Hydrological Impacts of Earthquakes, Landslides and Avalanches

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Introduction

NATURAL phenomena have always aroused human curiosity, admiration and scientific interest. Some of them are also looked upon with fear, because the colossal amount of uncontrollable energy which they display sometimes causes anything from slight material damage to devastation, loss of many human lives and substantial, permanent environmental changes. Earthquakes, landslides and avalanches are among these potentially destructive phenomena which, by generating the movement of gigantic rock masses, have various impacts, some of them of a hydrological nature.

Over the last few decades, which have seen spectacular scientific and technological development, much progress has been made in our knowledge of the origin and controlling factors of these phenomena: the earth sciences have made in-depth studies of the natural processes associated with the planet's evolution which cause the vast majority of earth movements; increasingly complex and sensitive instruments have been designed to monitor them in detail; and a complex theoretical basis has been developed to describe them in mathematical terms.

This spectacular progress has enabled us to define the regions or sites which are most prone to these phenomena, and, in some cases, to predict their occurrence with a certain margin of error; however, despite this, the movements in question continue to have damaging, sometimes even catastrophic effects because, after ignoring warnings and precursory signs, people fail to take the relevant preventive action to attenuate their negative impact.

It has, moreover, been demonstrated that human activity also produces potentially destructive earthquakes, landslides and avalanches, although presumably on a very small scale in comparison with those of natural origin, which has given rise to the conception of futuristic projects to control or attenuate the intensity of the natural ones.

The present paper contains a brief summary of current knowledge of such phenomena, a description of their main impacts with emphasis on those of a hydrological nature, and recommendations for various types of action to prevent human and material losses.

The Phenomena

A short survey of the causes and mechanisms of earthquakes, landslides and avalanches is necessary as a basis for considering their impacts and formulating recommendations to prevent or, at least, attenuate their harmful effects.

Earthquakes

An earthquake is a vibration and oscillation of the earth produced by a temporary alteration in the balance of rocks on, or below the surface. The most common natural causes are shifts in the earth's crust, volcanic activity and the collapse of rock masses. The vast majority of severe earthquakes are caused by the former, i.e. tectonic movement. It will be recalled that earthquakes are surface manifestations of seismic waves produced by friction, shock or subduction of the plates forming the earth's lithosphere.

Volcanic eruptions and the collapse of rock masses also produce vibrations which are perceptible sometimes at distances of up to several kilometres. However, in terms of energy, these seismic sources are insignificant by comparison with tectonic movements. In some cases, they can add the necessary momentary impulse to precipitate phenomena of another type (for example, landslides or avalanches), which were already imminent. In general, this also applies to artificial explosions, whose effect is relatively local.

On the other hand, variations in groundwater pressure may produce tremors of significant proportions, when they disturb the balance of rock masses. Indeed, the theory of regional flow systems postulates, and observations made in oil wells confirms that, at great depth, water is subjected to very high pressure; consequently, because of the mechanism described in Mohr-Coulomb's theory, the actual pressure and shearing resistance are relatively low, which explains the observed displacement of immense blocks of rock (several kilometres thick by hundreds of kilometres long) along fault planes with slight inclination (see Figures 1 and 2).

The above-mentioned mechanism also explains the origin of earthquakes recorded in areas where interstitial pressure is artificially increased. Cherry and Freeze (1979) quote two cases of seismic activity provoked by the injection of water into the subsoil through deep wells, to eliminate residual radioactive

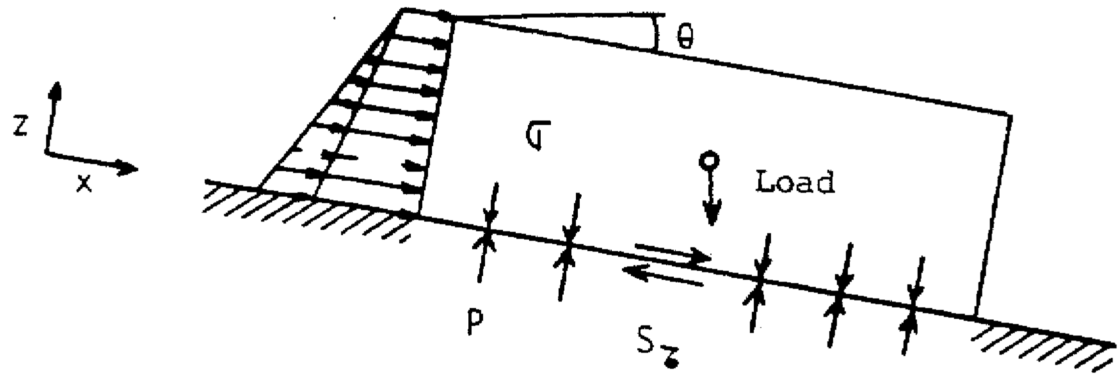

FIGURE 1 *The dominant role played by groundwater pressure in the equilibrium of blocks of rock*

