Prediction of landslide occurrence in urban areas located on volcanic ash soils in Pereira, Colombia

D. A. Rios · M. Hermelin

Abstract As a result of the 25 January 1999 Armenia earthquake, the city of Pereira (400,000 inhabitants), located on a volcanic ash-covered alluvial fan in the western limit of the Central Cordillera (Colombia), suffered 250 slope movements. After a complete inventory, a monitoring process of unstable areas was designed, based on repeated topographic surveys, soil pore saturation levels and visual inspections. The participation of the communities was crucial and permitted the prediction of slope movements between 2 weeks and 3 months in advance and the evacuation of the inhabitants. Three specific examples are discussed. The method could be improved by excavating observation trenches and observing in detail local rainfall. In all cases, the strong involvement of the community was considered indispensable for the success of the process.

Résumés En conséquence du séisme d'Armenia du 25 janvier 1999, la ville de Pereira (Colombie) de 400 000 habitants, située sur un cône alluvial recouvert de cendres volcaniques dans la partie ouest de la Cordillère Centrale, a été concernée par 250 mouvements de terrain. Après un inventaire complet, un système de surveillance des zones instables a été conçu, basé sur des levers topographiques répétés, des mesures de niveaux piézométriques et des inspections visuelles. La participation des communautés a été cruciale et a permis la prévision de mouvements de terrain entre deux semaines et trois mois en avance ce qui a permis l'évacuation des habitants concernés. Trois exemples particuliers sont présentés. La méthode pourrait être améliorée en réalisant des tranchées d'observation et en suivant en détail la pluviométrie locale. Dans tous ces cas, la forte implication de la communauté a été considérée comme indispensable pour le succès de la surveillance.

Keywords Colombia · Disaster prevention · Humid tropics · Slope movements · Urban risks

Mots clés Mouvements de terrain · Risques naturels · Prévention · Risques urbains · Zone tropicale · Colombie

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Introduction

Pereira, a city of 400,000 inhabitants located on a volcano alluvial fan in the western slope of the Central Cordillera, central western Colombia, was affected by the January 25th 1999 earthquake. This event (magnitude 6.2, depth 10 km) had its epicentre located 48 km south of Pereira (Fig. 1) and resulted in numerous fatalities as well as the destruction of large areas of the city of Armenia and surrounding towns. Many landslides were triggered by this event: in Pereira 250 slides or unstable areas were detected in the 10 months following the earthquake. As a result of this preliminary study, a systematic inventory was carried out that identified 136 more examples. These form the largest database on landslides available in Colombia (FVF 1999). This paper summarizes some of the results obtained from monitoring these unstable areas (Fig. 2).

Regional setting

Pereira was initially founded on the slightly inclined surface of the Río Otún fan, at an altitude of 1,300 m above sea level. The climate can be considered as equatorial, with an average temperature of 20 °C and no significant change during the year. The precipitation (generally ~2,700 mm per year) is evenly distributed, with two peaks during April and October (IGAC 1972).

The Río Otún fan is a thick sequence of coarse volcanic materials emplaced by Pliocene and Pleistocene torrential and laharic activities of the Río Otún, which originates in

