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ORIGINAL PAPER

The Third Hans Cloos Lecture. Urban landslides: socioeconomic impacts and overview of mitigative strategies

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Abstract As a result of population pressures, hillsides in the world's urban areas are being developed at an accelerating rate. This development increases the risk for urban landslides triggered by rainfall or earthquake activity. To counter this risk, four approaches have been employed by landslide managers and urban planners: (1) restricting development in landslide-prone areas; (2) implementing and enforcing excavation, grading, and construction codes; (3) protecting existing developments by physical mitigation measures and (4) developing and installing monitoring and warning systems. Where they have been utilized, these approaches generally have been effective in reducing the risk due to landslide hazards. In addition to these practices, landslide insurance holds promise as a mitigative measure by reducing the financial impact of landslides on individual property owners. Until recently, however, such insurance has not been widely available and, where it is available, it is so expensive that it has been little used.

Keywords Urban areas · Landslides · Mitigative measures · Grading codes · Early warning · Landslide insurance

Résumé Sous l'effet de la pression démographique, les zones urbaines s'étendent et les pentes avoisinantes sont souvent occupées à un rythme de plus en plus rapide. Ce développement urbain augmente le risque de glissements de terrain, déclenchés par des pluies ou des séismes. Pour contrecarrer ce risque, quatre approches ont été mises en œuvre par les experts en glissements de terrain et les spécialistes de l'aménagement de l'espace: (1) la limitation du développement urbain sur les zones sujettes à glissements de terrain; (2) la mise en œuvre et le renforcement des règles techniques relatives aux travaux d'excavation, de nivellement des terrain et de construction; (3) la protection des constructions existantes par des techniques permettant de limiter les dommages éventuels à venir; (4) le développement et l'installation de systèmes de surveillance et d'alerte. Lorsque ces approches ont été mises en œuvre, elles ont généralement apporté des résultats dans la réduction des risques liés aux glissements de terrain. En plus de ces pratiques, l'assurance contre les glissements de terrain représente une démarche prometteuse en réduisant l'impact financier des glissements sur les propriétaires particuliers. Jusqu'à une période récente, cependant, de telles assurances n'étaient pas largement répandues et lorsqu'il est possible aujourd'hui de s'assurer, les coûts sont si importants que l'assurance est peu utilisée.

Mots clés Zones urbaines · Glissements de terrain · Mesures de limitation des effets · Codes techniques de terrassement · Systèmes de surveillance et d'alerte · Assurance contre les glissements de terrain

Introduction

Population pressures are increasing in most of the world today and will certainly accelerate in the future. These pressures have resulted in rapid urbanization

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and development, much of it on hillsides. The world's urban population was estimated at 3 billion in 2003 and is expected to rise to 5 billion by 2030 (United Nations 2004). This increase in urban population will require considerable expansion of urban boundaries. For example, the land areas of the 142 cities in the United States with populations greater than 100,000 increased by 19% in the 15 year period from 1970–1985 (Schuster 1996). As a result of this urban expansion, housing development and the construction of industrial structures, urban transportation facilities and communications systems will disturb large volumes of geological materials. Much of this disturbance will be on hillsides that are susceptible to slope failure.

In addition to the pressures created by population growth, people are attracted to building on hillsides because of the natural beauty and the views from their property. As noted by Olshansky (1996, p. 1):

> "Hillsides pose unique problems for the construction and maintenance of human settlements. They are prone to natural hazards, and they topographically constrain the design of settlements. For these reasons, hillside lands often remain vacant long after adjacent valley floors are urbanized. Despite the constraints, they are attractive places to live because of the views and because of the sense of being close to nature."

Thus, much urban expansion is expected to take place in hillside areas. Ground failure by landsliding will be one of the most significant geological hazards affecting these new developments.

Along with the development of homes in residential subdivisions comes the entire fabric of infrastructure, such as streets, sidewalks, water and sewer lines and utility lines (Schwab et al. 2005). Such facilities require large amounts of grading, excavation and paving and the addition of significant areas of impervious surface. In addition, lawns and vegetation will require landscape irrigation. All of these modifications may contribute to slope instability.

In countries other than the United States, particularly developing nations, this pattern is being repeated, but with even more serious consequences. As development occurs, more and more of it will be on hillside slopes that are susceptible to landslide activity. All predictions are that worldwide slope distress due to urbanization and development will accelerate during the twenty-first century.

Population pressures are also contributing to increased landslide activity in other ways. An obvious example is the necessary construction of transportation facilities required by expanding populations. In landslide-prone areas, these facilities are often at risk.

The most common triggering mechanism of urban landslides is rainfall. However, earthquakes also trigger landslides in many urban areas. One notable feature of landslide hazards is the remarkable degree to which human activity can further the occurrence of these processes by destabilizing slopes that otherwise might have endured much longer between slope failures if left undisturbed (Schwab et al. 2005). Human alteration of the slopes can contribute to destabilization by (Olshansky 1996):

- Cutting slopes at steep angles or undermining the toes of slopes;
- Locating man-made earth fills on top of unstable or marginally stable slopes;
- Redirecting storm runoff so that flows are concentrated onto portions of slopes that are not prepared to receive them;
- Adding water to slopes by landscape irrigation or septic systems;
- Removing trees, shrubs and other woody vegetation.

Thus a general principle that must be observed in planning these new developments, or in redevelopment of existing urban areas, is that the building sites should be stable and not endangered by slope movements of any type (Záruba and Mencl 1982). Legget (1973, pp. 423–424) stated the following:

> "Anyone who has seen the havoc that can be wrought by a landslide in a developed urban area will appreciate that landslide study and prevention is one of the most important individual subjects within the field of engineering geology. It is a matter of steadily increasing importance in urban planning since the shortage of suitable building land around cities is forcing consideration of the use of sloping land with all of the consequent problems, of which the possibility of landslides is one of the most serious. If only because of the increasing use of hillside building sites in cities, the occurrence of landslides deserves the closest attention on the part of all urban planners."

As noted by Olshansky (1996, p. 7):

> "Despite the near unanimity of pleas in both the literature and local plans to minimize grading, the reality of hillside development in the United States is a proliferation of mass-graded subdivisions with level building pads."

There are at least three reasons for this increase in mass-graded subdivisions (Olshansky 1996): (1) it is an economical way to build; (2) housing demand is so extreme in urban areas that the hillsides are now being used for mass-produced housing; and (3) mass grading is the least expensive way to obtain a degree of stability of as many lots as possible in landslide-prone terrains.

To fully understand the impacts of landslides on urban areas, it is advantageous to review urban landslide case histories and their socioeconomic impacts. This paper presents outstanding examples of urban landslides from several countries and proposes a methodology for management of urban landslide hazards.

Socioeconomic impacts of urban landslides

The following cases of urban landslide activity are notable in regard to the extent of damage and/or numbers of casualties. In this discussion, landslide costs are given in US dollars for the time at which they were originally determined. In addition, the original values adjusted to 2005 US dollars are presented in parentheses; the adjustments were made on the basis of yearly cost-of living indices for the United States as established by the US consumer price index.

Biasca, Switzerland: September 1513

The city of Biasca overlooks the confluence of the Brenno River and the Ticino River in southeastern Switzerland. On 30 September 1513, during intense autumn rains, an unstable rock wedge, 10–20 million m^3 in volume, collapsed along a near-vertical fracture zone above the city (Eisbacher and Clague 1984). The disintegrating slab fanned across the Brenno River, damming the river and pushing a frontal wave of debris 100 m up the opposite valley wall. On 20 May 1515, the landslide dam was breached by overflow, resulting in an explosive surge of debris and water that engulfed Biasca and swept down the valley of the Ticino River into Lake Maggiore. About 600 people lost their lives in the debris flow flood, an example of a secondary loss from a landslide.

Piuro, Italy: September 1618

Despite its rugged mountain setting, the city of Piuro in northern Italy in the early seventeenth century became one of the most prominent urban areas in the region. After a week of almost uninterrupted rain in late August and early September 1618, 3–4 million m^3 of rock and surficial debris failed along a composite rupture surface dipping approximately 30° toward the city (Eisbacher and Clague 1984). Within seconds, the rock-debris avalanche buried some 200 buildings (Fig. 1) and killed approximately 1,200 people.

Huaraz debris flow, Peru, 1941

In 1941, a debris flow destroyed about 25% of the city of Huaraz in the Department of Ancash, Peru, killing an estimated 4,000–6,000 inhabitants (Bodenlos and Ericksen 1955; Ericksen et al. 1989). The debris flow, with a volume of at least 10 million m^3, swept 23 km down the Cohup Creek valley, through the northern part of Huaraz and into the Río Santa; it temporarily dammed the Río Santa. After 2 days, the dam was overtopped and breached and water and debris swept downstream to the coast, destroying settlements and farms in the valley of the Río Santa. This disastrous debris flow was the first major catastrophe to strike Huaraz in its 300 year existence; however, it was only a prelude to later landslide disasters in the area in 1962 and 1970 (see the following).

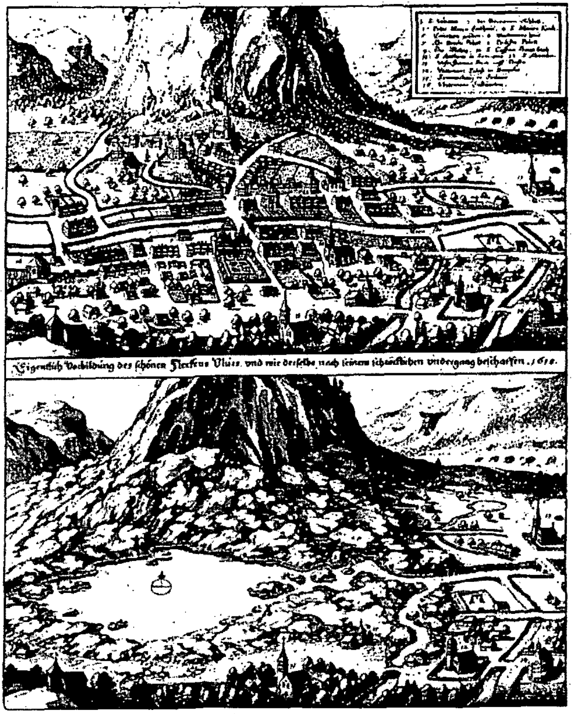

Fig. 1 The town of Piuro, Italy, before and after the September 1618 landslide disaster (Eisbacher and Clague 1984)

