Proceedings

Geohazards

Engineering Conferences International *Year* 2006

Earthquake-induced Landslides in Colombia

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Abstract

Landslides due to earthquakes in Colombia have been historically reported since 1530 when ground cracking, soil movements and liquefaction events were induced by an earthquake which magnitude has not been defined. Since then more than thirty earthquakes have been identified to have produced landslides in the country, in some cases consequences related to landslides have been more significant than those due to direct effects of the earthquake itself.

The author has compiled a database of landslides induced by earthquakes in Colombia from which relationships between earthquake magnitude and landslide characteristics have been explored. It has been found that residual and volcanic soils are very susceptible to landslides by seismic. Some cases show to have induced liquefaction on alluvial deposits of the main rivers and sea shores. Failure of landfills has also been observed.

Relationships between maximum epicentre distance to landslides and area affected by landslides and earthquake magnitude were found. The influence of precedent climatic conditions was observed in reducing the seismic load required to induce landslides and in the difference on slide mechanism.

Introduction

Geological, tectonics, topographic and climatic conditions, besides the uncontrolled anthropogenic intervention are the common causes of landslides in Colombia, which have in turn caused large social and economical losses from historical times.

Earthquake-induced landslides have been historically recognised to have caused extensive damage in Colombia. Data had not been systematically compiled until the author started a comprehensive review of historical and technical report in order to create the database of earthquake- and rainfall-induced landslides. This paper refers to those landslides associated to earthquakes, which have been reported since 1530. A preliminary database of earthquake-induced landslides has been compiled in Table 1 and some results in relation to common failure mechanisms, natural and man-made causes and consequences are analysed in this paper.

General setting

Colombia is located at the northwest of South America covering an area of 2,070,408 km^2 including insular lands, 35% of the area is located along the Andes Mountains.

Mountains are the result of the subduction of the Nazca plate beneath the South American plate, forming a massive and complex-structured series of three parallel ranges which cut across the country from its Ecuadorian border toward the north-northeast. Magdalena River flows between the Eastern and Central Cordilleras and the Cauca River between the Central and Western Cordilleras forming the two main basins.

Interaction between the Nazca, South America and Cocos plates induces the continuous raising of the complex mountain systems and the permanent tectonic activity that results in intensive rock fracturing and high seismic activity. High rate of regional uplift is compensated by intense denudation rates by erosion and landslides, the basin of the Magdalena River, the most important river in the country, produces in average 916 $t/km^2/yr$ of sediments.

The oldest rocks in the country are Precambrian igneous rocks that form low mountains to the eastern region of the country along the boundary with the Guyana Shield and isolated mountains to the eastern part of the Eastern Cordillera and the north isolated Sierra Nevada, which reaches 5,800 meters over sea level. The Central Cordillera is the highest reaching an altitude over 5,000 m over sea level, is composed by Palaeozoic metamorphic and Mesozoic igneous rocks, these rocks have suffered intensive weathering producing deep residual soils; ancient landslides have covered these rock by large coluvial and talus deposits, main basins along this cordillera have been cover by soft alluvial and lacustrian deposits. The Eastern Cordillera is composed by Tertiary (south) and Cretaceous (north) sedimentary shales, sandstones and limestones, these units are partially affected by acid intrusions originating metamorphic rocks. Shales of different consolidation levels are particularly prone to landsliding due to their rapid degradation and are extensively covered by alluvial and coluvial deposits. The Western Cordillera is composed basically by Cretaceous igneous rocks interbedded with some sedimentary deposits.

During the Quaternary, intense eruptive activity has occurred in the middle part of the Central Cordillera and in the southern part of the Western Cordillera. Some catastrophic episodes have been associated to recent volcanic activity as the El Ruiz lahar that destroyed the town of Armero in 1985.

The country is located within the Intertropical Convergence Zone (ITC), this condition generated high and frequent rainfalls characterised by a bi-modal annual distribution with rainy season in April-May and October-November, showing peak values in June and October. Normal conditions are strongly altered by the El Niño and La Niña phenomena; the El Niño induces exceptional rainfalls generating extensively landsliding around the country. Rainfalls have a marked spatial distribution controlled by the mountains (Snow, 1976). The Andes area is much like a "island" in a "sea of rain". Excluding the exterior slopes which report rainfalls as high as 4,000 mm per year, mean annual value for the Andes is around 1,500 mm. The pacific coast show exceptional large annual rainfalls reaching 6,000 mm.

Continuous tectonic and volcanic activity have produced in the past several catastrophic events causing, in some cases, total destruction of principal cities as it was the case of the 1875 earthquake that destroyed the city of Cucutá or the 1983 earthquake that destroyed Popayán. According to the Seismic Hazard Map of Colombia, most of the country lies in seismic areas ranged between high and medium level, in which Peak

Ground Acceleration can be as high as 0.4 g and 0.25 g, respectively, for 475 years return period (NSR, 1998).