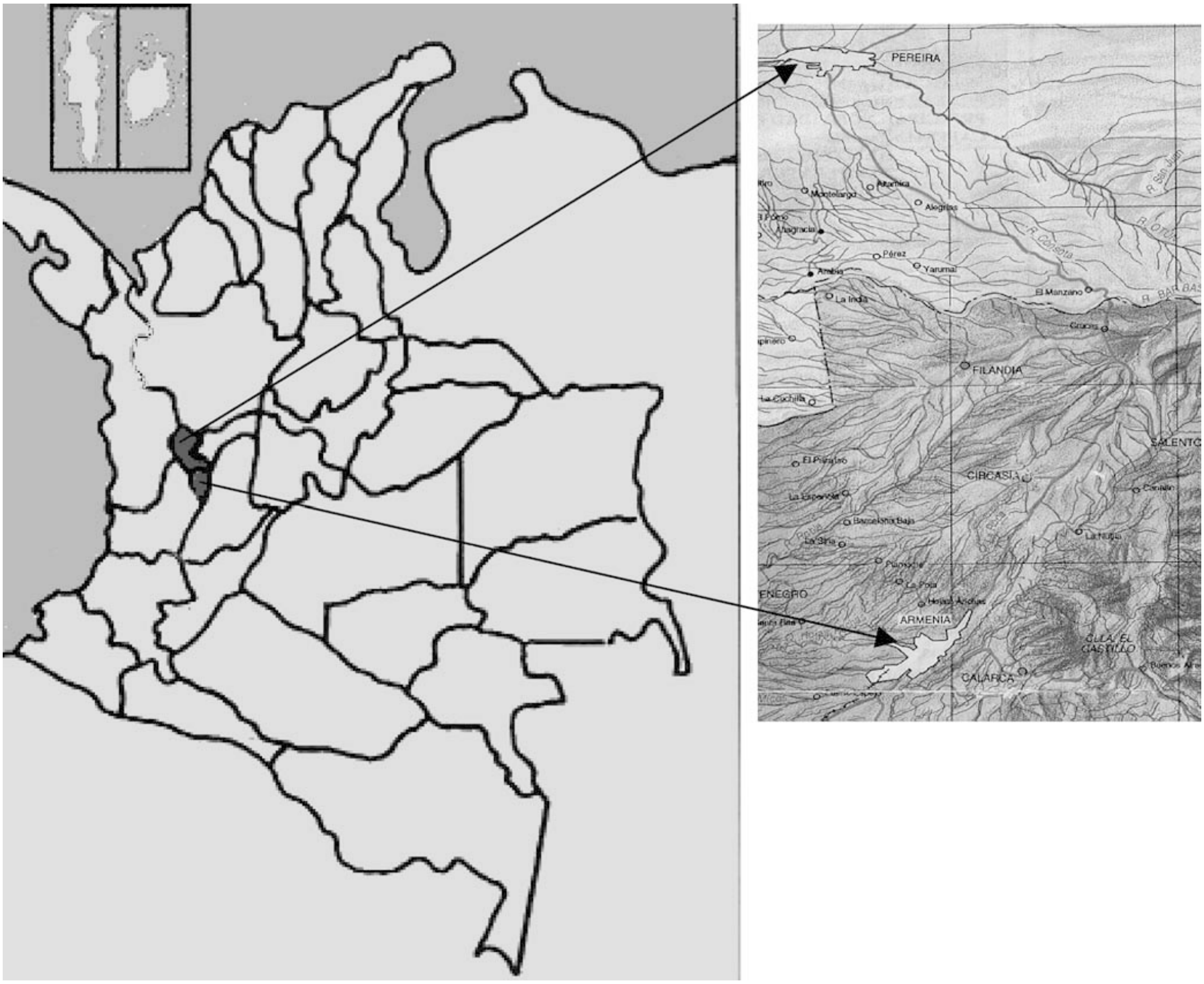

Fig. 1
Regional setting

the Ruíz-Tolima volcanic massif at an altitude of 5,300 m, some 30 km east of Pereira. (INGEOMINAS 1990).

The nearly horizontal surface of the fan is covered by weathered andesitic volcanic ash that reaches a maximum thickness of 8 m. Steeper slopes are also overlain by ash, although in thinner layers (Posada and Hermelin 1991). All these volcanic ashes are deeply weathered and only a very small fraction (1–2%) of primary minerals is conserved: most of the soils consist of clay minerals. The age of some of these ash deposits was obtained recently (Toro 1999).

As with many Colombian mountain cities and towns, Pereira, founded in the middle of 19th century, was initially located in an almost horizontal area. Further urban development has resulted in the occupancy of progressively steeper slopes, which were adapted by cutting terrace-like areas and re-distributing materials in order to provide building sites (Fig. 3).

In other cases, illegal developments started as shanty suburbs constructed mainly of "guadua", the local variety of bamboo, which has been progressively replaced by brick columns and walls (Fig. 4).

Methodology

Monitoring was carried out on the initiative of Fundación Vida y Futuro, a NGO which specializes in helping communities affected by disastrous events, and is under the co-ordination of government and private entities such as the Pereira Municipality, the local office for Disaster Attention and Prevention, the Fire Department, the Red Cross, etc. The monitoring programme was strongly supported by local communities, who participated directly in the observations and measurements. Three basic methods were used:

Topographic surveys

This method proved to be very effective in the follow-up of earth-fills located on natural soils. Large scale earth-fills are common in Pereira and have been affected by creep due to saturation, weight increase or vibrations (seismic or