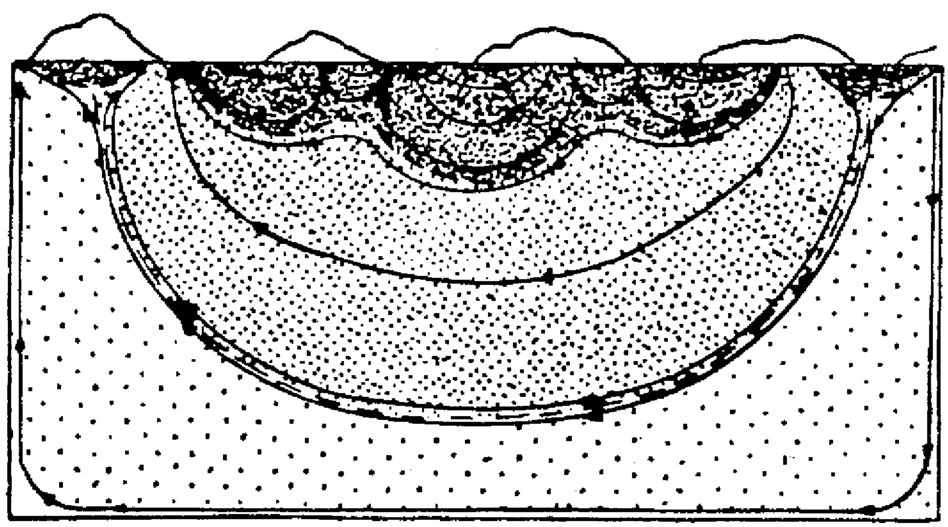

FIGURE 2 *Regional flow system (Toth, 1963) which includes several basins; at some depth the water is subjected to great pressure*

liquids and to extract oil deposits by the secondary recovery method. In both cases, it was observed that seismic movements began shortly after injection was started; close correlation was noted between the magnitude and frequency of earthquakes and fluctuations in hydraulic pressure; and it was demonstrated that the location of the epicentres coincided approximately with the injection site (see Figure 3).

Such experiments and the results of theoretical analysis have confirmed that groundwater pressure plays a very important role in fault movements, giving rise to the idea that catastrophic earthquakes can be prevented by artificially induced pressure changes, making it possible to liberate in a controlled manner the growing tectonic forces generated on the fault planes. Experiments have moreover been carried out showing the feasibility of this idea. The results

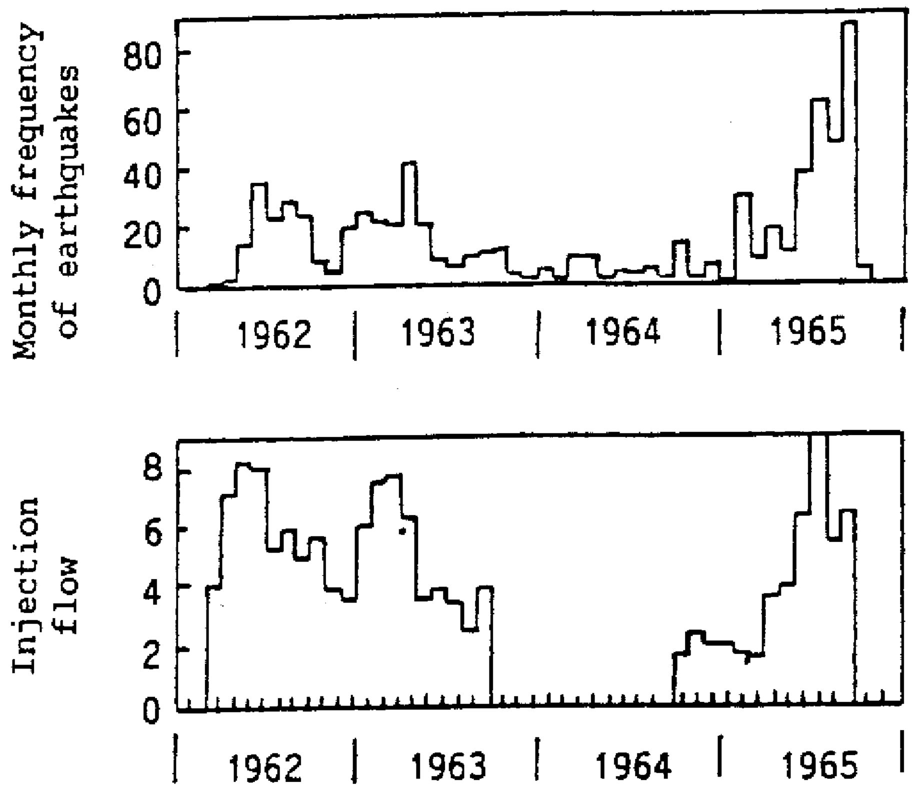

FIGURE 3 *Correlation between the injection of waste water and the frequency of earthquakes in Denver (according to Evans, 1966)*

obtained suggest that detailed, continuous observation of the behaviour of water levels in deep wells can provide indices which will help in earthquake forecasting.

Landslides

On sloping ground, the unconsolidated surface layer and consolidated underlying rock are subject to the action of gravity which, in certain conditions, can generate mass movements which are one of the geological processes modelling the planet's relief.

The most common causes of slides of rock masses are the force of gravity and groundwater. Gravity acts through the weight of the wedge of material which is liable to slide; any natural or artificial variation in this weight can affect the conditions of stability either favourably or adversely. An increase, by the addition of a load, favours the slope's stability when applied at the bottom, and reduces it when applied at the top. However, if the wedge loses weight, by erosion or artificial excavation, the reverse is the case.