Landslides caused by earthquakes

Reports of earthquake-induced landslides in Colombia have been compiled by Rodríguez (2001) and updated for the present study. Table 1 presents those cases that have been identified so far in the country. Earthquake inducing landslides characteristics, damages, and landslide mechanisms related to each case are also compiled in this Table. Areas affected by landslides during historical earthquakes are shown in Figure 1.

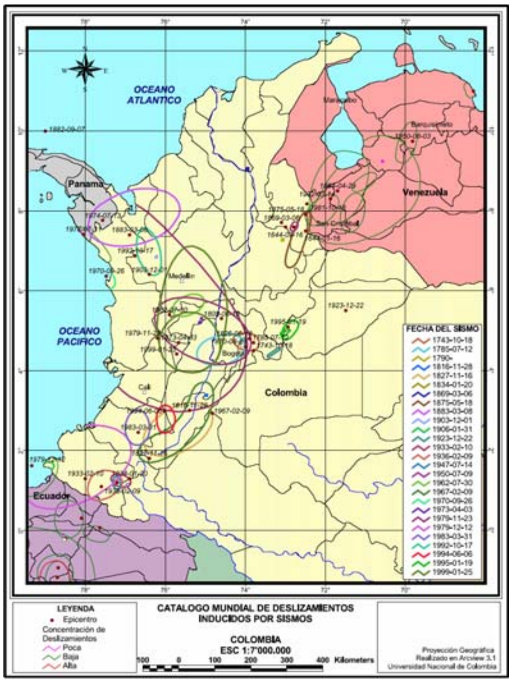

Figure 1. Areas affected by landslides during historical earthquakes in Colombia.

Landslide mechanisms. Earthquake-induced landslides in Colombia have been triggered in a wide range of materials and characteristics associated with intensity of seismic load and precedent rainfall conditions as shown in Table 1.

Rockfalls. These falls have commonly occurred in road and river cut slopes usually causing traffic disruption. Lithology units producing most rock falls included extensively fractured sedimentary, metamorphic rocks and volcanic tuffs. Rockfalls of sandstones blocks within the La Honda creek between Chipaque and Ubaque, are described as consequence of the 1644 earthquake, which epicentre was located near Bogotá. One person was killed by rockfalls during the 1967 earthquake in Baraya (Ramirez, 1975).

Soil falls. These slides usually are small volumes of disrupted volcanic or residual soil blocks that disintegrate, during movement, into small blocks or individual grains. They deposit material near the base of the slopes that commonly are steep road or river cuts. This failure mechanism was common during the 1999 earthquake that struck the coffee growing area formed mainly by volcanic ashes.

No	Date[1]	M_S[2]	Rain-fall Regime[3]	Min. intensity related to landslides (MMI)[4]	Damage[5]	Min acceleration related to the farthest disrupted slide[6] (g)	Area affected by landslides (km^2) Low[7]/High[8]	Maximum epicentral distance (km)			Geology[9]	Type[10]
								Cohe rent	Dis-rupted	Flow		
C1	1530-09-01		N									GC
C2	1610-02-03		N		70/-, RD, C, Ct		400/-					Sl,GC, Lq, Slu
C3	1644-03-16	6.0	M		RD,		565/-					Lq, GC, Sl, Rf
C4	1724-11-		M		Td							Sl
C5	1743-10-18	6.5	M		1/-, RD, Rd, C, Hb, Ct							Sl, GC
C6	*1785-07-12*	6.5	M		RD	0.01	8700/-		160			Sl
C7	1790-				RD							Sl
C8	1805-06-16	6.0	L		RD							Sl
C9	*1812-03-26*	7.0	N									GC, Sl, Rf
C10	1816-11-28		R					590				GC
C11	1820-06-		R		Rd							GC
C12	*1826-06-18*	7.0	M									GC
C13	*1827-11-16*	7.0	R		>300/491, RD, C,						Re	GC, Df, Lq, Rsl
C14	*1834-01-20*	7.0	Q		80/- TF, Td	0.03		70	70		Re, Vc	Sl, Lq, GC, Rf
C15	1869-03-06		D					165			Al	GC
C16	1870-08-01											GC
C17	*1875-05-18*	7.5	N		Td		5000/-	150	45		Al	GC, LS, Lq, Rf,