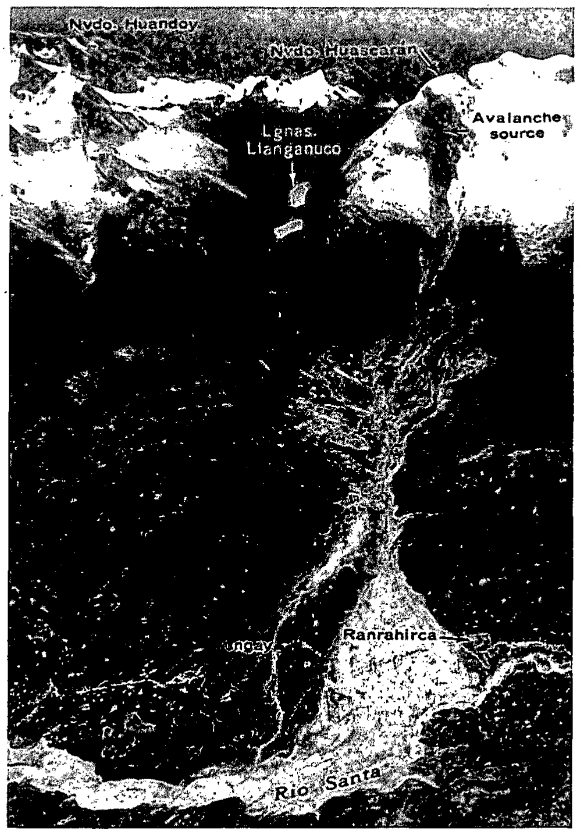

Fig. 2 1970 earthquake-induced debris avalanche on Nevados Huascaran, Peru. Town of Yungay is buried beneath the landslide in middle foreground. The avalanche descended approximately 3,500 m in travelling 14 km from its source to the Río Santa (Plafker et al. 1971) (Photo courtesy of Servicio Aerofotografico Nacional de Peru: June 13, 1970)

Nevados Huascaran debris avalanche, Peru, 1962

On 10 January 1962, a large debris avalanche was caused by the catastrophic failure of a hanging glacier at an elevation of 6,300 m on the north peak of Nevados Huascaran in the Cordillera Blanca of Peru (McDowell and Fletcher 1962; Morales 1966; Cluff 1971). The original ice avalanche transformed into a high velocity debris avalanche as it descended 4,000 m down the slopes of the highest peak in the Peruvian Andes, destroying everything in its path. McDowell and Fletcher (1962) noted that the elapsed time from inception of the avalanche to arrival at the town of Ranrahirca was 5 min, resulting in an average velocity of ~170 km/h. Nine small towns (including part of Ranrahirca) were destroyed and approximately 4,000–5,000 people were killed.

Nevados Huascaran debris avalanche, Peru, 1970

The greatest in number and most destructive landslides in the Andes known to have been triggered by a single event of any kind were those associated with the M7.75 earthquake of 31 May 1970, the epicenter of which was off the coast of Peru (Cluff 1971; Plafker et al. 1971; Plafker and Ericksen 1978). This earthquake triggered thousands, or perhaps tens of thousands, of landslides within a 30,000 km^2 area.

By far the most disastrous of the landslides triggered by this earthquake originated from the same north peak of Nevados Huascaran—the source of the 1962 debris avalanche described above. The 1970 debris avalanche consisted of 50–100 million m^3 of rock, snow and ice (Fig. 2). This mass travelled 14.5 km in falling from its source to the city of Yungay at an average velocity of 280–335 km/h (Plafker et al. 1971) Many farms and small settlements were obliterated, but the greatest damage and loss of life was in a densely populated area at the foot of the mountain. The city of Yungay (pre-landslide population: 18,000) and part of the town of Ranrahirca (pre-landslide population: 1,850) were buried by the high velocity avalanche; more than 18,000 people were killed in the two urban areas. Yungay was rebuilt at a new site a few kilometers north, out of the path of future avalanches.

Anchorage, Alaska, 1964

Youd (1978) estimated that ground failure caused 60% of the $300 million ($1.88 billion) total damage from the 1964 M8.3 Alaska earthquake; nearly all of the ground failure consisted of landslides, including lateral spreads. Five major landslides caused about $50 million ($314 million) in damage to non-military facilities in Anchorage, Alaska's largest city. Of special interest were land planning decisions related to the three largest slope failure areas: the Fourth Avenue, L Street and Turnagain Heights landslides (Hansen et al. 1966):

Fourth Avenue landslide

This landslide was a 15 ha block that moved horizontally about 5 m, destroying a significant part of Anchorage's downtown business district (Fig. 3). A Scientific and Engineering Task Force established by the federal government recommended that future developments in the Fourth Avenue landslide area be limited to parks, parking lots and small structures not more than two stories high (Hansen et al. 1966). The recommended restrictions were incorporated into an urban renewal plan that was relatively successful because much of the land belonged to the federal government and thus was easily controlled (Mader et al. 1980).

L Street landslide

The study by the task force indicated that this 29 ha block slide constituted a significant continuing hazard and they made the same recommendations as for the Fourth Avenue landslide. However, these recommendations were largely ignored for the L Street landslide because the land involved was privately owned and property owners felt that property compensation at post-disaster values was not sufficient inducement to relocate (Mader et al. 1980). In addition, local people seemed to believe that because a catastrophe had only recently occurred, another would not take place at the same location during their lifetimes.

Turnagain Heights landslide

The Turnagain Heights landslide was the largest and most spectacular of the 1964 slope failures, covering 53 ha and destroying 75 homes. The Alaska State Housing Authority presented a redevelopment plan for the landslide area calling for park and recreation uses (Mader et al. 1980). However, only the economically least desirable part of the landslide was actually developed as a park. As was the case for the L Street landslide, the main reason for only partial success in controlling redevelopment of the Turnagain Heights landslide area was the resistance of property owners to change to less intensive land use.

Río de Janeiro and Petropolis, Brazil, 1966–1967 and 1988

During the rainy summer season of December to March, the combination of steep slopes, heavy rainfall, residual soils and weathered rocks has made the coastal mountains of mid-southern Brazil particularly susceptible to major landslide activity. Urban growth in Río de Janeiro and nearby cities has spread from the lowlands onto slopes, and the attendant construction of highways has required huge side-hill cuts and fills. These human activities have caused many slope stability problems in urban areas (Da Costa Nunes et al. 1979).

Because of space limitations, all of these landslide events cannot be discussed here; instead, we will briefly review the most significant occurrences: the 1966–1967 disasters in Río de Janeiro Province and the 1988 major landslides in the vicinity of Río de Janeiro and Petropolis, a neighbouring city about 50 km to the north.

Fig. 3 Collapse of Fourth Avenue, Anchorage, Alaska, at the head of a 15 ha block slide triggered by the M8.3 Alaska earthquake of 27 March 1964 (Photo by US Army)

Fig. 4 The 18 February 1967 Bairro Jardim-Laranjeiras landslide, Rìo de Janeiro. This landslide resulted in the destruction of two apartment buildings and the deaths of 110 people (Da Costa Nunes et al. 1979) (Photo by Ruy Macial, Geo-Rio, Rìo de Janeiro)

Landslides in Río de Janeiro, 1966–1967

Unusually heavy rain fell in mid-southern Brazil during the summers of 1966 and 1967 (Barata 1969; Da Costa Nunes et al. 1969; Jones 1973). In 1966, the area most affected was metropolitan Río de Janeiro, where total loss of life from floods/landslides was estimated at 1,000.

In terms of casualties, one of Brazil's worst individual landslide events occurred in the Bairro Jardim-Laranjeiras district of Río de Janeiro on 18 February 1967. A high velocity debris avalanche triggered by heavy rain destroyed three buildings, two of which were apartment houses (Fig. 4), killing 110 people in the most tragic individual accident of its kind in Brazil (Da Costa Nunes et al. 1979).

Landslides in Petropolis and Río de Janeiro, 1988

In February 1988, heavy and persistent rainfall along the mountainous mid-southern coast of Brazil caused thousands of landslides in nearly the same region as in 1966–1967. Río de Janeiro and Petropolis again became disaster areas, sustaining a total landslide death toll of 320 (Nieto and Barany 1988; Ogura and Filho 1991). In Petropolis alone, 171 were killed, 600 were injured and 4,263 were left homeless. Perhaps as many as 80% of the landslides in these cities were related to human activities, mainly cuts and fills for highways and other construction.

Hong Kong, China

Natural slopes throughout heavily populated Hong Kong are steep; more than 60% of the land area is steeper than 15° and about 40% is steeper than 30° (Brand 1984). Slope failures are very common in the urban area of Hong Kong, and the consequences are often disastrous. The majority of these failures occur during periods of heavy rain and are small debris avalanches (or flows) of decomposed rock mantle that occur very rapidly with little or no prior warning (Lumb 1975). The scale of the problem is indicated by the fact that landslides have been responsible for the deaths of more than 470 people since 1948 (Malone 1998). The landslide problem is essentially the product of post-World War II urban growth, as most of these deaths resulted from the collapse of man-made slopes created by hillside development since the 1940s.

According to reviews by Lumb (1975) and Brand (1984, 1985), slope design in Hong Kong before the 1970s was based more on empirical considerations than on geotechnical evaluation. The standard cut slope at that time was about 60°, with some cuts being as steep as 70°. The conventional practice for angles for the construction of fill slopes was about 1–1.5 (about 33°). There were no standards that specified the type of fill material and the manner in which it should be placed. The lack of design and construction standards resulted in end-tipping from dump trucks being the standard practice for the construction of fills (Koo 1998).

Nearly all of Hong Kong's landslides are triggered by heavy rain. During the summer months the territory experiences intense rainstorms due either to tropical cyclones or to troughs of low pressure near the South China coast. Since central recording of landslide activity began in 1984, from 80 to 800 landslide events have been reported to the Geotechnical Engineering Office (GEO) annually (Malone 1998).

Especially notable were the destructive landslides that took place on 18 June 1972 during a severe rainstorm associated with a trough of low pressure (Malone 1998). The first slope failure was a flowslide (i.e., debris flow) that involved the collapse of the side slope of a 40 m high road embankment that had been constructed on sloping ground. The flowslide destroyed many huts in a temporary housing area, killing 71 people and injuring 60 others (Hong Kong Government 1972a, b). Later that day, another flowslide (Fig. 5) occurred in a private residential area on a steep hillside at Po Shan Road on Hong Kong Island (Malone 1998). Sixty seven people were killed and 20 injured when a 12-story apartment building was demolished under the impact of the fast-moving 50,000 m^3 flowslide (Vail 1984).

In August 1976, another disastrous landslide occurred; 18 people were killed in a fill-slope failure in northeast Kowloon (Koo 1998). The 1972 and 1976 events resulted in the establishment in July 1977 of the Geotechnical Control Office (renamed Geotechnical Engineering Office in 1991). Since its inception, this office has produced and published standards, guidelines and model specifications for the design and construction of slope works; a well-known example is the 1979 "Geotechnical Manual for Slopes" (Geotechnical Control Office 1979). Note that the number of annual deaths due to landslides has decreased considerably since the establishment of the Geotechnical Control Office (Malone 1998).