Generally, groundwater is a determining factor for landslides. The moisture which occupies only part of the pores confers a certain cohesion on the unconsolidated material, through the surface tension of the film of water

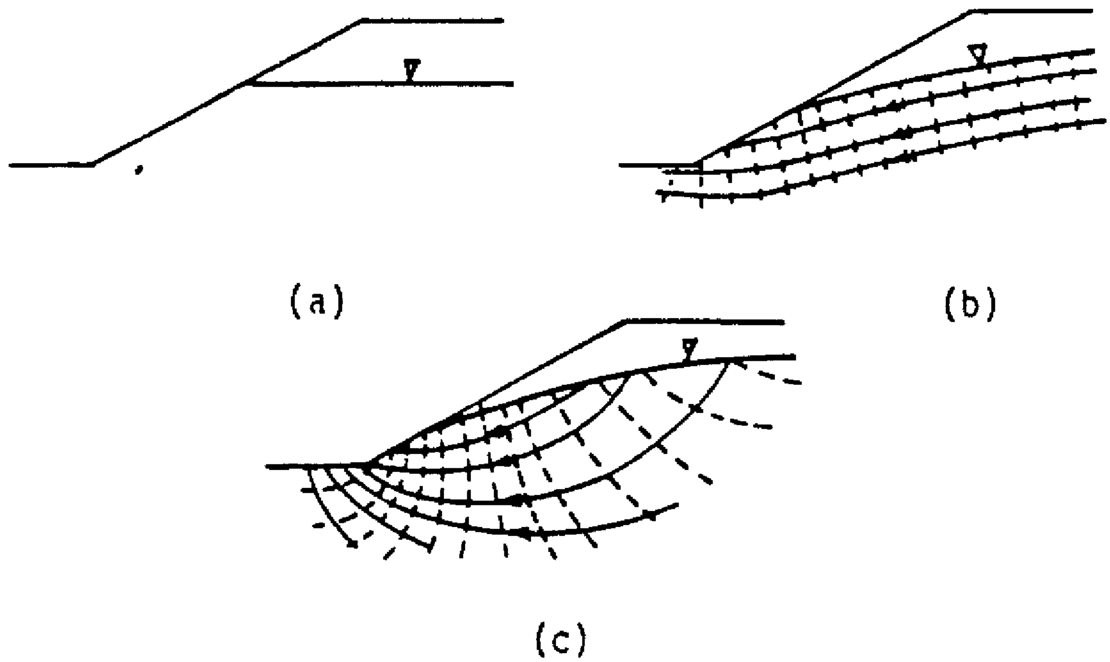

FIGURE 4 *Piezometric distribution commonly assumed in engineering works (a) and (b); distribution which is common in natural slopes situated in discharge areas (c)*

adhering to the grains; when the infiltrated water fills the pores, expelling the air, it breaks the surface tension and, consequently, reduces the material's cohesion while increasing its weight. The most important hydraulic factor in this process is pressure, because it directly influences the material's shearing resistance (Cherry and Freeze 1979).

Of all the factors controlling landslides, interstitial pressure is the least well known because there is usually insufficient instrumentation in the field, whether through underestimation of the importance of instruments, technical difficulties or economic restrictions. Because of this, the piezometric distribution is estimated using methods developed in the field of soil mechanics. However, when the slopes are very large, this approach may lead to dangerous underestimation of hydraulic pressure, since common hydrodynamic conditions are frequently presupposed in engineering works, and not the particular conditions of the regional flow systems. Special attention should be given to this hydrogeological aspect when the slope in question is located in a regional discharge zone (see Figure 4).

The flow regime also plays a determining role in the landslide mechanism. In some cases, it is reasonable to assume this as estabished for practical purposes; but in the majority of cases it is clearly transitory, especially when certain climatic and geohydrological factors are combined. For example, in sloping land, intense rain can cause a complex system of saturated-unsaturated flow and a rise in the water table of a magnitude and duration which depend on the rain's characteristics, the topography and various geohydrological

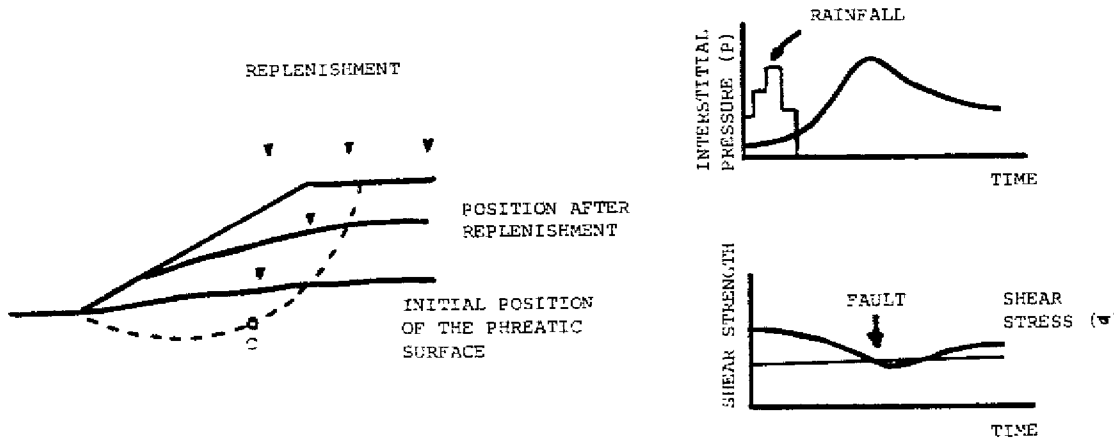

FIGURE 5 *The increase in interstitial pressure caused by infiltration can cause landslides*

factors (moisture content and hydrodynamic properties of the material). Because of the rise of the water table, the water pressure increases and the shearing resistance decreases proportionately throughout the plane of weakness and a landslide may then occur. This explains why many movements of this type take place after rainfall or snowmelt (see Figure 5).

