower part of the flow channel) is equipped with an ultrasonic sensor and a camera suspended upon the channel which provide detailed information about the flow height and the surface velocities as function of time. A hydraulic pressure cell and a pressure transducer located in the same cross section provide measurements of total and fluid pressures present at the base of the debris flow. Debris flow induced ground vibration are also measured by means of 3 geophones located along the channel 100 m far from each other.

Complete and detailed information regarding the monitoring system are reported in vol. 2 (UPD, chapt. 5).

Data collected by the monitoring system in the two years of activity (1997, 1998) and referring to three events occurred at Acquabona are presented in vol. 2 (UPD, chapt. 6) and in the "Acquabona '98" CD-Rom attached to vol. 2.

11. Measurements of displacements in the source area

Measurements of displacements in the source area of a debris flow permit to evaluate slope deformation before and during failure and, in some cases, could be used as an alarm gauge. Devices employed for displacements measure depends mainly from the initiation mechanism of debris flow.

In hillslope regions, where most debris flows initiate as superficial failures of soils, the classical devices used in geotechnics for slope movement monitoring can be successfully employed. In three monitored sites in Utah and California, for example (Harp et al., 1990), the installed displacement meters consisted of light-weight braided wire cable attached to a potentiometer; in the La Honda instrumentation site (Wilson &

Wieczorek, 1995) an extensimeter has been installed between two scars in a debris flow initiation area.

The little time that usually elapses between the initiation of a superficial soil failure and its mobilization into a debris flow does not permit other classical surface (surface levelling, triangulation, line of sight, tiltmeters, terrestrial stereography) or subsurface (inclinometers, shear-strip indicators, borehole extensiometers) measurements to be successfully employed. These devices could be usefully employed in some special cases, for example to monitor an active landslide that periodically dam the river at its toe causing a debris flow when the temporary lake outbursts. In this case, however, and in general if the initiation mechanism of the debris flow is not by landsliding (e.g., firehose effect, mobilization of torrent deposits, rill and gully erosion), the measurements of displacements in the source area are extremely difficult to perform and, since now, no attempt to perform such measurements has been yet published.

12. Real time management of debris flows

Due to their peculiar characteristics, such as extemporaneousness, rapidity of occurrence, high propagation velocity, short duration, destructiveness the task of dealing with the real time management of debris flows is a particularly difficult one. However structural measures, such as the construction and maintenance of deposition basins, check dams, channel linings are often both too expensive and not capable of completely guaranteeing the safety of the inhabitants of villages and the users of transportation routes present on the fans of debris flow prone torrents. Therefore the development and use of warning systems has been pursued by several researchers as a tool to face this often devastating kind of phenomenon.

Warning systems are probably more reliable for the protection of transportation routes than for the protection of villages, since it is simpler to impede in time the use of an infrastructure to a temporary user than to move in time an inhabitant from an endangered dwelling. This latter fact must be taken into account, since it has already happened (recently in Sarno, Italy but also in Canada as reported by Hungr et al. (1987)) that people were swept away and killed while attempting to flee an endangered house while the house remained undamaged. Davies (1997) suggests that good information is needed about the warning time reliably available and the time needed to reliably evacuate an area in order to be able to make a decision as to whether event-triggered warning and evacuation is a suitable hazard mitigation strategy. However he considers that it is likely that an event-triggered warning will not give sufficient time for reliable evacuation. If this is the case the only remaining possibility is a warning based on antecedent catchment conditions and weather forecast (Davies, 1997). In general it is important to clearly state that the use of warning systems requires an accurate education of the interested population (Seminara & Tubino, 1993; Cheng et al, 1997).

Following Hungr et al. (1987) warning systems can be classified in three different categories: *advance warning*, *event warning* and *post-event warning systems*. *Advance warning systems* are intended to predict the possible occurrence of a debris flow event before its occurrence, by monitoring predisposing conditions. *Event warning systems,* or event-triggered warning systems as Davies (1997) calls them, detect a debris flow while it is already in progress and provide an alarm and eventually a public warning is issued.

Post-event warning systems are intended to detect the fact a debris flow has occurred to allow appropriate measures. These will be treated separately in the following.

12.1. Advance Warning System

The most common pre-event warning systems for debris flows use correlations of rainfall data with debris flow occurrence, even though field evidences seem to indicate that rainfall or rainfall intensity cannot be used as the sole basis of a debris flow warning system (Hungr. et al., 1987). A well known rainfall intensity-duration threshold is that proposed by Caine (1980) and reported in the chapter regarding the monitoring of rainfalls. Another threshold is that of Wieczorek (1987), also reported in that chapter.

A well known weather observation system located in an area subject to debris flows was installed in 1983 by the Ministry of Transportation and Highways in British Columbia, immediately north of Vancouver (Hungr. Et al., 1987), however no data have been published yet on this system.