No	Date[1]	M_S[2]	Rain-fall Regime[3]	Min. intensity related to landslides (MMI)[4]	Damage[5]	Min acceleration related to the farthest disrupted slide[6] (g)	Area affected by landslides (km^2) Low[7]/High[8]	Maximum epicentral distance (km) Cohe rent	Dis-rupted	Flow	Geology[9]	Type[10]
C18	1883-03-08	6.0	F		RD	0.01	15000/-		110	110	Al, Re	Lq, Sl, LS
C19	1903-12-01	5.0	F	VII	RD	0.02			45		Al	Sl, GC
C20	1906-01-31	8.1	Q		Cm	0.01	400*/-		280		Al	SL, Lq, SSl
C21	1923-12-22		M		Rd, Cm			90				Sl
C22	*1936-01-09*	7.0	Q-R	V?	>250/-, RD, Td, C, Bd, Ct, TF	0.04	5200/-		55		Vc, SR	Sl, Df
C23	1947-07-14	5.5	R	VII	Cm, Aq	0.03	620/-		23.5		Vc	Sl, Rf, GC, Df
C24	*1950-07-09*	7.0	N	VII?	Rd	0.04	335/-		13		MR, Re	GC, Sl, Rf
C25	1962-07-30	6.7	I	VI	Rd		2500/-					Sl
C26	1967-02-09	7.1	R	VI	1/98, RD, Rd	0.01	15000/-	165	210		Al	Sl, GC, Lq
C27	*1970-09-26*	6.6	F	VII	C, TF, Rd, Bd, Td, RD, Aq		950*/-		30		Re, Al	Sl, Lq, Df, GC
C28	1973-04-03	6.7	I	VI	Rd	0.02			80			Sl
C29	1979-11-23	6.5	I-J-K-G	V	81?/-, R, RD	0.01	70000/36000		350			Sl, Df
C30	*1979-12-12*	7.7	Q	VII	Rd, Aq, Hd, Sub	0.01	350000*-	190	235	190	Al, La, Af, Co, SR	GC, Lq, LS, Slu, Rf, Rsl

No	Date[1]	M_S[2]	Rain-fall Regime[3]	Min. intensity related to landslides (MMI)[4]	Damage[5]	Min acceleration related to the farthest disrupted slide[6] (g)	Area affected by landslides (km^2) Low[7]/High[8]	Maximum epicentral distance (km)			Geology[9]	Type[10]
								Coherent	Dis-rupted	Flow		
C31	1983-03.31	5.1	R	VI	Rd, Ri, Aq	0.02	5000/-	55			Al, Re	Sl, GC, Slu
C32	*1992-10-17*	6.8	F-G	VI	TF, RD, Es, Rd	0.02	7000/-		100		Al, Af	Sl, Lq, LS, GC
C33	1994-06-06	6.7	R	VII	many/271, TF, Td, Bd, Rd	0.05	2900/-		35		Re, Vc, Co, SR	Sl, Df, GC, Rf, Slu
C34	1995-01-19	6.7	M	VII	Rd	0.05	1400/500		40		Co, Al, RS, RM	Sl, Rf, Df, Rsl,
C35	*1999-01-25*	5.6	I		Rd	0.01	50000/20000		300		Vc, Re, Al	Sl, GC, Sf

1. Bold dates refer to subduction events; Italic refers to multiple events.
2. Magnitudes before 1900 taken from Ramirez (1975), M_S: surface wave magnitude.
3. Rainfall regimes as reported by Snow (1976).
4. MMI: Modified Mercali Intensity.
5. Socioeconomic damage associated to landslides: (#d/#t) number of deaths due to landslides over total number of deaths, Rd: roads blocked; Aq: damage in water supply systems; C: cultivated area destroyed; Ct: Cattle died; RD: River Dammed; Td: Towns destroyed, Cm: communication lines destroyed; Ri: railway blocked; Es: electric station damaged; (?): contradictory or not precise information; Bd: bridge damaged; TF: tropical forest destroyed: Hb: houses buried, Sd: school damaged; Pt: port affected.
6. Accelerations estimated by using the appropriate attenuation relationship.
7. Areas of low-intensity landsliding truncated by coastline are noted by an asterisk.
8. Low and High in table refers to area enclosing low and high landslide concentration, respectively.
9. Natural deposits in which landslides were reported: Re: Residual soil; Co: Coastal deposits; Col: Colluvial Al: Alluvial; Vc: Volcanic soil; IR: Igneous rock; Lq: Liquefaction; De: Deltaic deposit; La: Lacustrine deposits.
10. Failure type: Sl: Disrupted slides; Slu: Slumps; Rf: Rock falls; LS: Lateral spreads; GC: Ground Cracks; SSl: Submarine slides; RSl: Rock slides; (?): contradictory or not precise information.

Disrupted rockslides. These are commonly translational slides along discontinuities dipping out of the slope face. Road and river cuts have shown to be very prone to this kind of slides, which are also seen to be induced in areas where previous intense rainfalls have fallen such as during the earthquake in 1827 for which intense rainfalls where reported the same day inducing a rockslide that dammed the Suaza River (Ramirez, 1975). Rockfalls and rockslides developed in steep slopes in the serrated low hills of Tertiary sandstones south of Patia River were induced during the December 1979 earthquake.