The influence of water is still usually more difficult to analyze when slopes are formed by slightly fractured rock of complex structure because the distribution of stresses and water pressure is determined by specific structural breaks: faults, fractures and stratification planes, which makes it indispensable to make a detailed study of the structural geology and of the geohydrological conditions of the area in which the particular slope is located. Furthermore, because of the very low porosity of the slightly fractured rock, the infiltration causes big fluctuations in the water table, increasing the risk of landslides in the rock wedges during the rainy season (see Figure 6).

Besides gravity and water, which are the main causes of the vast majority of landslides, there are other contributing factors. As pointed out earlier, excavations at the base of a slope make the latter less stable, since, when the lateral support is removed, there is a reduction in the normal stress and shearing resistance which act on the potential landslide area. Strong vibrations caused by earthquakes, impacts or explosions can precipitate the movement of a slope which was already in a precarious state of equilibrium. Certain chemical changes in the material can also reduce shearing resistance.

Mohr-Coulomb's fault theory, conventional methods of slope stability analysis, and triaxial tests with their respective modifications and variants taking into account complex conditions constitute the theoretical and experimental tools to analyze most problems related to this type of movement (Juarez and Rico, 1980). Essentially, landslides of natural origin, whether slow

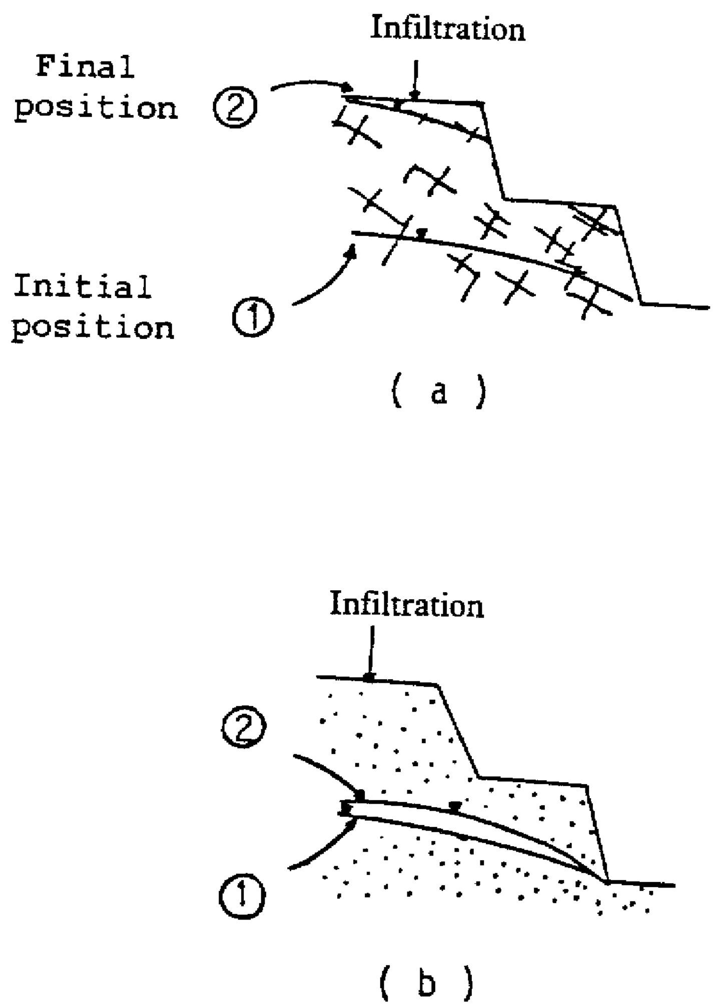

FIGURE 6 *Infiltration of the same volume of water causes much greater rises in the water table in (a) slightly fractured rock than in (b) porous material*

or fast, small or large, have the same cause, and are analyzed with the same tools as those in engineering works (see Figure 7).

Both in the unconsolidated detrital cover and in the very fractured and weathered rocks, which form a hydrologically continuous medium, the slippage plane resembles a cylinder since the detached block has a circular outward motion along what is known as a 'slope fault'. Frequently, a depression forms in the upper part of the fallen block which collects rainwater and facilitates its infiltration, thus helping the movement to continue (see Figure 8). The material's anisotropy with respect to its shearing resistance modifies the form of the landslide area, deflecting it from the circular arc. In stratified, rocky land, it is more common for blocks to become detached by sliding along a stratification plane, i.e. with a translation motion, whilst in slightly fractured rocks this area takes on very irregular forms determined by the fracturing pattern.