Abbotsford, New Zealand, 1979

On 8 August 1979, after 70 days of slow movement, the velocity of a large landslide in Abbotsford, a suburb of the city of Dunedin on the South Island of New Zealand, suddenly increased dramatically. In about 30 min, the 18 ha slide, with a volume of 5.4 million m^3, moved

Fig. 5 The 1972 rainfall-triggered Po Shan Road landslide, Hong Kong, which killed 67 people when a 12-story apartment building was destroyed by the 50,000 m^3 flowslide (Photo by Geotechnical Control Office, Hong Kong Government)

about 50 m (Schuster 2000; Hancox 2002). There were no casualties, but 69 houses were destroyed, condemned or relocated. Unusually heavy rainfall during the preceding decade (one of the wettest in 60 years), resulting in the rise of groundwater levels, undoubtedly was a major cause of failure.

The Abbotsford landslide disaster assumed national importance beyond socioeconomic costs. For example, it pointed out deficiencies in the New Zealand Earthquake and War Damage Act, which provided landslide insurance for building damage but not for the value of the land. A Commission of Inquiry was organized by the government to investigate the causes of the landslide, adequacy of preventive measures, planning of the subdivision, suitability and possible improvement of existing legislation, availability of insurance and procedures for preventing similar disasters (Commission of Inquiry 1980).

Nevado del Ruiz debris flow, Colombia, 1985

Because of its high annual rainfall, mountainous topography and frequent seismic and volcanic events, Colombia has a long history of catastrophic landslide activity. Nevado del Ruiz, the northernmost active volcano in the Andes, underwent a minor eruption on 13 November 1985, triggering catastrophic mudflows and debris flows (lahars) that killed more than 22,000 people and destroyed more than $212 million ($383 million) in property (Herd 1986; Garcia 1988; Voight 1990; Mileti et al. 1991).

The main lahar, which descended the eastern side of the volcano, down the valley of the Río Lagunillas, devastated the city of Armero (Fig. 6). More than 20,000 people perished in Armero (population: 29,000), most of them crushed or buried in their homes, and more than 5,000 were injured (Voight 1990). In addition to the casualties, the lahar destroyed or damaged 5,000 homes, 343 commercial establishments, 50 schools and two hospitals (Voight 1990).

The eruption of Nevado del Ruiz and the succeeding debris flow activity were not a surprise. Alerted by more than a year of precursory activity of the volcano, scientists had prepared a hazard zoning map that accurately predicted the tragic effects of the eruption weeks before it occurred (Voight 1990; Mileti et al. 1991). The tragic loss of life was due in large part to the failure of local authorities to plan and carry out an adequate emergency-response program.

Similar volcanic debris/mud flows had devastated the same valleys after eruptions of Nevado del Ruiz in 1595 and 1845 (Mojica et al. 1986; Voight 1990). Acosta (1846, translated and quoted by Voight 1990) described the 1845 event: "*Then, descending along the Lagunillas from its sources in the Nevado del Ruiz, came the immense flood of thick mud which rapidly filled the bed of the river, covered or swept away the trees and houses, burying men and animals. The entire population perished in the upper and narrower parts of the Lagunillas valley.*" Armero, which did not exist during these earlier disasters, was built on the deposits from these previous lahars.

Fig. 6 Debris flow/mud flow (lahar) that destroyed most of the City of Armero, Colombia, following the 1985 eruption of Nevado del Ruiz. Most of the city was covered by the flow; more than 20,000 people perished (Photo by Richard Janda, US Geological Survey)

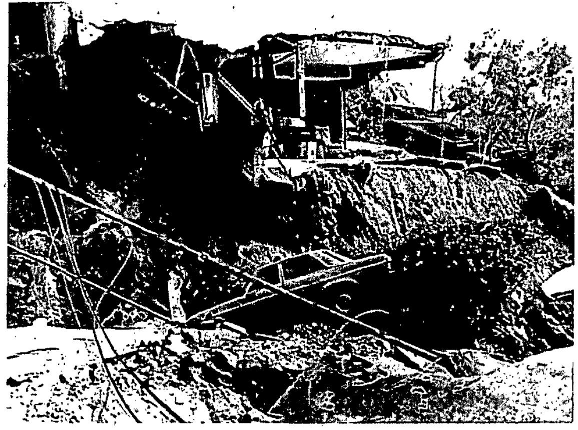

Fig. 7 Damage caused by the 1978 Bluebird Canyon landslide, Laguna Beach, California, that destroyed 25 homes, parts of three streets and the area's public utilities (Photo by Woody Higdon, courtesy of Leighton and Associates, Inc)

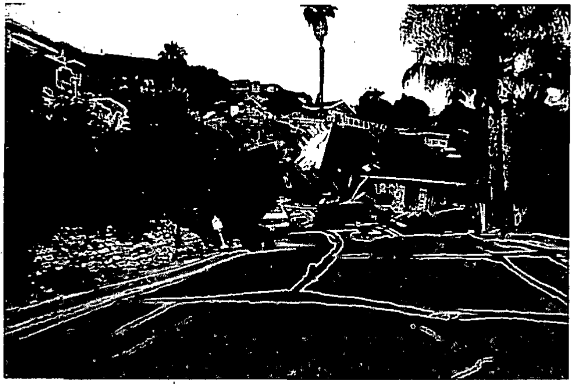

Fig. 8 Damage caused by the June 2005 Bluebird Canyon landslide (adjacent to area shown in Fig. 7) that destroyed or badly damaged 18 "million-dollar" homes (Photo by James C. Bowers, U.S. Geological Survey)

Los Angeles and vicinity, California,

The hillsides of Los Angeles did not begin to be populated until the 1910s and 1920s, after the flatlands became too crowded (Olshansky 1996). For example, between 1946 and 1962, 37,000 hillside residential lots were developed in the City of Los Angeles (Scullin 1983). This development of hillside properties undoubtedly was a major factor in the triggering of subsequent landslides.

Severe rains that have triggered major landslide activity have plagued the Los Angeles area several times in the past 50 years. The most costly individual landslide was the Big Rock Mesa slide along the Malibu coast just west of Los Angeles. This large creeping mass movement, which began in the late summer of 1983, resulted in the condemnation of 13 houses and threatened 13 others. The individual homes ranged in value from $400,000 ($750,000) to more than $1 million ($1.9 million). During 1984, many lawsuits related to this landslide were filed by property owners against Los Angeles County and several private consultants. According to a deputy county counsel, the total of legal claims against Los Angeles County as a result of the slide was more than $500 million ($940 million; Association of Engineering Geologists 1984).

Other noteworthy landslides that have done serious damage to suburban communities in the Los Angeles area occurred in Laguna Beach (1978 and 2005) and La Conchita (1995 and 2005). The 2 October 1978 Bluebird Canyon (Laguna Beach) landslide destroyed or damaged 50 homes (Fig. 7) (Miller and Tan 1979; Tan 1980). This landslide caused direct losses estimated at $15 million ($45 million).

On 2 June 2005, another landslide occurred in Bluebird Canyon, this time destroying or badly damaging 18 "million-dollar homes" (Fig. 8). As a result of this slide, the Los Angeles City Council endorsed an ordinance that will limit the size of new homes to be built in the area (Science Daily 2005). Dubbed the "anti-mansionization" ordinance, the proposed law will restrict homes built on 750 m^2 lots to a maximum floor space of 225 m^2 or 40% of the lot size, whichever is greater. The measure is an effort to combat the construction of large buildings on small lots in a landslide-prone area.

Severe winter storms in January and March 1995 brought above normal rainfall that triggered damaging debris flows, deep-seated landslides and flooding to Los Angeles and Ventura Counties in southern California (Harp et al. 1999). The most notable of several deep-seated landslides triggered by the storms was the 4 March 1995 La Conchita landslide (Fig. 9) in the small residential community of La Conchita, which lies northwest of Los Angeles. This reactivation of part of an ancient complex slump-earth flow in marine sediments destroyed or badly damaged nine houses (O'Tousa 1995; Jibson 2005). Because the slide moved at only a moderate rate (tens of metres in a few minutes), there were no casualties.

On 10 January 2005, the left side (looking downstream) of the 1995 La Conchita landslide remobilized due to heavy rainfall, this time as a high velocity debris flow that destroyed 13 houses and badly damaged 23 others (Fig. 10) (Jibson 2005). This 200,000 m^3 debris flow moved at an estimated velocity of 10 m/s (Jibson 2005), fast enough that 10 residents were unable to evacuate in time and were killed. The flow overwhelmed a $450,000 steel and timber retaining wall that had been constructed at the toe of the 1995 landslide in an attempt to keep landslide debris off the road (Fig. 11).

Homeowners have been pressing for money to stabilize the hillside in the aftermath of the La Conchita landslides. However, Ventura County officials have rejected their pleas, arguing that it is not safe for anyone to live in the area and that future slides could subject the county to lawsuits. As a result of this disagreement, the Governor of California has set aside $667,000 for a year-long study that will "examine the geologic, economic, social and environmental factors necessary to craft a sound and equitable solution" (Griggs 2006).

San Francisco Bay region, California

The San Francisco Bay region of central California has endured many episodes of landslides caused by winter/spring rainfall. For example, an intense rainstorm on 3–5 January 1982 in central California dropped as much as one half the mean annual rainfall within a period of 32 h, triggering landslides and floods throughout ten counties in the vicinity of San Francisco Bay (Ellen et al. 1988). More than 18,000 of the landslides were transformed into debris flows that swept down slopes or drainages with little warning. Throughout the San Francisco Bay region, thousands of people vacated homes in hazardous areas, roads were blocked causing entire communities to be isolated, public water systems were destroyed and telephone and power systems were disrupted. Altogether, the storm damaged or destroyed 6,300 homes, 1,500 businesses, tens of kilometers of roads, bridges and communication lines (Ellen et al. 1988). Landslides accounted for 25 of the 33 deaths attributed to the storm. As a result of the damage, 930 lawsuits and claims in excess of $298 million ($600 million) were filed against city and county agencies in the San Francisco Bay area (Smith 1982), an amount considerably exceeding total property losses.

Heavy rainfall associated with a strong El Niño storm caused more than $10 million ($12 million) in landslide damage to private property in Alameda County, San Francisco Bay Region, during the winter and spring of 1997–1998 (Godt et al. 2000). The National Weather Service recorded 1,003 mm of rainfall, or 226% of normal, for the period September–March 1997–1998. Godt et al. (2000) related costs of private property damage in Alameda County from the 1997–1998 winter storms to construction age of the structures, to determine whether changes in building codes and practices had helped to reduce landslide losses. They found that damage costs per housing unit for housing built since 1960 were less than one half those for housing built between 1939 and 1959. They attributed this decline in per-housing-unit costs of landslide damage with decreasing age of construction to improved slope, foundation and drainage engineering practices by builders and to the apparent effectiveness of changes in grading regulations.