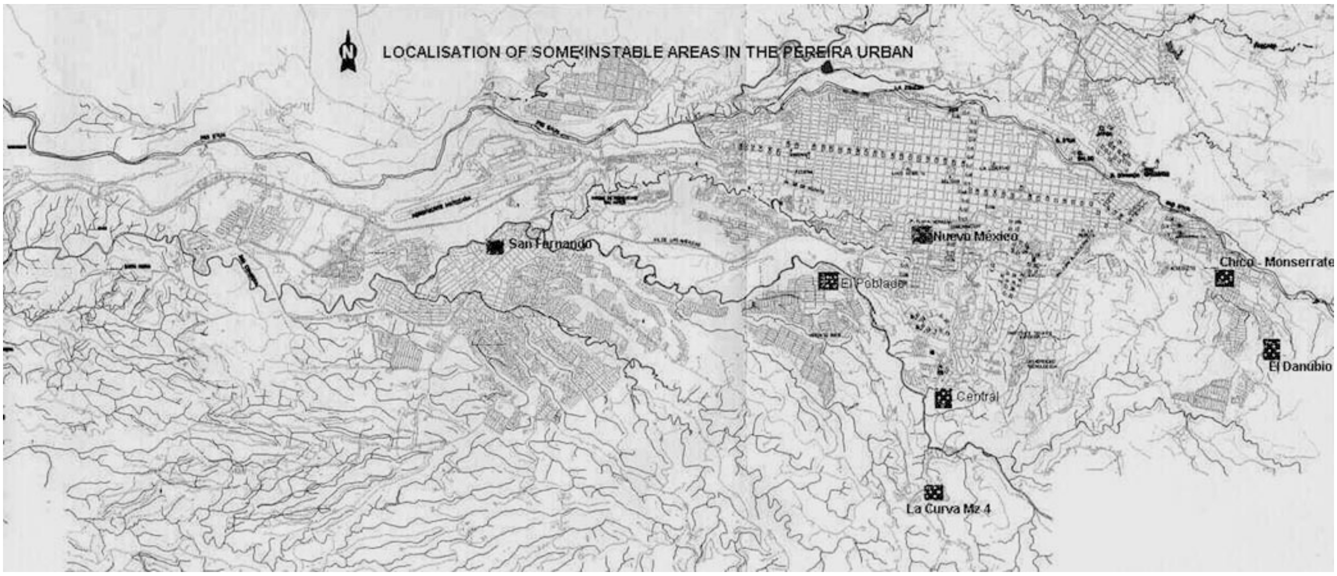

Fig. 2
Localization of unstable areas in the Pereira urban area

due to traffic). This method has also been used to control the behaviour of talus used for slope stabilization. Topographic measurements were carried out using theodolites and levelling rods marked at 5 mm intervals. Bench marks were installed in unstable areas and in control areas. Active sites were surveyed daily. Areas that were less active, but that support housing projects, were re-surveyed every 2 days, or twice a week if they were not inhabited.

Monitoring of saturation level

In Pereira, several talus slopes failed abruptly without showing previous displacement, a fact that made prediction impossible by topographic surveys. These slopes, cut in weathered volcanic ash, lose their cohesion as a consequence of excessive overload, but primarily as a result of the influence of high humidity and the steepness of the cut slope. Stability depends mainly on friction (ϕ) and, in view of the very limited cohesion, sudden failure can occur. In such situations where the moisture content of the soil may be greater than the liquid limit of the deposit, the movement is usually quick. To monitor saturation level, the moisture content of the talus was compared with the liquid limit values in the layers most prone to failure. This measurement was carried out as follows:

1. Vertical drilling for visual description of materials, until reaching the layer more prone to failure. The depth of this layer was registered and samples taken.
2. Drilling used a 100 mm diameter auger. The drill holes were conserved by lowering perforated PVC tube to the likely zone of failure. The hole was then sealed with paraffin wax and a cover emplaced.
3. Index tests, including Atterberg limits and particle size analyses, were undertaken on the original samples. Further samples were tested for natural moisture content.
4. Samples were taken after every rainfall event, leaving some time for infiltration.

Daily visual monitoring

Some talus slopes appeared to have only a low to moderate susceptibility to failure. In these areas, a reconnaissance and follow-up programme was designed to determine their behaviour. After daily visual appraisals, a new hazard evaluation was carried out and some of the following decisions could be made:

Fig. 3
Scene of earth-filled area affected by a slide, Barrio Caracol, Pereira

Fig. 4
Slope in Chico District, Monserrate (Pereira)

1. to start topographic or saturation monitoring;
2. whether it was necessary to evacuate the inhabitants;
3. what stabilization works (if any) should be recommended.

Daily visual monitoring provided the opportunity to meet the community, to become familiar with their problems and, hence, to include their requirements in the planning of future works. When communities are involved in this type of decision, they are generally ready to co-operate in future maintenance and preservation works.

Results

The application of the three previously outlined methods allowed the successful prediction of eight landslides in the Pereira urban area; many lives and properties were saved (Table 1).
The three following examples describe in more detail how the procedure worked.

Caracol La Curva Mz 4

Two hundred low income families live in Caracol La Curva (Fig. 3). The methods used were topographic surveys and visual monitoring, which allowed small displacements in the underlying earth-fills to be detected. The slope where this settlement is built has a height of 10 m and a length of 150 m, with gradients of almost 100% (45°) in the upper part and about 20% (10°) in the lowest third.
The deposits consist of clay with alluvial clasts and, importantly, very heterogeneous, non-compacted, man-made fills. Both infiltrated rainfall and waste waters from the community contribute to the progressive development of slope instability.
As a result of the monitoring process, several houses were evacuated. Two were destroyed by the 24 February slide, 6 weeks after evacuation.