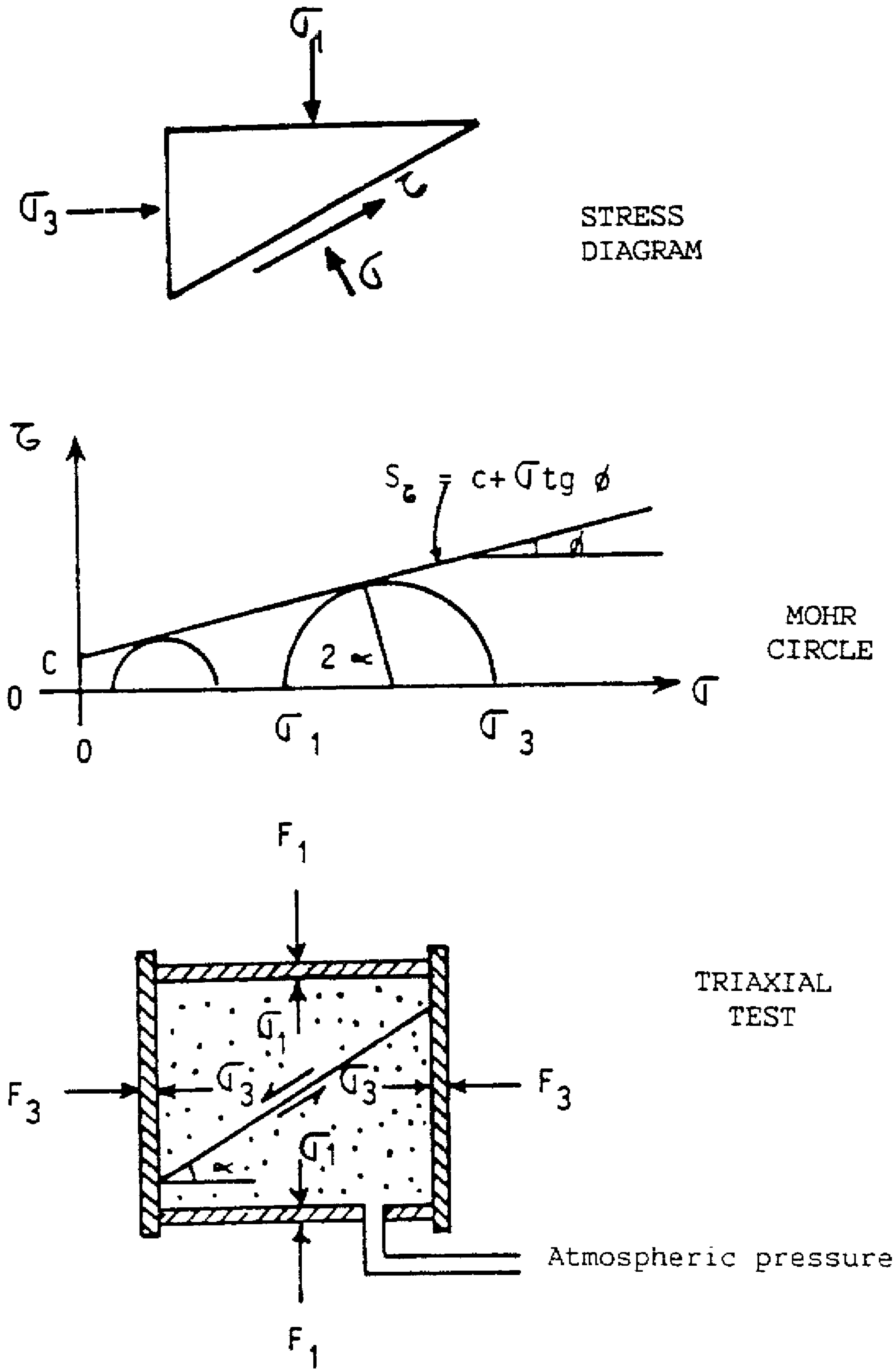

FIGURE 7 *Theoretical and experimental bases for the analysis of slope stability*