More recently Wilson et al. (1993) have described an operational, real-time warning system for debris flows installed in the S. Francisco Bay Area (California) since 1986, <u>which has already issued successful public warnings</u>. This system has been developed by the United States Geological Survey (USGS) and The National Weather Service (NSW), it is called ALERT (Automated Local Evaluation in Real Time) and consists of a network of radio telemetered rain gages across the S. Francisco Bay Region. The USGS has also installed a network of shallow (30-140 cm) piezometers on a hill slope in the La Honda study area where Wieczorek (1987) developed his threshold levels.

This warning system considers two complementary thresholds that relate to different time scales:

1) an antecedent rainfall threshold, requiring an accumulation of a certain amount of rainfall during the season and
2) a storm threshold requiring that a crucial combination of rainfall intensity and duration be exceeded during the course of the storm.

The USGS uses two methods to determine antecedent thresholds, depending on the investigated area:

1) seasonal rainfall totals are tracked for alert gages across the Bay area (250-400 mm are required depending on soil type and thickness (Keefer et al., 1987))
2) shallow piezometers are monitored in the La Honda area to find out when they first respond strongly to storm rainfall.

Once the antecedent rainfall threshold has been exceeded, approaching storms are evaluated to see if the intensity and duration of the expected rainfall are sufficient to trigger debris flows. At the beginning, in 1986, the debris-flow warnings were based on empirical rainfall thresholds that have been consolidated since then into a pair of relationships that outline a continuous spectrum of size and frequency of debris flows (Fig. 11). The lower “safety” threshold is adapted from Wieczorek’s (1987) and represents a rainfall level below which significant debris flow hazards are considered unlikely. The upper “danger” threshold represents a rainfall level above which abundant debris flows, large enough to destroy structures, are likely to occur across broad areas.

As a storm begins, rainfall intensities are monitored through the rain gages of the network and observed rainfall amounts are combined with the estimates contained in the Quantitative Precipitation Forecast (QPF), issued twice a day by the NWS, and then compared to the warning thresholds to determine the level of hazard and the type of public statement to be issued. The QPF contains an estimation of the amount of rainfall expected in each of four 6-hour periods, for the following 24 hours. For storms with rainfall levels just above the lower threshold, a brief statement may be added to a NWS "*Urban and small stream flood advisory*", warning motorists that roadways may be obstructed by rock falls or debris flows. A stronger statement is issued if rainfall is forecast to approach the upper threshold; this is called *Flash-Flood/Debris Flow Watch*. The strongest statement, a *Flash-Flood/Debris Flow Warning*, is issued for storms with rainfall levels above the upper threshold since such rainfalls could trigger numerous, massive debris flows leading to loss of lives and substantial property damage. This statement is also issued if report of significant debris flow activity are received. It is important to notice that sample texts for these debris-flow statements have been prepared with wording agreed upon by both the USGS and NWS, so that timely advisories can be issued with a minimum preparation of time.

Rainfall was below average in the S. Francisco Bay region between 1986 and the date of the report by Wilson et al. (1993), however several advisory statements were issued in response to unusual events that actually triggered a number of debris flows and rock falls. It is worth noticing, thinking of the recent disaster in Campania (Italy) caused by mudflows favored apparently by summer forest fires, that a special warning threshold was devised for the area stripped of vegetation by the Oakland firestorm occurred on October, 20 1991.

A similar, more prudential warning system is employed in New Zealand on the Kowai River to protect the village of Blandswood (Hall & Davies, 1992). The Kowai River is not precisely a debris flow prone torrent, but in the past has produced log-jam induced flash floods having the appearance of debris-laden surges 3-4 m high that have caused damages and casualties. Investigations have shown also in this case that two conditions are necessary for such events to occur: a very wet catchment due to 15-day antecedent precipitation of 70 mm or more and a one-day fall of 100 mm or more. Thus a two-stage system has been adopted. Stage I alert comes into force whenever the antecedent 15-day precipitation exceeds 70 mm and inhabitants are informed that a state of readiness exists. Synoptic weather monitoring begins at this time to forecast weather situations that could cause intense rain on the Konway catchment at least 12 hours in advance. If this occurs Stage II alert comes into force and an evacuation is ordered to take place in daylight and with ample time.

Also in China correlations of rainfall data with debris flow occurrence are used as warning system (Zhang, 1993). A relationship between 10 min precipitation intensity and precipitation of the antecedent 14 days was worked out in the Jiangjia Gully (Fig. 12) and during 1982-1984 it successfully forecasted 20 debris flows with only two failures. Through a precipitation telemetering apparatus the forecasts were made 20-40 min. ahead of the occurrences.