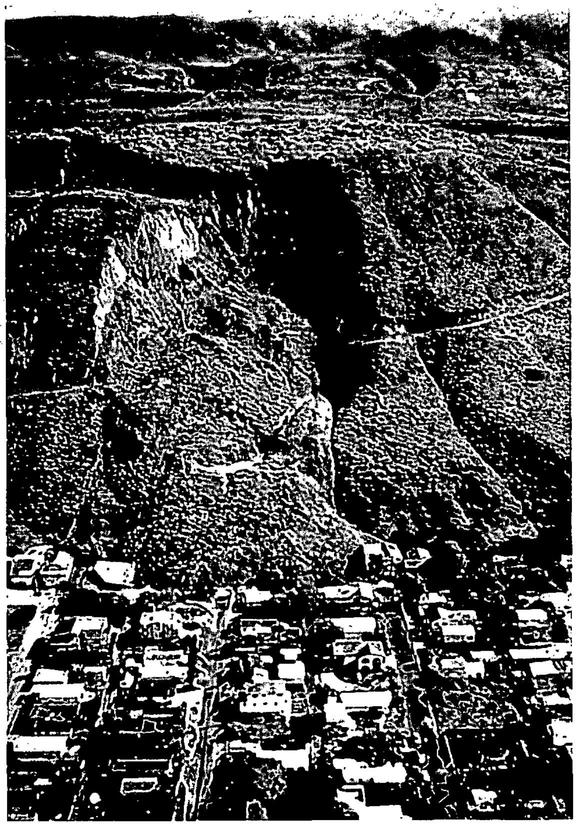

Fig. 9 The 4 March 1995 rainfall-triggered La Conchita, California, landslide that destroyed or badly damaged nine homes. This landslide was a reactivation of part of a prehistoric landslide. Because the slide moved relatively slowly, there were no casualties

As reported by Youd and Hoose (1978), the San Francisco Bay region is also susceptible to earthquake-induced landslides. Especially notable were landslides triggered by the 1906 M8.3 San Francisco earthquake. Although cost and casualty data are not readily available, Youd and Hoose noted that dozens of landslides and other cases of ground failure occurred in San Francisco as a result of the earthquake. Because major

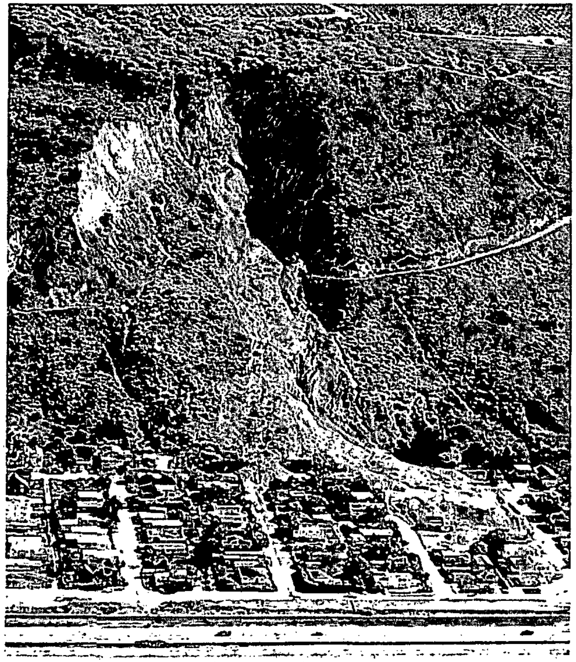

Fig. 10 The 10 January 2005 remobilization of part of the March 1995 La Conchita, California, landslide (Fig. 9). The high-velocity debris flow destroyed 13 homes and badly damaged 23 others. The debris flow moved at an estimated 10 m/s (Jibson 2005), fast enough that ten residents were unable to flee the landslide and were killed (Photo by Jonathan Godt, US Geological Survey.)

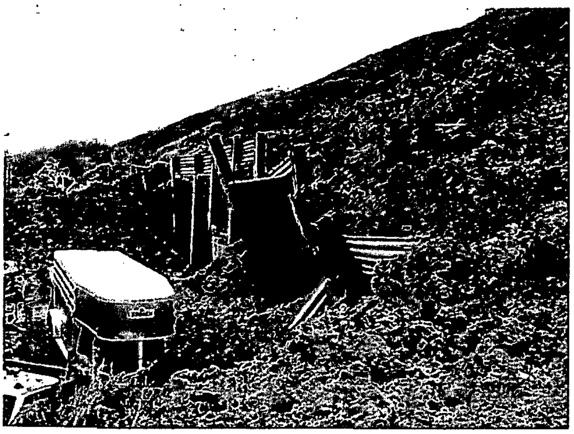

Fig. 11 Steel and timber retaining wall that was overwhelmed by the 2005 La Conchita, California, debris flow (Photo by James O'Tousa, Geologist, Ventura County, California)

earthquakes are expected in the future in this area, there undoubtedly will be new cases of earthquake-induced ground failure.

Urban areas on the north coast of Venezuela, 1993, 1999

Total annual landslide losses in Venezuela have been estimated by Zuloaga (1995) at $55 million ($70 million). Until the year 2000, most of these losses had occurred in metropolitan Caracas, the capital and largest city in Venezuela, which is situated on uplands near the north coast. From a socioeconomic perspective, landslide problems in Caracas can be divided into two groups: (1) landslides in low income "barrios," where property damage due to landslide activity commonly is not significant but loss of life can be high; and (2) landslides in moderate to high cost residential areas (Schuster et al. 2002). Of the approximately 4 million inhabitants of Caracas, it has been estimated that about 40% live in low income barrios that grow in population at an annual rate of about 20%.

Every year the hills of Caracas are subjected to landslides, most of which are associated with heavy rain that falls mainly from May to October in areas where annual rainfall averages about 1,000–1,100 mm. An excellent example of a catastrophic landslide in Caracas is the September 1993 landslide that completely destroyed seven expensive homes (Fig. 12) and a 150 m section of street in a high cost residential neighbourhood (Schuster et al. 2002). This landslide caused no casualties but blocked the main access to the suburban development, adversely affecting 20,000 families.

Several hundred thousand people reside in a narrow Caribbean coastal zone on the north slope of the Cordillera de Costa in the state of Vargas, north of Caracas. In mid-December 1999, this area was hit by Venezuela's worst natural disaster of the twentieth century; several days of torrential rain (911 mm in 3 days) triggered avalanches/flows of mud, boulders, water and trees that killed as many as 30,000 people, mostly in urban areas along the coast (Salcedo 2000, 2001; Wieczorek et al. 2000; Larsen et al. 2001). The Venezuelan Civil Defense agency reported that landslides and floods destroyed more than 23,000 homes, damaged at least another 64,700 homes and did much damage to infrastructure and lifelines (Figs. 13, 14) (Salcedo 2000). The disaster caused economic losses of about $1.8 billion ($2.1 billion) (Salcedo 2000) to $2 billion ($2.4 billion) (Merifield 2001). The landslides were mainly debris flows a few metres or less in depth, but in many cases hundreds of metres wide.

San Salvador, El Salvador, 2001

Although El Salvador, the smallest of the Central American nations, has often been impacted by land-

Fig. 12 Homes in high-cost residential area of Caracas, Venezuela, that were destroyed on 29 September 1993 by a rainfall-triggered landslide (Photo by D. A. Salcedo, Universidad Central de Venezuela)

slides caused by both heavy rainfall and earthquakes, documentation of socioeconomic losses for these events has mainly been limited to those caused by earthquakes. Rymer and White (1989) noted that for the previous 130 years, ten major earthquakes had hit El Salvador; each event triggered as many as hundreds to thousands of landslides.

In January 2001, El Salvador was again hit by a major earthquake (M7.6), which triggered many landslides that severely impacted the nation, causing approximately \$1 billion (\$1.1 billion) in damages and a large number of casualties. Especially hard hit was Las Colinas, a neighbourhood of Santa Tecla, a suburb of the capital, San Salvador. Much of the neighbourhood was buried by a landslide with a volume estimated at 300,000–500,000 m^3 (Fig. 15) (Aleman 2001). Hundreds of homes were destroyed and as many as 1,000 people were killed in this one event.

Fig. 13 December 1999 debris flow damage to the city of Caraballeda, north coast of Venezuela (Photo by L. M. Smith, Waterways Experiment Station, US Army Corps of Engineers)

Mitigation strategies for control of urban landslides

Key planning issues for development in urban areas

Lack of landslide insurance tends to push affected home and business owners to seek restitution for landslide losses from local governments, especially if they feel they can make a case that local officials were negligent in permitting or inspecting the failed development. This raises the following questions (Schwab et al. 2005):

- How much responsibility does local government bear for ensuring that development in landslide-prone areas is safe?
- What level of risk does the property owner assume in choosing to live or do business in a high risk area?
- What is the builder's responsibility for ensuring that the slope remains stable?
- Is local government responsible for educating property owners on issues such as proper landscaping and water usage?

It is important to stress that, although it is possible to provide engineering solutions in landslide-prone areas, these solutions are often expensive and may be risky (Schwab et al. 2005). Even with the best engineering methodology, and in spite of the best intentions, grading may not be done exactly as specified, construction mistakes may be made and slopes may still be de-stabilized. Thus restricting or prohibiting development in landslide-prone areas may often remain the wisest option for loss mitigation, in spite of pressures to the contrary.

Major policy options for landslide hazard mitigation in urban areas

Three basic options are available to decision makers who are confronted by landslide hazards in urban areas (Schuster 1991; Schuster and Kockelman 1996):

1. Take no action, either before or after the landslide activity,
2. Provide relief and rehabilitation efforts after the landslides occur, or
3. By means of mitigative action, avoid or prevent landslides before serious damage occurs.

Prior to about 1950, the first two of these options prevailed. However, since that time and as the result of sociological and technical advances, the concept of prevention of urban landslide disasters by land use management or physical mitigative measures has be-

Fig. 14 December 1999 debris flow damage to the city of Caraballeda, north coast of Venezuela (Photo by L.M. Smith, Waterways Experiment Station, U.S. Army Corps of Engineers)

Fig. 15 The January 2001 landslide that demolished part of the Las Colinas neighborhood of Santa Tecla, a suburb of San Salvador, the capital of El Salvador. Photo was taken after the slide had been cleared from the streets at the toe of the slope (Photo by Edwin Harp, U.S. Geological Survey)

come more widely practiced and continually more effective.