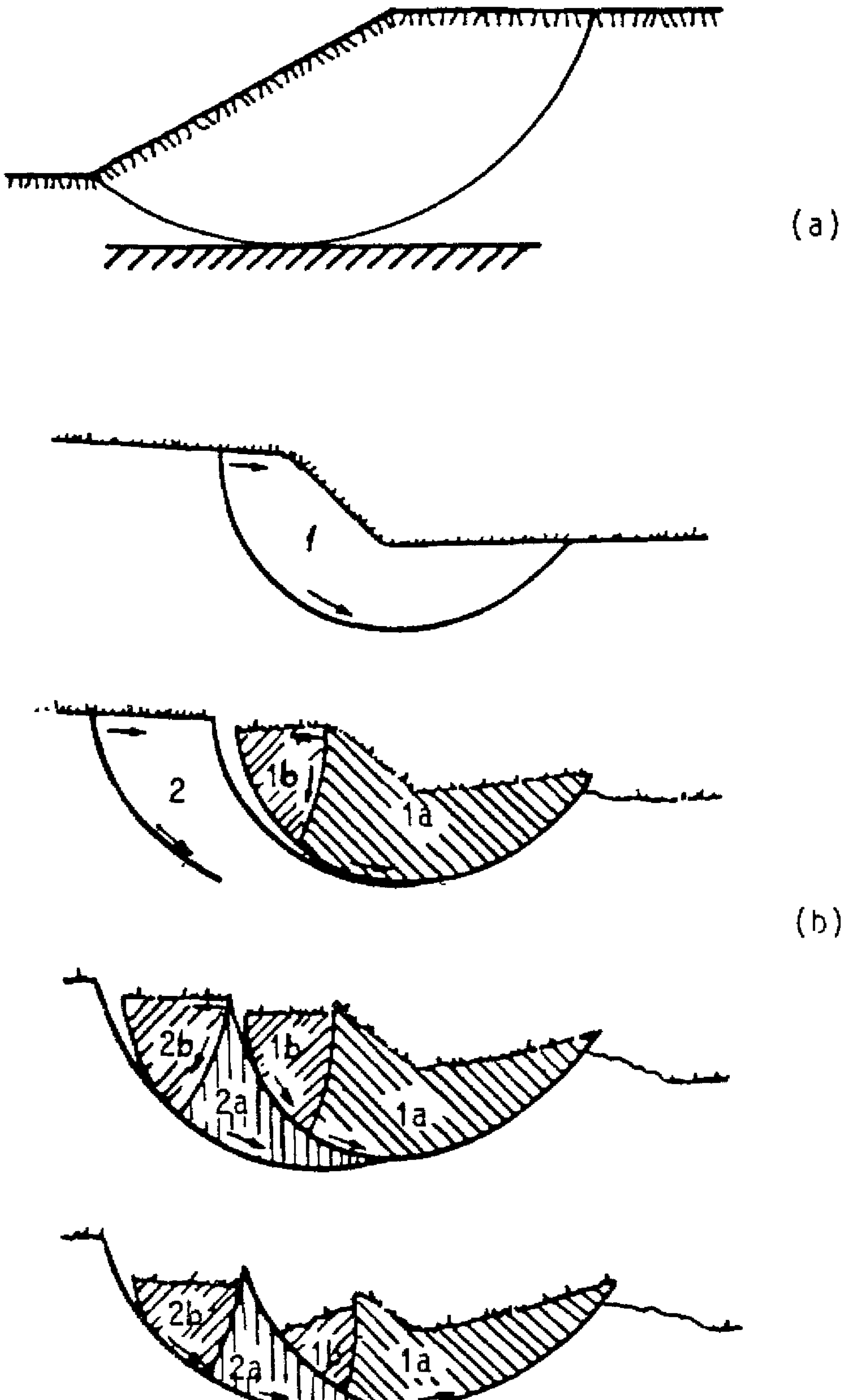

FIGURE 8 *(a) Rotative landslide of a slope; (b) fragmentation of the block removed by successive landslides*

Landslides can be fast or slow. In the former case, when they are spectacular and easily perceptible, they are less destructive. Their magnitude can vary from a local phenomenon on a single slope to the removal of the side of a mountain. Within this range, the most catastrophic are sudden slips of a rock mass along a plane of weakness. The technical literature contains various spectacular cases of movements of this type, most of which take place in land made up of marine sedimentary rock.

When the unstable material is detached by a flush of water generated by a violent storm or a thaw, a mudslide occurs, composed of rocks, soil and water, which progresses down the slope along channels and valleys forming a tongue of mud which can form balls of great size and carry them along. These mudslides transport gigantic volumes of material in alpine and desert areas with sparse vegetation and fast surface runoff.

The slow landslides are less perceptible and destructive than the fast ones, but, since they happen almost continuously over long periods of time, they transport much greater volumes of material than the fast, spectacular ones. In zones with tropical and temperate climates, the soil and underlying weathered layer form a plastic mass which flows slowly downhill, even on moderately sloping land protected by natural vegetation. The movement is facilitated by a high moisture content in the subsoil and other processes which detach the material and facilitate the work of gravity.

The so-called 'soil-flow' which is common in the upper latitudes, consists in the slow movement of the detrital cover which is alternatively frozen and thawed; like the landslide, it progresses downhill and water cannot percolate through the strata which are still impermeable because of the ice, and the surface layers become saturated acquiring the consistency of mud, which flows even on moderately sloping land.

Avalanches

In cold-climate mountain regions, avalanches bring gigantic volumes of snow to rivers and glaciers in addition to a very considerable solid load, made up of blocks of rock, detritus and trees which are picked up in the downward movement. The sliding is caused by gravity assisted by atmospheric factors and by natural or artificial vibrations from earthquakes, explosions and intense noise. Avalanches play an important role in the phenomenon of glaciation, since in a very short time they can add to a glacier volumes of snow which are equivalent to those precipitated over several years (Martinec, 1989).

Hydrological Impacts of the Phenomena

The phenomena covered in this paper have many impacts with very varied nature and intensity, from minor local damage to regional devastation with the loss of numerous human lives; some impacts are of a hydrological nature.

Earthquakes

Apart from the serious damage in urban areas, which is only too well known, a severe earthquake can have various indirect hydrological impacts which, in turn, cause secondary disasters. The most common hydrological sequels are: modification of the piezometric distribution or of the natural discharge conditions of aquifers, caused by the alteration of the underground geological structure which is sometimes reflected in sudden changes in water levels in wells and the discharge from springs; destruction of sandy strata, which also causes fluctuations in groundwater levels; pollution of aquifers which is favoured by the cracking of the land, etc. An earthquake often also has hydrological effects associated with landslides and cracks in dams or riverbanks (Yoshino, 1989).

Mexico is often subject to these phenomena: it is estimated that approximately 3% of the planet's seismic energy is liberated in this country; on average, an earthquake with an intensity of more than 7 on the Richter scale occurs once every two years, and, during the present century, eight earthquakes measuring 8 or more on the Richter scale have been recorded. This considerable activity is caused by the interaction of four tectonic plates: North America, Pacific, Cocos and Caribbean; the first two of these are displaced with different relative movements, giving rise to the seismic activity which affects the north-western part of Mexico. However, it is the convergence of the plates which is the main cause of the telluric movement; in particular the subduction of the Cocos plate below that of North America in the southern part of Mexico has caused many earthquakes with an intensity greater than 7.