It is worth noticing that already in 1987 the Canadian Ministry of Transportation and Highways had contingency plans which stressed the role of highway patrols in debris flow hazards mitigation activities. These patrols had to observe water discharge changes and flow discoloration. This to emphasize the need and importance of a constant alertness both for the authorities in charge of civil protection and the involved people and that no automatic system will be never able to completely eliminate.

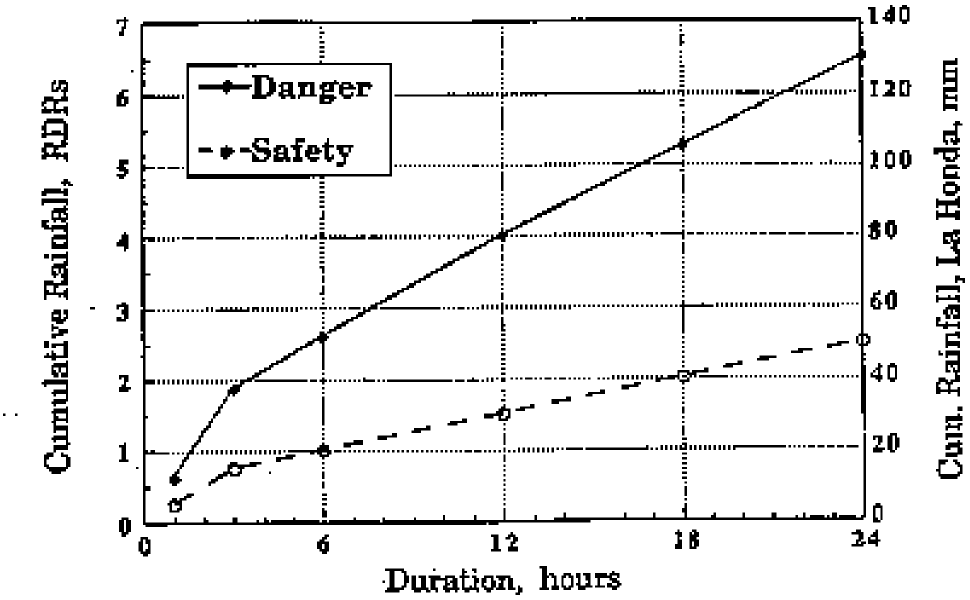

Figure 11 – Rainfall thresholds for triggering debris flows in the S. Francisco Bay Area (California), expressed as cumulative rainfall (RDR or mm) versus duration for peak rainfall periods (after Wilson et al., 1993). Rainy-Day-Ratios (RDR) for a given location is defined as the mean rainfall for the month divided by the mean number of rainy days (days with >1 mm rainfall) in that month. RDR is introduced to take into account orographic effects which lead to wide variations in local precipitation amounts.

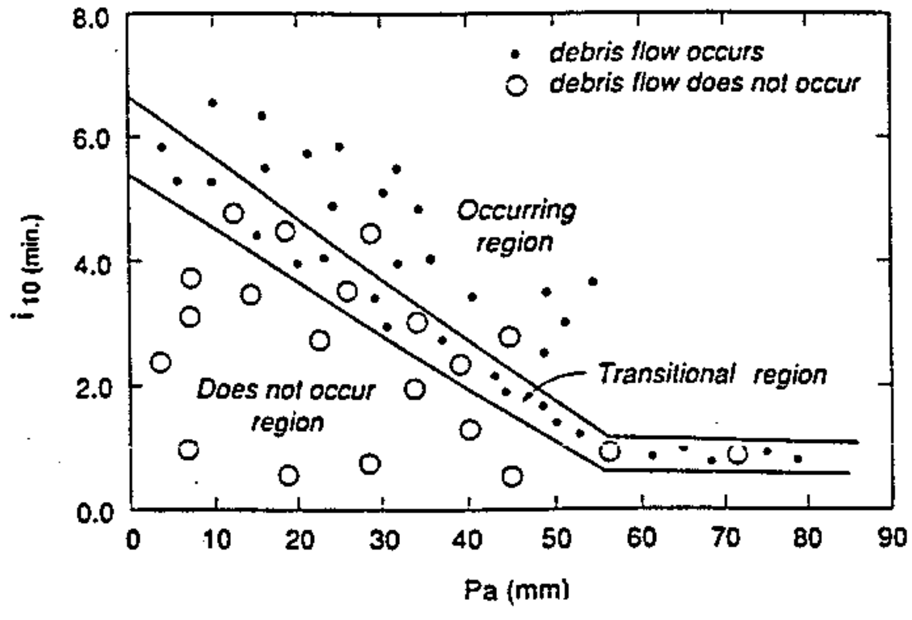

Figure 12 – Relationship between i_{10} (intensity of precipitation 10 min.), Pa (14 days antecedent precipitation) and the occurrence of debris flows in the Jiangjia Valley, China.