San Fernando Mz 18

This talus slope was studied by a topographic survey and monitoring of saturation levels. It was the ground water levels that were finally used to recommend evacuation. The 250 m long talus slope is up to 10 m high with housing on the upper and lower parts. It consists of an upper layer of non-uniform, dark brown organic soil, with partly man-made fill to an observed thickness of 5 m. Below is a grey-brown sandy silt referred to as the middle layer. The lower layer consists of a yellowish-brown sandy silt with varying amounts of sand, which is considered to have formed in situ by the weathering of volcanic ash.
The upper layer has a density of 2.26 ton (t) m^3 compared with 2.6 of the common natural soils in the region. The

Table 1
List of predicted landslides in Pereira

District	Evacuation	Slide occurrence
El Danubio Mz26 casa 18	23 December 1999	15 January 2000
Caracol La Curva Mz 4	4 January 2000	24 February 2000
San Fernando Mz 18	24 February 2000	7 April 2000
Nuevo Mexico-El Camionero	6 April 2000	7 March 2000
La Dulcera calle 28. Casa 28	3 May 2000	19 May 2000
La Libertad Cra 11 calle 66	10 May 2000	1 June 2000
Chicó Monserrate (entire talus)	28 March 2000	22 June 2000
Nuevo México. Calle 25 No 14B-18	30 May 2000	23 June 2000

Table 2
Mechanical properties at San Fernando site. *W* Natural moisture content; *LL* liquid limit; *PL* plastic limit; δh humid unit weight; δd dry unit weight; *C* cohesion; Ø friction angle; *Gs* solid specific weight; δsat saturated unit weight

Layer	Properties								
	W (%)	LL (%)	PL (%)	γh (ton/m^3)	γd (ton/m^2)	C (ton/m^2)	ϕ	Gs	γsat (ton/m^3)
Upper	68	67	46	1.38	1.02	4.1	0.0	2.26	1.5
Middle	60	80	55	1.4	0.8	1.6	34.3°	2.6	1.47
Lower	77	94	64	1.43	0.87	2.7	11°	2.54	1.47

natural moisture content (W) is very close to the liquid limit and is indicative of a poor quality soil that is likely to experience failure. The liquid and plastic limits of the lower layer material are similar to those found elsewhere in the region in soils derived from volcanic ash (Table 2). The monitoring indicated that the upper layer had moisture contents that slightly exceeded the liquid limit; therefore, a decision to evacuate was taken on 24 February 1999. A failure occurred 2 weeks later following torrential rainfall.

Chicó-Monserrate

This slope was monitored by visual observations (Fig. 4). Its height is 50 m, its length is 100 m and it supports 25 illegal buildings. The natural soils are covered by man-made earth-fills with thicknesses of 2–5 m and contain a significant proportion of litter. The slope reaches 100% (45°) in several places and its natural moisture content is very high, particularly in the middle of the slope. The houses have been affected by small mass movements and several showed cracks, sliding and water infiltration in floors and walls.
After evacuations were carried out in March and April, three slides occurred on 22 and 23 June 1999, mainly affecting the evacuated areas.

Main factors generating instability

In the Pereira urban area, the main factors generating instability are:

1. Human activity — this is probably the main factor as it involves the occupancy of areas that are completely unsuitable for housing, earth-fills and excavations in steep slopes, inappropriate cultivation, etc.
2. River bank excavation by streams.
3. Seismic activity — the January 1999 earthquake triggered numerous slope processes in many unstable areas.

Conclusions

The monitoring programme described here was carried out over a period of more than 6 months. During this time, the main factors causing landslides were identified and understood.
Continued sampling for groundwater level monitoring may be made easier by the excavation of permanent trenches. Continuous observation of precipitation, which can be carried on with simple community operated pluviometers, would very useful for the prediction of slides. It would permit an important correlation with saturation level and topographic and visual measurements.
Finally, the involvement of communities in the observation and monitoring of slope processes is of outstanding importance and does much to engender co-operation with ongoing works and, where necessary, evacuations.

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References

FVF (Fundación Vida y Futuro) (1999) Inventario de taludes en la ciudad de Pereira
IGAC (1972) Monografía del Departamento de Risaralda, Bogotá
INGEOMINAS (1990) Mapa geológico de Risaralda. Escala: 1:200,000. INGEOMINAS, Bogota
Posada BO, Hermelin M (1991) Bases Físicas para el Plan de Desarrollo del Area Metropolitana Pereira-Dosquebradas. AGID Report, no 16, pp 61–74
Toro GE (1999) Téphrochronologie de la Colombie Centrale (département d'Antioquia, abanico de Pereira). Une approche stratigraphique, géochimique, minéralogique et géochronologique (par ^{14}C et traces de fission).Thèse de Doctorat, Université Joseph Fourier, Grenoble