Unquestionably, the most destructive of these occurred on 19 September 1985, affecting the most densely populated part of the country, Mexico City, a megalopolis of 18 million inhabitants, with extreme intensity. This earthquake was, in fact, made up of two movements of 8.1 magnitude, occurring 27 seconds apart, whose epicentres were located in the Pacific Ocean, some 800 km from Mexico City; on the following day, 36 hours later, another quake occurred which was 7.5 on the Richter scale. Among the main consequences were: more than 10,000 dead and a much greater number wounded, 412 buildings demolished and many more damaged, seriously damaged communication systems, a medical centre practically demolished, pollution of many aquifers by leaks into the sewerage system, power and water supplies cut off in large urban areas, etc., all of these effects being concentrated in the valley which Mexico City occupies, where the movement's intensity was accentuated by the subsoil's characteristics.

Within this valley, the only hydrological consequence of any importance was the pollution of the aquifers in some areas, brought about by the cracking of the earth and breakage of the sewerage pipes and canals for removing waste water; several landslides also occurred in the surrounding mountains, but without significant hydrological implications. On the other hand, in basins in

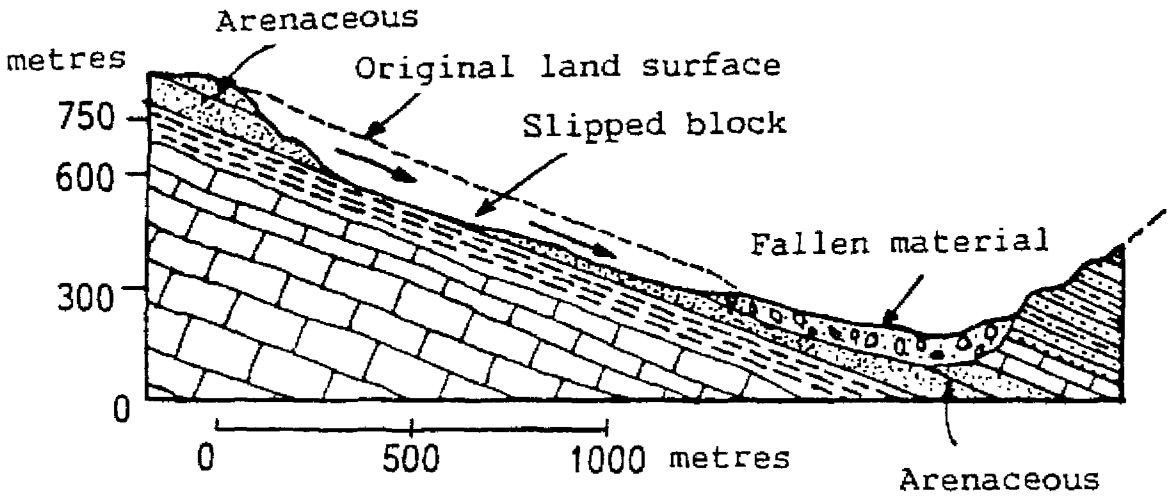

FIGURE 9 *Landslide in Wyoming*

the neighbouring state of Morelos, a sudden drop in water levels in wells scattered over a large area was observed immediately after the earthquakes, as well as the gradual reduction of the discharge from large springs, from a total discharge of more than 1,000 l/s to about 70 l/s.

Landslides

Landslides have various hydrological impacts, some of them being potentially destructive. Frequently, the material which is removed forms a dyke which obstructs the course of a surface stream; the water accumulates until it lowers or destroys the dyke, resulting in flooding (Peña and Klohn, 1989).

The technical literature contains a case which occurred in Wyoming in 1925. A block of 40 million m^3 fell off the side of a mountain because the percolated water reduced the cohesion between the strata; the rock mass slid along a slippage plane, crossed the valley, and smashed against the opposite side with such force that it produced a 'wave' 100 m high and 'backflow' forming a detrital layer 70 m thick; the water retained there gave rise to a lake 8 km long, which overflowed causing flooding downstream (see Figure 9, Leet and Judson, 1954).

The hydrological consequences are usually more serious when a large rock mass falls into a body of water, since the wave caused by the shock can produce destructive waves. A less harmful consequence is the change in runoff regime of a stream, which is caused by the large volume of sediment deposited in its channel.

Avalanches

The hydrological consequences of avalanches are essentially similar to those of landslides described above. Depending on factors which have been fully described by J. Martínez, the seasonal runoff regime is speeded up or slowed