12.2. Event Warning Systems

The purpose of an event warning system is to provide an alarm when a debris flow occurs and is in progress. Hungr. et al. (1987) report that the only device of this type to have been used in British Columbia was installed in 1983 on Alberta creek and consisted of two trip-wire sensors with radio transmitters located in the middle reaches of the creek and a receiving unit in the protected dwelling. Due to a distance of 1.7 km from this latter the system could provide a warning period of the order of 3 minutes. Hungr. et al. (1987) question the effectiveness of this system, which was never tested by a debris flow and was disconnected twice by other causes during the first winter of its operation. They claim that warning systems could be valuable in protecting bridges carrying frequent traffic with the activation of warning lights, as it happens in Japan. Since highway and railway officials are reluctant to use them for their unreliability causing false alarms Hungr. et al. (1987) emphasize the need of the development of more reliable systems.

An *event warning system* based on the use of pendulums hanged over the creek and connected to a radio transmitter is in use in France in the S. Bernard catchment (Maurienne Valley, Fig. 7).

A similar system, based again on the use of pendulums hanged from a bridge over the torrent, is in use in another French stream, the Ravoire Torrent. These pendulums are connected to an electric cable which trigger a siren located in the Pontamafrey village, which is built on the fan. This system was installed after the ruinous debris flow event occurred in 1965. The siren allows the inhabitant to lift up a drawbridge that crosses the torrent. A deviation railway is also present in case an event damaged the main track.

In the Claret Torrent two vertical wire ropes have been set at the entrance of a tunnel to detect propagation of debris flows.

In China an ultrasonic mud-level warning device was successfully used in 1985 in the Jiangjia Gully during three debris flows (Zhang, 1993).

In Switzerland near Visp, in the Ritigraben Torrent two seismic sensors have been installed connected to a hardware and software-packet, that prevent false alarms, caused by wild animals or stone falls. The alarm signal is sent to the local police station and to two traffic lights of the near district road (Visp-Mattertal), that turn to red for 15 minutes and blink yellow after.

In Japan Itakura et al. (1997) have recently proposed an acoustic sensor that does not require maintenance, takes continuous measurements and consumes a small amount of electrical power. The sensor is made of a microphone installed inside a stainless steel pipe. A prototype model caught expected data at the Nojiri River in Japan back in 1991, so an advanced model was designed, fabricated and tested. If the output amplitude exceeds a threshold level during more than 2 sec, the sensor system gives the alarm. This sensor system has been set since 1993 at two points of the Nojiri River and good results have been already obtained.

In the USA Lahusen has developed an automated debris flow detection instrument, which he has called Acoustic Flow Monitor (AFM), and has deployed it at numerous sites since 1990 to calibrate and improve it. It uses a geophone with a higher frequency response (10-300 Hz) than a typical earthquake seismometer (0.1 - 20 Hz) in order to avoid noise from more distant sources (lower frequencies do not attenuate as rapidly as higher frequencies). This system constantly monitors the amplitude, frequency and continuous duration of ground vibration signals searching for the pattern typical of debris flows. Data are radio telemetered at regular intervals and whenever the detection criteria are met (Lahusen, 1998, personal communication).

In China Zhang (1993) reports of a sensor called groundophone (DT-1 model) developed by the Acoustics Institute of the Chinese Academy of Sciences for detecting the vibrational waves produced by the passage of a debris flow. During the period between 1984 and 1985 an improved version of this sensor, capable of telemetering the data, was able to detect 14 debris flows having discharges as low as 10 m^3/s.

It is worth noticing that warning systems based on the use of seismic sensors are used also for snow avalanches (Lepettre et al., 1996; Decker et al., 1997)

12.3. Post event Warning systems

Post event warning systems are easy to provide and can be invaluable on transportation routes, when these do not carry frequent traffic, where they warn of a disruption such as a burial of road surface by debris or a bridge collapse (Hungr. et al., 1987). This type of system is widely used in Canada to protect the Canadian Pacific Railway System (C.P.R.S.). The devices employed are of three different types. A first type of device consists of two lengths of thick wire mounted on wooden posts to form a 1.2 m high fence. Each wire connects to a “controller box” containing a spring and latch switch that closes when the pre-set wire tension either increases or drops. A second type of device consists of chain-link fencing reinforced with slats and suspended from a horizontal wire connected to the controller box. The switch is triggered by the increased tension as the debris flow lifts the fence panels to pass underneath them. The advantage of this second device is that it is easy to restore it after an event. A third, simpler type of device uses a weak copper link in the wire to interrupt the current, instead of the controller box system. Hungr. et al. (1987) state however that frequent false alarms make these devices unpopular with railway maintenance personnel.

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