Pre-requisites for mitigation of urban landslide hazards

Successful urban landslide hazard reduction programs are most commonly based on ready availability of the following (US Geological Survey 1982):

(a) Technical information related to the hazards and risks posed by landslides in the area. These can consist of: (1) digital information, including images, landslide inventories and geological maps and reports; (2) non-digital information, including hard copies of images, inventories, maps and reports; (3) reports on technical research, loss estimation, and application of remedial measures; (4) data from real-time monitoring of slopes; (5) weather information and hazard alerts; and (6) manuals, videos and other training materials (Committee on the Review of the National Landslide Hazards Mitigation Strategy 2004).

(b) A technical community of geologists, engineers and urban planners who are able to utilize, and enlarge upon, this data base;

(c) A concerned and able municipal government; and

(d) An urban population that realizes the value of and supports the hazard reduction program.

Historical landslide inventories provide some of the most crucial information in the hazard identification phase of the urban planning process. Landslide hazard maps are especially important as pre-requisite information. In addition, the development and use of geographic information systems (GIS) has played an increasingly prominent and valuable role in hazard mapping and mitigation. Table 1 illustrates many of the data types that geologists can provide, and planners should use, in pursuing the common goal of landslide loss reduction. Once this information is incorporated into a local GIS, planners can use it to analyze various data layers and make informed decisions about acceptable land uses and the risks they may entail (Schwab et al. 2005). In addition, recent development of high resolution digital elevation mapping using Light Detection and Ranging (LIDAR) is also proving valuable for landslide detection and mapping, especially in wooded areas where pre-existing landslides are often difficult to recognize.

Such information, as used in planning for urban development, can be displayed on sets of maps that combine geological information on the location of documented landslides (inventories) and of slopes that are landslide-prone, the specific types of landslide hazards involved, and the locations of existing land uses, critical facilities and infrastructure that could be affected by landslide activity (Schwab et al. 2005).

Outreach activities, such as hard copy publications, web-based information and "hands-on" workshops are needed to inform urban communities of the seriousness of development in landslide-prone areas and the advantages of recognizing and dealing with the problem (Committee on the Review of the National Landslide Hazards Mitigation Strategy 2004). Such activities should describe the impacts of landslide hazards, which can include loss of life, injuries, financial losses to the private and public sectors and lawsuits.

Table 1 Overview of input data for landslide hazard analysis (after Soeters and van Westen 1996)

Data layers for slope instability hazard zonation	Accompanying data in tables	Method used
Geomorphology		
1. Terrain mapping units	Terrain mapping units	SII + walkover survey
2. Geomorphic units	Geomorphic description	API + fieldwork
3. Landslides (recent)	Type, activity, depth, dimension, etc.	API + API checklist + field-work + field checklist
4. Landslides (older)	Type, activity, depth, dimension, age, etc.	API + API checklist + landslide archives
Topography		
1. Digital terrain model	Elevation classes	With GIS from topographic map
2. Slope map	Slope-angle classes	With GIS from DTM
3. Slope direction map	Slope-direction classes	With GIS from DTM
4. Slope length	Slope-length classes	With GIS from DTM
5. Concavities/convexities	Concavity/convexity	With GIS from DTM
Engineering geology		
1. Lithologies	Lithology, rock strength, discontinuity spacing	Existing maps + API + fieldwork, field/lab testing
2. Material sequences	Material types, depth, USCS classification, grain-size distribution, bulk density, c and φ	Modeling from lithologic map + geomorphic map + slope map, field description, field/lab testing
3. Structural-geology map	Fault type, length, dip, dip direction, fold axis, etc.	SII + API + fieldwork
4. Seismic accelerations	Maximum seismic acceleration	Seismic data + engineering geologic data + modeling
Land use		
1. Infrastructure (recent)	Road types, railway lines, urban extension, etc.	API + topographic map + fieldwork + classification of satellite imagery
2. Infrastructure (older)	Road types, railway lines, urban extension, etc.	API + topographic map
3. Land-use map (recent)	Land-use types, tree density root depth	API + classification of satelliteimagery + fieldwork
4. Land-use map (older)	Land-use types	API
Hydrology		
1. Drainage	Type, order, length	API + topographic maps
2. Catchment areas	Order, size	API + topographic maps
3. Rainfall	Rainfall in time	From meteorological stations
4. Temperature	Temperature in time	From meteorological stations
5. Evapotranspiration	Evapotranspiration in time	From meteorological stations and modeling
6. Water table maps	Depth of water table in time	Field measurements of K_{sat} + hydrological model

SII satellite image interpretation, *API* airphoto interpretation, *DTM* digital terrain model, *GIS* geographic information systems, K_{sat} saturated conductivity testing

Local governments in many cases have developed landslide hazard reduction programs that have value to other public and private organizations. For example, the State of Colorado, under the auspices of the US Federal Emergency Management Agency (FEMA), has produced a report (Jochim et al. 1988) that proposes to reduce landslide losses by:

1. Determining local governmental resources, plans and programs that can assist in reduction of landslide losses;
2. Identifying local needs that must be addressed to reduce landslide losses;
3. Identifying and developing state agency capabilities that can deal with local needs;
4. Educating local and state officials and emergency-response personnel on landslide hazards and on potential methods of landslide loss reduction. Communities must be convinced that it is in their own best interests to avoid the effects and repercussions of landslide disasters;
5. Generating cost-effective hazard mitigation projects that will reduce landslide losses.

Similar plans have been prepared by the cities of Cincinnati, Ohio, (Hamilton County Regional Planning Commission 1976) and Portola Valley, California (Mader et al. 1988). A comprehensive guidebook for local and state governments that wish to reduce landslide losses has been sponsored and published by FEMA (Wold and Jochim 1989). The American Planning Association has recently published an instructive manual entitled "Landslide Hazards and Planning" (Schwab et al. 2005), which focuses mainly on the reduction of urban landslide losses.

Approaches to landslide hazard mitigation

Careful development of hillside slopes can reduce economic and social losses caused by slope failure by avoiding the potential hazards, by reducing the damage potential, and/or by warning the at-risk population.

Landslide risk in urban areas can be reduced by four regulatory approaches (Kockelman 1986; Schuster and Kockelman 1996):

1. Restricting development in landslide-prone urban areas, a function assisted by mapping landslide susceptibility;
2. Requiring (by means of codes) that grading, excavation, landscaping, construction, vegetation clearance, and drainage activities not contribute to slope instability;
3. Protecting existing developments and population by physical mitigation measures, such as slope geometry modifications, drainage, counterfort berms that serve as buttresses, and protective barriers;
4. Development and installation of monitoring and warning systems.

The first two approaches can be promoted by public legislation. In the United States, such legislation usually is under the jurisdiction of local governments. However, most other countries that are subject to major landslide losses have incorporated a strong provincial or federal role in landslide hazard mitigation to ensure consistent standards of practice at the provincial, municipal and private levels (Swanston and Schuster 1989).

These mitigative measures, when used with modern technology, can greatly reduce losses due to landslides. Schuster and Leighton (1988) estimated that these measures could reduce landslide losses in California by more than 90 percent. Slosson and Krohn (1982) noted that implementation of these practices had already reduced landslide losses in the city of Los Angeles by 92–97%.

Restricting development on landslide-prone slopes

Probably the most economical and effective way to reduce landslide losses is by land use planning to locate developments on stable ground and to relegate landslide-prone slopes to open space, parks or other low density uses. This practice, which is commonly known as avoidance, is accomplished by (1) discouraging, regulating, or preventing new development on unstable slopes and by (2) removing or converting existing development (Kockelman 1986). Where total avoidance of the landslide risk is not a realistic option, communities often adopt policies that attempt to limit the types and/or densities of development in landslide-prone areas as a means of minimizing the exposure to risk (Schwab et al. 2005).

Discouraging, regulating, or preventing new development

Where feasible, the most effective, and often the most economical, means of reducing urban slope failure losses is to discourage new development on landslide-prone hillsides. Methods of discouraging development of hillsides that have proven successful in the United States are (U.S. Geological Survey 1982):

1. Government acquisition of property: A sure-fire way to prevent unwise development on slopes is for the community to acquire the property for some passive use, such as open space or parkland (Schwab et al. 2005). Once the community owns the property, it is then able to control development for the public interest, generally by declaring it off limits to development, even by the community itself. Government agencies can prevent new development on landslide-prone properties by acquiring these properties by purchase, condemnation, donation, tax foreclosure, or devise (will).
2. Disclosure of urban landslide hazards to potential property buyers: Local governments can ensure that public records on urban land ownership include information on slope failure hazards. Governments can discourage development on landslide-prone hillsides by enacting hazard disclosure laws that alert potential buyers to the slope hazards (Kockelman 1986). Another approach is to establish disincentives in situations where development may be allowed in spite of landslide hazards. For example, a disincentive can exist where an urban government allows development on landslide-prone terrain with the provision that the developer must disclose to property purchasers that they are buying property with a potential natural hazard (Committee on the Review of the National Landslide Hazards Mitigation Strategy 2004). As an example, Santa Clara County, California, requires every purveyor of property within the county's fault rupture, flood and landslide zones to provide potential buyers with written statements of the geological hazard to the property.
3. Limiting public investment—exclusion of public facilities: Most private development is dependent on the extension of public infrastructure, such as water and sewer lines, for its economic viability (Schwab et al. 2005). This makes public investment policy a powerful tool in directing development away from landslide-prone areas and towards other areas that are less hazardous. Municipal

governments can prohibit construction of public facilities, such as water and sewer systems, streets, and sidewalks, in landslide-prone areas, which will prevent or restrict development in these areas.

4. Public education: A successful program of land use control requires the support of the affected population. Thus, an important component of landslide hazard mitigation is the sharing of hazard-related information with the public in a way that clarifies its significance. When the public is properly informed of the existence of hazards, it most often will support reasonable land use controls that will reduce losses from the hazards.
5. Public awareness of legal liabilities: Property owners and developers can be made aware of legal liabilities that they may have in the event of landslide damage.
6. Posted warning signs: Warning signs posted by local governments alert prospective property owners and developers to potential landslide hazards.
7. Tax credits and special assessments: Tax credits can be made available to the owners of properties left undeveloped in landslide-prone terrains. Conversely, special assessments can be levied on landslide-prone properties if they are developed.
8. Denying loans for development or construction: Lending institutions can discourage development or construction in landslide-prone terrains by denying loans for these purposes.
9. Prohibitive insurance costs: The high cost of insurance or the non-existence of insurance coverage for development in landslide-prone areas can discourage such development and can encourage land use that is less susceptible to landslide damage.