Coherent slides. Coherent slides consist of large blocks of soil or rock, separated by fissures and grabens that move remaining relatively intact. Total displacements are relatively small. Slumps move predominantly by sliding along basal shear surfaces that are curved or concave upward, so that the headward rotation of the slide occurs. Slumps were reported during the December 1979 earthquake that struck the southern zone of the country covered by volcanic deposits. Ground cracks and rotational slides were identified along the Colina de Belén-Popayan road after the 1983 earthquake (INGEOMINAS, 1986).

Disrupted soil slides. These slides usually consist of shallow sheets of volcanic and residual soils that disintegrate during movement. Most of the slides formed along weak zones such as the interface between weathered and fresh materials. Disrupted slides are also common in alluvial deposits along riverbanks; in this case highly-saturated materials disintegrate and move rapidly, reaching long distances from the source area. Other materials producing small disrupted slides during Colombian earthquakes are man-made fills and flood plain alluvium. Is worth of noting the 1994 Páez earthquake which induced hundreds of small shallow traslational slides on residual soils, which confluent to the Páez River and generated a large avalanche that destroyed small villages and produced important economical losses and killed more than 200 people (Schuster and Highland, 2001).

One of the major consequences related to disrupted slides are the damming of creeks and rivers such as during the 1827 earthquake that dammed the Cauca river near Puracé and the La Honda creek near Neiva, both dams broke down and produced debris flows that in the later case buried at least 161 people, other 21 people were buried in other point. Disrupted slides during this earthquake seem to be related to intense rainfall reported the same day. A total of 300 people were reported to be buried by landslides and debris flows during this earthquake (Ramirez, 1975).

The largest slide ever reported caused by earthquakes consists of a huge disrupted slide triggered by the 1834 earthquake, which induced failure of an area of 16,7 km long and 11 km wide, this slide produced extensive damage to natural rainforest and destroyed the town of Santiago de Sibundoy killing 80 people (Ramirez, 1975), the area is covered by volcanic ashes and tuffs. The 1936 earthquake also caused large damage in slope of volcanic soils, in this case a large slide destroyed the La Chorrera village killing between 250 to 300 inhabitants, and apparently this event was associated with large precedent rainfalls able to saturate the soil (Ramirez, 1975).

Lateral spreads, liquefaction and flows. Lateral spreads and flows are slides in which the movement takes place primarily by fluid-like flow. The fluid basal zones of lateral spreads are commonly made up of sand or silt that has been liquefied by build up of dynamic pore water pressure. These slides initiate in very gentle slopes in flood plain alluvium, alluvial fan sediments, deltaic, lacustrine and coastal deposits. Liquefaction of alluvial soils was reported for the 1644 earthquake along the Tunjuelito River, during the 1875 earthquake along the Pamplona and Tachira (Venezuela) rivers, during the December 1979 earthquake in the Pacific coastland rivers within the epicentral area, and during the 1992 Murindó earthquake along the Atrato, Murindó and Sucio Rivers. Subaqueous slides have been inferred along the coastal deposits as those that cause damage to the cable between Buenaventura and Panamá during the 1906 Tumaco earthquake.

Seismic shaking to induce landslides. Lack of strong-motion records around areas affected by earthquake-induced landslides makes it difficult to define the minimum seismic loads required to trigger landslides. In Colombia the minimum earthquake magnitude historically related to landslides is M_S=5.0, which corresponds to the 1903 earthquake. Landslides in Colombia have occurred at earthquake intensities as low as modified Mercali intensity (MMI) V, as happened during the December 1979 earthquake. Usually historical earthquakes include landsliding in intensity levels VI and VII. Large epicentral distances where landslides have been induced seem to be controlled by slope susceptibility rather than seismic load as can be seen by low values of minimum accelerations related to farthest slides.

Conclusions

Earthquake-induced landslides in Colombia show to be generated mainly on residual, alluvial, and volcanic soils; rock slides are common on sedimentary- and volcanic-rock deposits. In tropical environments slopes are generally densely vegetated, and landslide damage is more dramatic in terms of environmental changes due to reduction of tropical forest areas. Landslides in rock masses are common by densely fracturing induced by tectonic activity. Superficial degradation of intensively fractured and thinly stratified shales contributed significantly on instability of these rock masses during earthquakes. Landslide types include fast-moving falls and disrupted slides; low-moving coherent block slides and slumps in volcanic and residual soils are also frequent. Liquefaction of man-made fills, alluvial and coastal deposits are commonly reported after earthquakes in the area. Although most of the landslides have been reported for Mercalli intensities higher than VI, minimum acceleration related to farthest slides show that slope susceptibility and precedent rainfalls control seismic lad required to induce failures.

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