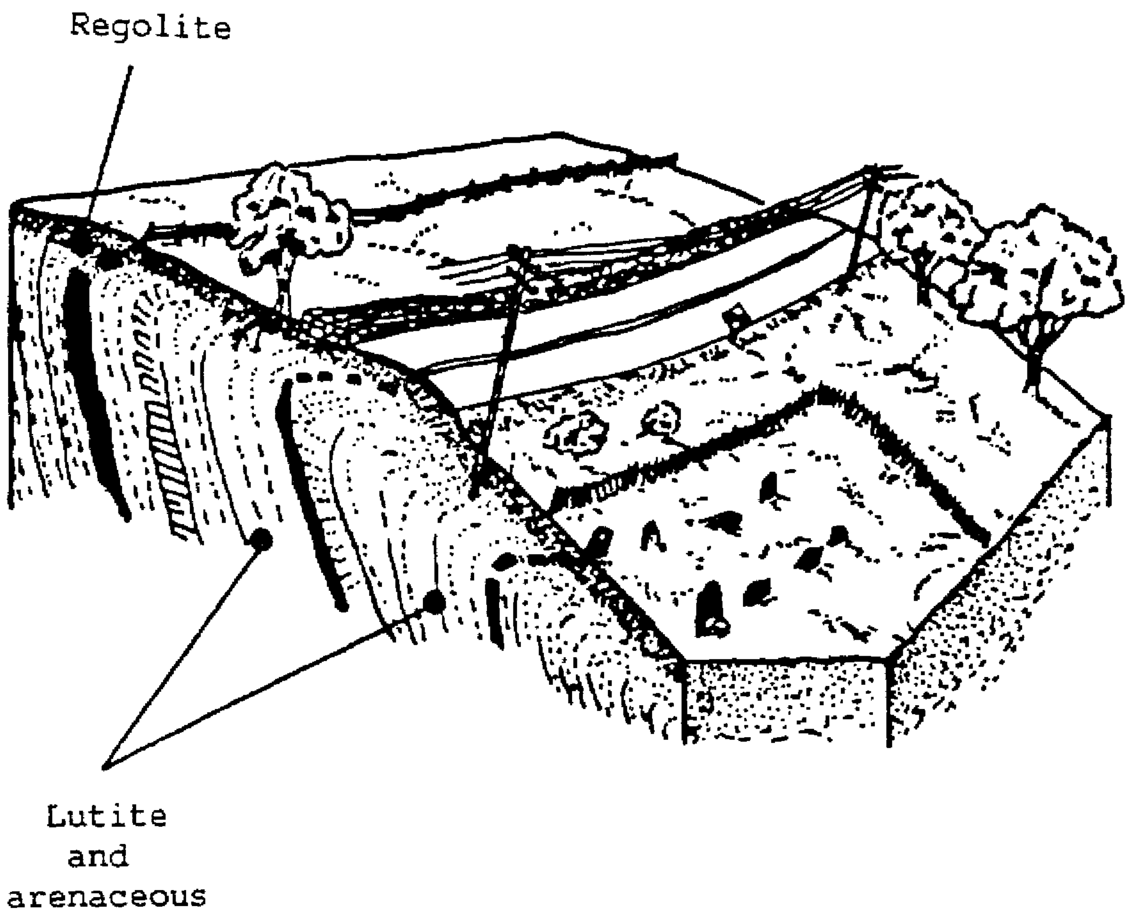

FIGURE 10 *Landslide of the cover of regolite and deformation of the underlying strata*

down, in accordance with the thawing conditions of the snow added to a glacier; this modification can be favourable when it has a regulating effect (Martinec, 1989).

On the contrary, if the load of the avalanche obstructs the course of a river, the hydrological consequences are generally harmful and can be even catastrophic: the water is temporarily stored and later suddenly liberated, eroding the bank and giving rise to extraordinary flood waves with disastrous secondary effects. Similar impacts are produced by snow and ice masses falling into water bodies.

Recommendations to Attenuate the Harmful Hydrological Consequences of Disasters

Some of the hydrological consequences of earthquakes, landslides and avalanches in certain regions threaten human life and activities. The prevention of such consequences represents a formidable scientific and technological challenge requiring the co-ordinated participation of multidisciplinary groups.

It is generally supposed that the occurrence of these phenomena is unpredictable and therefore takes everyone by surprise; however, in reality, nearly all have precursory signs. For example, some earthquakes are preceded by abnormal fluctuations in groundwater levels or by gaseous emanations; the probability of a landslide is indicated by cracks growing in the ground and on engineering works, displacement of the soil profile, and inclination of tree trunks (see figure 10). Presumably, some animals perceive signs indicating the imminence of a natural phenomenon of some magnitude. Unfortunately, such indices are not observed in time or they are observed by witnesses who cannot interpret them, as happens with most of the rural population.

On the other hand, it is certainly true that, because of their extreme complexity, these phenomena are difficult to predict precisely; however, studies made in various scientific disciplines, and the statistics collected on this subject in various countries have enabled us to identify the regions which are most subject to them, as well as to draw up safety standards, design criteria and relevant emergency programmes to prevent or attenuate their consequences. With this objective in mind, the following specific recommendations are put forward:

- to map the zones which are most subject to these phenomena, with regard to their climatic, topographical, geological, hydrological and geohydrological characteristics. An interdisciplinary effort is indispensible for analyzing these aspects; they are often rightly studied with an emphasis on one or several specialized aspects, but the combination of their results is missing;
- to give special attention to the geohydrological aspects in the analysis of slope stability, since it has been demonstrated that groundwater plays a dominant role. In particular, careful consideration should be given to the structural geology and natural piezometric distribution in ground made up of stratified and fractured rocks;
- to develop a specific methodology to discover the underground hydrology of massifs;
- to install instruments in zones and engineering works which are most vulnerable to the phenomena in question, and set up continuous observing programmes in order to collect data to identify the beginning of one of them;
- to include in dam projects the simulation of a rise in the regional water table caused by infiltration in the reservoir and its influence on the stability of adjacent sloping terrain;
- to review the criteria used for the siting and design of engineering works and adapt them to the particular conditions of each zone;
- to make a study of the underground geological structure in earthquake zones in order to know the distribution of geological formations which are most affected by the passage of the waves;
- to promote the exchange of information, experience and new methodologies between specialists in the various disciplines related to the hydrology of disasters.

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