Removing or converting existing development

Damage to existing structures and development can be prevented or reduced by evacuating the area or by converting existing facilities to uses less susceptible to landslide damage. Permanent evacuation of the at-risk area commonly requires public acquisition of the land. Conversion of existing structures and facilities to uses that are less vulnerable to landslide damage can be undertaken by property owners or developers, or in the case of public properties, by the government.

Government regulation of development

It is unrealistic to assume that development and construction in landslide-prone urban terrains can be discouraged indefinitely by the non-regulatory methods noted above. Thus, government regulation often is necessary. In the United States, such restrictions are generally imposed and enforced by local governments by means of zoning districts and regulations. Local regulations not only must require detailed landslide hazard mapping, but must ensure that the quality of this mapping meets appropriate technical standards. Such standards for landslide hazard mapping and interpretation should be spelled out in local regulations and the maps and reports prepared on the behalf of the developer should be reviewed by a qualified geologist on behalf of the local government (Committee on the Review of the National Landslide Hazards Mitigation Strategy 2004).

Examples of regulations of land use in areas prone to landslide activity are (Schuster 1991; Schuster and Kockelman 1996):

Land use zoning regulations: Land use zoning provides direct benefits by regulating development in landslide prone urban areas. Zoning is a tool that designates the allowable categories of land use for specific areas of the community. Under zoning ordinances enacted and enforced by local governments, sites of planned building structures are commonly moved from landslide prone terrains to stable ground and more suitable uses, such as parks, greenbelts, recreation areas, woodlands and non-irrigated agriculture, may be substituted. These land uses may also incur relatively small economic losses if slope failures do occur. Regulations can include provisions that preclude specific land uses or operations that could cause, or be vulnerable to, slope failure, such as construction of buildings or roads, irrigation systems and storage or disposal of liquid wastes. An example of a regulatory approach would be the restriction or prohibition of lawn watering in cases where the resulting moisture load from watering could destabilize the slope.

Zoning regulations can also restrict the density of development in landslide-prone terrains. The 1960s saw the advent of slope density ordinances that linked maximum allowable density (or minimum lot size) directly to the steepness of the site (Olshansky 1998). Restricting density of development is a common approach because high density brings obvious problems for landslide-prone areas, including increased amounts of the following (Schwab et al. 2005):

(a) Impervious surface as a result of building roofs and paving for roads and parking areas;
(b) Excavation in potentially unstable soils;
(c) Removal or disruption of native vegetation;
(d) Drainage facilities that may increase moisture locally, thus increasing slope instability.

Table 2 Typical slope-density zoning requirements for a landslide-prone area (after Schwab et al. 2005)

Slope of land	Maximum building lots per acre[a]
Up to 10%	1.0
10–14.9%	0.9
15–19.9%	0.8
20–24.9%	0.7
25% or steeper	No development allowed

[a] 1 acre = 0.404 ha

An example of requirements for maximum allowable density for slopes is presented in Table 2.

Soeters and van Westen (1996) have distinguished between landslide hazard zonation as the responsibility of earth scientists and vulnerability analysis as being in the domain of planners, social scientists and engineers. Zonation requires detailed understanding of landslide processes and the means of identifying landslide hazards. On the other hand, determining vulnerability requires knowledge of the impact of landslide hazards on people, the built environment and the local economy. It thus involves consideration of land use, building density and economic recovery from disasters. What is essential is that planners and decision makers know enough about the danger signals that are identified by earth scientists to be able to interpret them in ways that will yield effective policy to protect the public (Schwab et al. 2005).

Sewage disposal regulations: Residential sewage disposal systems that rely on ground absorption (septic tanks, leaching fields and seepage pits/beds) can saturate the surrounding geological materials and contribute to slope failure. Thus the design and installation of these facilities should be regulated in landslide-prone areas.

Success of development restriction in landslide-prone urban terrains

In the United States, implementation of avoidance procedures has met with mixed success. In some areas, and particularly in California, restriction of development on landslide-prone slopes has been extensive and such programs usually have been successful. However, in many US states that have major landslide problems, there are no widely accepted procedures or regulations that consider slope failures as part of the land use planning process (Committee on Ground Failure Hazards 1985).

Land use zoning probably has been the most effective method of regulating development. In San Mateo County, California, a landslide susceptibility map (Brabb et al. 1972) has been in use since 1975 as a zoning map that controls the density of development. For landslide-prone terrains, only one residence is permitted for every 16 ha of land. From 1972 to 1982, all of the new landslides that occurred in San Mateo County (mostly slumps and slides) were either reactivations of pre-existing landslides or were in areas that had been mapped as being highly susceptible to landslides. Thus the zoning procedure was very successful up to that time. However, in 1982, after intense rainfall, thousands of debris flows took place in areas where few had been noted previously (Brabb 1984). Thus, the 1972 map had accurately predicted slumps and slides, but was not successful in the prediction of debris flows. The debris flows had not been expected because the landslide susceptibility map had been based on air photo interpretation that had recognized only deep-seated landslides.

The best examples of removal or conversion of existing development to reduce landslide losses have been those in which existing developments have been destroyed or damaged by slope failures, and as a reaction to these losses, the original development was replaced by usage less prone to damage by slope failure. Such efforts have generally been only partially successful because of the resistance of developers, property owners, or even the cities themselves. An excellent example is the previously mentioned City of Anchorage, Alaska, which sustained heavy damage from soil slides that were triggered by the 1964 Alaska earthquake. As a result of the earthquake, a Scientific and Engineering Task Force was established by the federal government to assess the damage, to evaluate future hazards and to make recommendations that would minimize the impact of future earthquakes or landslides. The task force's recommendations were enacted on government land within the city but were largely ignored by private property owners.

Excavation, grading, and construction codes

Excavation, grading, and construction ordinances have been developed in many countries to ensure that construction on landslide-prone terrains is designed and carried out in a manner that does not impair hillside stability. These ordinances commonly (Schuster 1991; Schuster and Kockelman 1996):

(a) Regulate, minimize, or prohibit excavation and fills;
(b) Provide for proper engineering design, construction, inspection and maintenance of cuts and fills;
(c) Control disruption of natural drainage and vegetation; and

(d) Enable and enforce proper design, construction, inspection and maintenance of surface and subsurface drainage systems.

In the United States there is no "uniform" ordinance that is applied nationwide to achieve standardization of the above criteria. Instead, to ensure stability of hillside slopes on private lands, municipal, county and state governments apply design and construction ordinances that fit the needs of their specific jurisdictions. However, codes for excavation and grading that have been developed for federal projects—such as those standards used by the US Army Corps of Engineers and the US Bureau of Reclamation, both of which are in charge of major construction efforts—often are used by local governmental organizations (Committee on Ground Failure Hazards 1985).

In the United States, development of grading and excavation ordinances based on geological hazards began in southern California in the 1950s. At that time, a rapidly expanding population caused a spiralling demand for residential building sites, leading to intensified development of hillside terrains (Scullin 1983, p. 14). In addition, improvements in earthmoving equipment have made development of hillside terrains economically feasible. The resulting poorly organized development of hillsides, combined with unusually heavy rainfall in the early 1950s in southern California, resulted in significant slope failure activity and major economic losses. Consequently, the City of Los Angeles in 1952 adopted the first grading code in the United States. Since that time, these ordinances have become increasingly detailed and comprehensive, particularly in the Los Angeles area. The heavy rainfalls of 1962, 1969, and 1978 in southern California spurred further major grading code changes. For the City of Los Angeles, four different code periods, related to these heavy rainfall years, have been identified for hillside slopes (Schuster and Leighton 1988):

1. Pre-1952: Period of no grading code regulations and little or no soil engineering or engineering geology for hillside developments.
2. 1952–1962: Period of initial grading code regulations with emphasis on geotechnical engineering and compaction and placement of fills, but little on engineering geology.
3. 1963–1969: Period of more sophisticated and detailed grading code regulations requiring soil engineering and engineering geology through design and construction stages; differentiation of responsibilities of the design civil engineer, geotechnical engineer and engineering geologist; and requirements for subsurface exploration and stability analyses.
4. 1970-present: Period of further refinement of grading ordinances and more stringent requirements of geotechnical engineering and engineering geology; emphasis on a more quantitative approach, e.g., strength parameters, safety factors and stability analyses; emphasis on mud flow (debris flow) mitigation and proper design of structures below and above natural slopes.

In Los Angeles, a local government requirement for reports from both registered geotechnical engineers and certified engineering geologists indicates the increasing awareness of the important role of qualified consultants. Geotechnical reports are generally required not only before development but also during and following development, in order to insure that all of the professional recommendations have been followed. Appropriate engineering geological and geotechnical inspections and mapping during grading operations are now commonplace. In fact, a geological map prepared to show as-graded conditions is now considered by planners and developers to be one of the most useful tools for assessing the stability of an existing hillside sub-division.

Comprehensive standards for determining slope stability have been adopted by local government agencies in California, particularly in southern California. These standards now apply not only to cut, fill and buttress-fill slopes but also to natural slopes associated with hillside development and to both deep seated and surficial potential landslides. In addition, engineering geological investigations are expected to identify potential debris flow/mud flow terrains and recommend their avoidance as building sites, or, if the areas are already developed, recommend steps to divert potential debris flows/mud flows away from structures. Special attention is now required for ravines, gullies and similar depressions on natural slopes, because these features commonly concentrate erosion and mass movement problems. Where existing slopes do not have safety factors of at least 1.5, engineered corrective measures are advisable.

Use of codes by local governments

Local governments in California, particularly in the Los Angeles area, have progressed further than most other areas in the United States in improving grading and construction codes related to hillside development and in securing the necessary staffs to enforce these codes. In northern California, the town of Portola

Valley, 50 km south of San Francisco, was another early leader in adopting safeguards against geological hazards, including landslides (Mader and Crowder 1971). In 1967–1969, Portola Valley retained an engineering geologist, passed ordinances based upon geological hazard data, required geological reports to accompany sub-division maps and required the review of these reports by the town-employed engineering geologist. Another example of similar use of an engineering geologist in northern California was by San Mateo County in 1969 (Leighton 1975). The value of the procedures and requirements so effectively demonstrated by these two local governments resulted in their adoption by other counties and major municipalities.

A typical recent ordinance is that of the City of Salem, Oregon, which went into effect in November 2000 (Community Development Department 2006). In regard to land development activities, the Salem Landslide Hazard Regulations: (1) prohibit removing trees on slopes 60% or greater until a geological assessment is submitted and approved by the Public Works Department; and (2) prohibit grading in areas that are mapped for water-induced and earthquake-induced landslide hazards until a geological assessment or geotechnical report is submitted and approved by the Public Works Department.

Olshansky (1998) has conducted a survey of hillside plans and ordinances for 190 local governments throughout the United States. As shown in Table 3, the most frequently cited strategies in this survey were grading controls (72%), mandated planting or replacement of vegetation (65%), requirements for technical studies by professional geologists or engineers (59%), limits on vegetation removal (57%), building setbacks (56%), restrictions on type or design of building (53%), and restrictions on maximum land use intensity (47%)

The establishment and enforcement of codes by local governments may vary a great deal. Jurisdictions with high landslide potential are not always those that enlist the necessary geotechnical assistance or adopt the most advanced planning requirements and grading and construction ordinances. Furthermore, although slope stability constraints are geotechnically recognized and defined in most jurisdictions with hillside problems, they are not necessarily accepted by local governments and the public. Some communities still need to be made aware of the significance of their landslide problems and the feasibility of mitigation alternatives. Some local governments stress non-technical aspects of landslide mitigation, such as the political and procedural steps in qualifying for a building project, aesthetic aspects such as non-development of ridge tops or steep slopes, and restrictions on the dust, noise and hours of grading activities. Others stress technical performance by consultants and still others rely on strict enforcement of technical recommendations. The history of code development demonstrates time and again that a sound code can fail unless it is applied properly.

Table 3 Implementing strategies used by 190 responding jurisdictions, based on a survey of local governments in the United States (after Olshansky 1998)

	Number of responses	Percentage
1. Land use and lot size	138	73
Specifying maximum density or intensity	89	47
Specifying minimum lot size or dimensions	82	43
Specifying permitted uses	68	36
Requiring no-build areas (a minimum percentage)	19	10
2. Site design and construction	166	87
Grading	136	72
Setbacks	107	56
Open space	74	39
Clustering	61	32
Impervious surface coverage	50	26
3. Building restrictions	136	72
Type or design	101	53
Maximum height	86	45
Materials restricted	75	39
Fire safety as basis	50	26
Orientation/siting	40	21
Maximum footprint	23	12
4. Tree/vegetation restrictions	148	78
Mandated replacement or planting	124	65
Limited removal	109	57
Fire safety as basis	68	36
Vegetation management mandated	53	28
5. Road and parking restrictions	116	61
Road standards	79	42
Roads parallel to contours	72	38
Parking restrictions	67	35
Common access drives	27	14
6. Other design regulations	53	28
Lighting	42	22
Signage	23	12
7. Procedural and policy strategies	169	89
Require technical studies by professionals	113	59
Variances or special exceptions	79	42
"Grandparenting" of existing uses	68	36
Conditional uses permitted	56	29
Transfer development rights, density bonuses	40	21
Homeowners associations	19	10

Populous counties, sizable municipalities and smaller urban communities with significant hillside development and strong tax bases generally strive to employ or retain at least one engineering geologist to advise on matters related to geological hazards, particularly landslides. The geologist assists in seeing that geological ordinances are adequately taken into consideration in the planning and building processes. He or she commonly serves as an advisor in overall land use planning of the jurisdiction, based on the mapping of geological constraints that he or she either undertakes or administers.

Four requisites need to be met to successfully implement urban grading and construction codes from a geotechnical standpoint (Schuster and Leighton 1988):

1. Strong geotechnical performance in identifying, characterizing and evaluating the landslide problems;
2. Adequate agency review of the consultants' products and agency field trips during and after grading activities;
3. A board of appeals to weigh possible disputes between the geotechnical consultants and the agency; and
4. Recognition of the importance of geotechnical considerations by other professional people and the general public.

The thoroughness and effectiveness of these complementary roles have varied tremendously in the past, but have markedly improved in recent years.

Success of hillside regulations

Codes and professional practices have been shown to reduce landslide monetary losses by more than 90 percent. The City of Los Angeles provides an impressive example of the effective use of excavation and grading codes as deterrents to landslide activity and damage in the development of hillside slopes. As noted above, the Los Angeles loss reduction program relies heavily on regulations that require specific evaluations of landslide potential by engineering geologists and geotechnical engineers before construction. The benefits resulting from these regulations were illustrated by the distribution of landslide damages in Los Angeles during severe storms in 1968–1969 and 1978. During the storms of 1968–1969, for a comparable number of building sites, damage to sites developed before enablement of excavation/grading codes in 1952 were nearly 10 times as great as the damage to sites developed after 1963 (Slosson 1969). Similar results occurred for the 1978 storms (Table 4).

Protecting existing development by physical mitigation measures

Unfortunately, many urban areas were developed prior to the application of the avoidance and regulatory methods outlined above and development of hillside slopes that are subject to slope failure will continue. Thus, mitigation for existing development is a critical element of a community's plans for addressing landslide hazards. Land use planning programs for landslide-prone terrains should include physical mitigative measures to protect structures, property, lifelines and people. Erley and Kockelman (1981) have divided these protective measures into (a) physical methods of control of unstable slopes and (b) monitoring and warning systems.

Physical controls: categories of slope stabilization

The most effective and commonly used physical techniques for control of unstable slopes are (Schuster 1995):

1. Surface and subsurface drainage: Because of its high stabilization efficiency in relation to cost, drainage of surface water and/or groundwater is the most widely used, and generally the most successful, slope stabilization method (Hutchinson 1977; Committee on Ground Failure Hazards 1985). Surface water is typically diverted from unstable slopes by means of ditches. Subsurface drainage as a means of lowering the groundwater table has traditionally consisted of one or more of the following technologies: (a) drainage trenches, (b) drainage wells, (c) drainage galleries, adits, or tunnels, (d)

Table 4 Relationship between slope failures and modern grading codes for Los Angeles building sites for the catastrophic February 1978 southern California rain storm (after Slosson and Krohn 1979)

Building code in effect	Number of sites developed	Number of site failures	Percentage of site failures	Damage costs (1978 dollars) (million)
Pre-1963 (pre-modern code)	37,000	2,790	7.5	$40–4
Post-1963 (modern code)	30,000	210	0.7	$1–2

sub-horizontal (commonly called "horizontal") drains drilled either from the slope surface or from drainage wells or galleries, and (e) sub-vertical drains drilled upward from drainage galleries. Most often these systems drain by means of gravity flow; however, pumps are occasionally used to lift water from low-level collector galleries or wells.

2. Slope modification: Increased slope stability can be obtained by removing all or part of the landslide mass. The most effective removal is usually at the head of the slide because this action reduces the driving force on the landslide.
3. Earth buttresses (berms): Earth buttress counterforts placed at the toes of unstable slopes are often successful in increasing stability. This is the most common mechanical (as opposed to hydrological) method of slope stabilization (Committee on Ground Failure Hazards 1985).
4. Earth retention systems: Where methods (1) through (3) will not achieve stability by themselves, structural controls, such as retaining walls, geosynthetic meshes, piles, caissons, anchors and/or internal reinforcement of the earth materials comprising the slope, are commonly used to prevent or control slope movements. In most cases, earth retention systems are used in conjunction with drainage and/or slope modification. Properly engineered retention systems are useful in stabilizing most types of slope failures where these failures do not involve large volumes and where lack of space precludes slope modification or the construction of counterfort berms. However, use of retention structures should be limited to control of small scale landslides because they are seldom effective on large ones (Fig. 11) (Baker and Marshall 1958).

Structural debris barriers, such as deflection walls, are often used to divert debris/mud flows from critical areas and structures. In addition, debris storage basins behind check dams collect these flows before they reach critical areas. In the United States, these structures, which are expensive engineering works, most commonly are built by government agencies.

These physical control measures have been discussed at length in the landslide literature (e.g., Zaruba and Mencl 1982; Schuster 1995; Holtz and Schuster 1996; Wyllie and Norrish 1996). Their main shortcoming is the relatively high cost, which restricts their use to those sites for which avoidance is not feasible. Thus they are most commonly used where landslide costs are high because of high population densities and property values. All of these measures are in common use worldwide, and all are continually being improved by modern methods of analysis, design and construction.

Research on the analysis, design and fabrication of systems for sub-surface drainage, rock fall control and soil retention will continue to provide new approaches to development and use of these physical slope stabilization systems. Particularly important is the development of new, economical, strong, corrosion resistant and environmentally acceptable materials that can be used as elements in stabilization systems for both rock and soil slopes. For steep rock slopes, new computerized approaches allow increased understanding of the rock fall process that will lead to better understanding of the process and thus to better rock fall control. Modern experimental techniques, such as use of the geotechnical centrifuge, complement analytical approaches to better understand the mechanics of failure of retention systems, thus leading to improvements in design.

Because of the costs involved, physical measures of mitigation are not always a popular option with the public or policymakers. For this reason, it is all the more vital that hazard mitigation policy be supported by solid documentation of existing landslide hazards and of the losses the community will suffer if it does not act to reduce landslide risks (Schwab et al. 2005).

Monitoring systems and techniques

Instrumentation and associated monitoring techniques have made significant advances during the past quarter century. Landslide-prone slopes can be monitored to provide warning of impending movement to downslope residents. Monitoring techniques include field observation and the use of extensometers, piezometers, inclinometers, tilt meters, electrical fences and trip wires, which are often automated and can include alarm-reporting capabilities. Recent innovations in monitoring techniques include the use of acoustic instruments, laser beams, television, web cameras, guided radar and vibration meters. Data from these devices are often telemetered to central receiving stations.

Adequate planning is required before a specific landslide is instrumented. The plan should proceed as follows (Mikkelsen 1996):

1. Determination of types of instruments required;
2. Definition of the location and depth of instrumentation and number of instruments;
3. Selection of types of instruments best suited for the required measurements;
4. Development of the necessary data acquisition techniques; and

5. Decision as to the management and presentation of the acquired data.

Field instrumentation is most often used on landslides that have already exhibited some movement. Because small movements of an earth mass before, or even during, incipient failure are usually not visually evident, instrumentation may be needed to provide valuable information on incipient as well as fully developed landslides. In this respect, use of instrumentation is not intended to replace direct field observations. Instead, instrumentation augments other data by warning of impending significant movements or of the presence of conditions known to precede movement. Typical situations for which various instruments have been found valuable are (Mikkelsen 1996):

(a) Determination of the thickness and shape of the sliding mass to enable definition of the appropriate strength parameters at failure;
(b) Quantitative determination of lateral and vertical movements of the sliding mass;
(c) Quantitative determination of the rate (velocity) of movement of the landslide mass;
(d) Monitoring of groundwater levels or pore pressures associated with landslide activity so that effective stress analyses can be performed;
(e) Monitoring of the activity of marginally stable natural or cut slopes, including identification of the effects of construction activity or rainfall;
(f) Provision of remote digital readout to a remote alarm system that can warn of potential danger; and
(g) Monitoring and evaluation of the effectiveness of various physical mitigative measures.

Monitoring systems are installed primarily to protect lives and property, not to prevent landslides. However, these systems often provide warning of slope movement in time to allow the construction of physical control measures that will reduce the immediate or long-term landslide hazard.

Real-time warning systems

One of the most significant areas of current landslide mitigation research involves the development of real-time warning systems for landslides triggered by major rain storms. In cases such as the 1999 landslide disaster on the north coast of Venezuela, a significant percentage of the victims might have been saved if an early warning system had been deployed in the region (Marin-Nieto 2003). Campbell (1975), as a result of his study of the 1969 debris flows in Los Angeles, suggested a debris flow warning system for the area based on National Weather Service forecasts and radar imagery. He noted three necessary elements for his proposed system:

1. A system of automatic rain gauges capable of recording total rainfall on an hourly basis;
2. A weather mapping system capable of noting centers of high intensity rainfall in the storm area, and, at frequent intervals, plotting the locations of these centers with respect to the locations of gauges with adequate registry for accurate transfer to slope maps or topographic maps; and
3. An administrative and communications network to collate the data, recognize when critical thresholds have been exceeded in particular areas and warn the residents of the areas.

In 1987, a system such as that envisioned by Campbell (1975) was developed for the San Francisco Bay area, California, by the US Geological Survey in co-operation with the National Weather Service. This system was based on (a) geological determination of terrains susceptible to landslides, (b) empirical and theoretical relations between thresholds of rainfall duration/intensity and landslide initiation, (c) real-time monitoring of a regional network of telemetering rain gauges, and (d) National Weather Service precipitation forecasts (Keefer et al. 1987; Wieczorek et al. 1999). The system was successful in early trials, but was later terminated because of lack of operational funds (Wilson 2005). In 2005, the US Geological Survey (USGS) and the National Oceanic and Atmospheric Administration (NOAA, which includes the National Weather Service) proposed establishment of early warning systems for debris flow prone areas in the United States, but noted that funding for these systems is currently not available (US Geological Survey 2005). However, the USGS–NOAA proposal noted that it is feasible at no additional annual operating cost to establish a debris flow warning system for recently burned areas using rainfall intensity-duration thresholds developed by the USGS and applying those thresholds to the Flash-Flood Monitoring Program of the National Weather Service. Rainfall intensity-duration thresholds for debris flow occurrence have been developed for parts of southern California using detailed analyses of rainfall and debris flow response data from recently burned areas. These quantitative thresholds provide an improvement over the present method of identification of dangerous rainfall conditions based on professional opinion and experience.

It is our understanding that landslide early warning systems currently are active in Hong Kong, Brazil, the UK and the State of Oregon, USA. Probably the most extensive and successful landslide warning system in the world is that in Hong Kong. This system is jointly operated by the Geotechnical Engineering Office and the Hong Kong Observatory, which acts as Hong Kong's weather service. Based on Hong Kong Observatory forecasts and rainfall data from an extensive network of automatic rain gauges, "landslip warnings" are issued when it is predicted that numerous (>10) debris flows are likely to occur within the city (Wilson 2005). The rain gauge network consists of 86 automatic gauges operated by the Geotechnical Engineering Office and 24 by the Hong Kong Observatory. The original rainfall thresholds for numerous debris flows were: 24 h rainfall exceeding 200 mm or 60 min rainfall exceeding 70 mm (Brand 1999).

In 1996, after decades of landslide/debris flow disasters, the city of Rio de Janeiro, Brazil, installed an alarm system ("Alerta Rio") for landslides triggered by heavy rainfall. This system is based on a telemetric network of 30 automatic rain gauges installed by the Fundacão Instituto de Geotechnica do Municìpio do Rio de Janeiro (GEO-RIO). GEO-RIO has established the following rainfall intensity thresholds for issuing warnings: 30 mm/h, 70 mm/24 h, or 100 mm/96 h (d'Orsi et al. 2004). From January 1998 to December 2003, 42 warnings of landslides and/or flash floods were issued, all during the summer rainy season.

The only such system currently active in the United States was established by the State of Oregon in 1997. This debris flow warning system is staffed by meteorologists from the Oregon Department of Forestry, geologists from the Oregon Department of Geology and Mineral Industries and engineers from the Oregon Department of Transportation. Advisories are broadcast over National Oceanic and Atmospheric Administration weather radio and over the state Law Enforcement Data System (Wilson 2005).

Dramatic landslide events in developed areas on the south and east coast of England led in the 1990s to installation of remote real-time monitoring systems that provide telemetered data utilized in early warning systems of landslide-prone slopes (Clark et al. 1996). The automatic monitoring sensors include electrolevels (tilt meters), extensometers (crack meters), settlement cells and piezometers. Continuous recording of the output from such sensors has provided the basis for real-time monitoring and early warning systems and forecasting of coastal landslide behaviour.

Landslide insurance as a mitigative measure

Insurance coverage for landslides is uncommon. It is almost never a standard coverage, and is difficult to purchase inexpensively as a policy endorsement. However, although insurance programs do not reduce urban landslide hazards directly, as do the mitigative measures discussed above, landslide insurance can provide a financial mechanism for spreading the landslide damage costs among broad categories of those at risk. Landslide insurance can also be linked to incentives for reducing risks (Committee on the Review of the National Landslide Hazards Mitigation Strategy 2004). For example, the high cost of non subsidized landslide insurance for development in landslide-prone terrains can discourage such development and encourage lower risk land uses (Schuster and Kockelman 1996). The use of insurance as a method of landslide hazard reduction has the following advantages over other strategies (Olshansky and Rogers 1987; Olshansky 1990):

1. In theory, landslide insurance provides an equitable distribution of costs and benefits.
2. Landslide insurance encourages hazard reduction if premium rates reflect not only the degree of hazard but also the effectiveness of physical mitigation measures.
3. The use of insurance to lower the impact of landslide hazards appeals to those who are opposed to government regulation.

Although the concept of privately funded landslide insurance is an appealing one, it has certain drawbacks in practice, notably because (Olshansky 1990, 1996):

(a) Insurance actuaries have found that landslide loss records are insufficient for establishing risk-based rates for landslide insurance;
(b) Most landslide losses are "catastrophic," in that affected structures are generally totally destroyed rather than sustaining only minor damage, and;
(c) The problem of "adverse selection," which is the tendency for only those who are in landslide-prone areas to purchase insurance (Olshansky 1996). That is, without mechanisms for expanding the pool of insurance policyholders, only those who are at greatest risk will purchase policies, thus making it uneconomical to offer insurance.

The most successful application of insurance to landslide hazards thus far has been in New Zealand, where a governmentally subsidized natural disaster insurance program covers the full range of natural disasters: earthquakes, volcanic eruptions, hydrothermal activity, tsunamis and natural landslides (Committee on the Review of the National Landslide Hazards Mitigation Strategy 2004). Coverage is primarily for property loss or damage, but there is also limited coverage for land loss resulting from any of these hazards. A disaster fund, accumulated from a surcharge to the national fire insurance program, reimburses property owners for losses (O'Riordan 1974).

In the United States, "public" (i.e., government backed) landslide insurance is available for "mudslides" under the National Flood Insurance Program, which was created by the Housing and Urban Development Act of 1968. The insurance on these "water caused" landslides is provided by private insurance companies but is underwritten and subsidized by the federal government. However, this program has not been effective, mainly because of difficulty in defining "mudslide" and in mapping mudslide hazard zones (Olshansky and Rogers 1987).

In the past, standard private insurance carriers have not issued landslide insurance policies in the United States. Recently, however, such coverage has been underwritten in a few states by Lloyds of London. At about 40 cents per year for every $100 of coverage—or $1,200 per year on a $300,000 house—the coverage is very expensive (ConsumerAffairs.com 2005). In addition, the insurance covers only the structure itself, not the property, and coverage will not be issued for an area that has been shown to be historically at risk from landslides.

Distributing landslide costs by means of home-owner associations and assessment districts

Two additional types of financial arrangement—home-owner associations and special assessment districts—can be considered for financing landslide hazards (Committee on the Review of the National Landslide Hazards Mitigation Strategy 2004). These organizations can levy special geological hazard fees that can be used to fund remedial actions prior to, or in the aftermath of, landslide activity. The conditions and covenants that govern home-owner associations can require assessments that will financially care for properties that fail due to landslides. The home-owner association may actually assume the responsibility for maintenance of major areas and facilities that are owned in common by the association. Another vehicle for remedial action is through the establishment of special assessment districts. These are political jurisdictions created by local or state governments for the purpose of taxing district residents in order to carry out designated functions, e.g., the financing of landslide damages in the district. For example, the State of California has established statutory provisions that allow creation of Geological Hazard Abatement Districts.

Conclusions

In spite of significant progress in the application of mitigative measures, worldwide population pressures have resulted in increasing landslide hazards on urban hillside slopes. These hazards continue to cause significant property damage and casualties in urban areas that are expected to increase in the future. The most common triggering mechanism for urban landslides is excessive rainfall; earthquakes also rank as a major triggering factor. In addition, human alteration of hillsides often contributes to slope instability by (1) cutting slopes at grades that are too steep, (2) locating earth fills on top of unstable or marginally stable slopes, (3) re-directing rainfall runoff so that flows are concentrated in unstable or marginally stable terrains, (4) adding water to the slope by landscape irrigation or from septic systems and (5) removing trees, shrubs and other woody vegetation.

To counter these hazards, a wide range of landslide hazard mitigation techniques has been developed. These techniques consist of: (1) restricting development in the landslide-prone terrains (i.e., avoidance); (2) requiring by means of codes that excavation, grading, landscaping, construction, vegetation clearance and drainage activities not contribute to slope instability; (3) protecting existing developments and population by physical mitigation measures; and (4) developing and implementing monitoring and warning systems. These methods have been used individually or in combination to reduce losses from existing or potential landslides.

Although insurance coverage for landslides holds promise as a potential mitigative measure, coverage is not broadly available at present because (1) insurance actuaries find it difficult to establish recurrence intervals on which to base premium rates; (2) "adverse selection," which results in the tendency for only those who live in landslide-prone areas to purchase insurance; and (3) of the fact that most landslide losses are "catastrophic," in that affected structures usually are totally destroyed rather than sustaining minor damage. Thus, where landslide insurance is available, it tends to be expensive and, as a result, few home-owners purchase coverage.

Another means of spreading landslide costs over a broader base is the establishment of home-owners associations and special assessment districts. These organizations can levy geological hazard "taxes" on all property owners within their jurisdictions, the monies being used as "insurance" against landslide losses.

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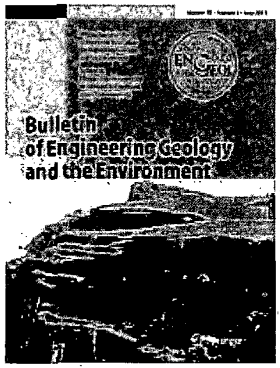

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