Landslide Hazards: Geotechnical Aspects and Management Policies

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ABSTRACT

The landslides that frequently occur in the hilly areas in Jordan, particularly along the roads and highway routes during the years of intense rainfalls, resulted in a substantial increase in the cost of projects and delay in their completion, in addition to the deportation of people affected or endangered by landslides from their homes. The paper discusses the common characteristics of the landslide-prone areas in Jordan as well as the main causes of slides and their consequences. It discusses the role of site investigation and monitoring systems in reducing the hazard intensity as well as the total cost of construction. Classification of landslide-prone areas, according to the level of risk and cost of prevention/mitigation measures into prohibitive, restricted and regulated areas is suggested. This classification aims at controlling the construction activities in the areas susceptible to landslides risks.

The different components of landslide risk management are defined and discussed with the suggestion of establishing a National Hazard Management Board to be responsible for drafting of landslides risk management policies.

KEYWORDS: Landslide hazards, Geotechnical aspects, Management policies, Jordan.

INTRODUCTION

Natural weathering and erosion agents as well as the dynamic forces of earthquakes, volcanic eruption and mountain-building movements dictate the topographic and geomorphological features of earth. Slopes exist because of the shear strength of earth materials that resist the driving forces resulting from gravity and other external stresses. Landslides occur when driving forces exceed the resisting forces. Some of them are rapid and catastrophic, while others are slow. Rapid catastrophic landslides are often due to sudden loss in resisting forces or sudden increase in driving forces. Earthquakes, heavy rain and snowfalls combined with sudden rise in cleft water pressure and rapid drawdown of water in reservoirs often lead to sudden landslides, especially in jointed and weathered rocks. Slow slides often occur in cohesive soils with plastic stress-strain behavior, where little or no loss in shear resistance occurs with the increase in strain. Thus, we can conclude that natural slopes are the product of geological, hydrodynamic, erosional, geodynamic and environmental processes. Human activities involving deforestation, blasting, cutting, filling, impounding water in reservoirs and dewatering or rapid drawdown of water in reservoirs often trigger landslides, particularly in slopes existing in a critical state of stability.

Deep cuts often lead to the day lighting of outcrops of weak layers with slippery surfaces leading to sliding upon saturation with water. Differential weathering of weak strata leads to the development of cracks in the overlying stronger beds. This eventually leads to rock falls or to toppling failure of steeply standing blocks of

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rocks separated by joints and bedding planes from the rock mass.

High fills on slopes, especially those with pre-existing slip planes in areas that suffered from old landslides, often lead to landslides.

Many areas in Jordan had in the past fifty years suffered from landslides and rock falls, particularly along highway routes. The adverse geological conditions, intense rainfalls, scour erosion, poor drainage conditions and improper human activities in addition to frequent seismic tremors are the main causes of these landslides.

TYPES AND CLASSIFICATION

Skempton and Hutchinson (1969) presented a classification for the types of mass movements. They classified them according to their modes and forms as falls, rotational slides, translational slides, compound slides and flows. They also presented illustrations for multiple and complex landslides.

Table 1. Main types of landslides*

Type of movement			**Type of material**		
			Bedrock	**Engineering soils**	
				Predominantly fine	**Predominantly coarse**
Falls			Rock fall	Earth fall	Debris
Topples			Rock topple	Earth topple	Debris topple
	rotational		Rock slump	Earth slump	Debris slump
Slides	Translational	Few units	Rock block slide	Earthblock slide	Debris block slide
		Many units	Rock slide	Earth slide	Debris slide
Lateral spreads			Rock spread	Earth spread	Debris spread
Flows			Rock flow	Earthflow	Debris flow
			Rock avalanche		Debris avalanche
			(Deep creep)	(Soil creep)	
Complex and compound			Combination in time and/or space of two or more principal types of movement		

*Hunger et al. (2001).

Varnes (1978) presented a classification of landslides based on the mode of failure and the type of slope material. The main types include rock and soil falls, planar and rotational slides as well as debris, sand, loess and silt flows.

Rock falls involving rock fragments of different sizes are very common in steep slopes of jointed stratified rocks. They pose serious threats to traffic, engineering structures and human life. Depending on the steepness of the slope, rock fall modes may range from simple rolling (in 1.25H: 1 V slope) to bouncing (in 1/2H: 1V slope) to free fall (in 1/4H: 1V slope) as illustrated by Ritchie (1963).

Toppling failure of rocks occur in vertically or sub-vertically jointed rock masses whenever the base to height ratio of the rock block is less than the tangent of the slope angle.

Based on the above classifications and modifications introduced by Hunger et al. (2001), Table 1 shows the main types of earth movements. The type of landslide mainly depends on the type of material, physical and mechanical characteristics of slope material, geometry of slope, stratigraphic and structural characteristics of slope material, hydrogeological conditions, climatic conditions and the main triggering factors of earth movement.

Some slides are small and localized and some are very large and extend few kilometers in length. Some are very slow (<5 mm/ hr) and some are very fast (>120km/hr). Some are triggered by human activities, e.g. blasting and cut and fill operations and some by natural factors, e.g. earthquakes, scour erosion during floods and intense rainfalls. Leaking water from pipelines, vibrations from traffic and heavy machinery, rapid drawdown in reservoirs, tsunamis and strong wave action may also trigger landslides and rock falls. Deforestation, improper agricultural practice, poor drainage conditions and the blockage of natural drainage channels further exacerbate slope instability problems.

LANDSLIDES IN JORDAN

Most of the 44 landslides studied by the author occurred along the major highways in Jordan and in particular along Amman-Jerash-Irbid highway, Amman-Naur-Dead Sea highway and at the construction sites of some projects like Wadi Es-Sir Sewage Treatment Plant, Kufranja Dam and along roads within some towns like: Salt, Wadi Mousa, Ajloun, Jerash, Tafila among others.

Common Characteristics of Landslide Areas

It has been noticed that most of the landslide areas were either not investigated before construction or were subjected to inadequate site investigation. The inadequacy evolves from the deficiency in the scope, depth and poor distribution of the investigation works as well as from poor interpretation of the field and laboratory testing results.

Highway engineers are mainly concerned with the geometric standards and the balance between cut and fill volumes in the selection of the alignment and the design of the highway routes. They pay no or little attention to the paleogeological history of the areas through which the highway passes or to their engineering-geological and hydrogeological conditions.

Most of the landslide areas in Jordan are characterized by the following features:

1. Poor quality of the slope materials which often exist in moderately to highly weathered and jointed state.
2. Presence of moderately to highly plastic wet interbeds of shale or clayey marls.
3. Unfavourable orientation of geologic strata.
4. Poor drainage conditions.
5. Moderately intense to intense annual rainfalls.
6. Poor foundation materials dominated either by colluvial deposits or wet plastic silts and clays.
7. Presence of pre-existing slip planes due to the occurrence of old landslides as evidenced from their geomorphological features.
8. Moderately steep to steep topography overlooking, in many cases, water courses that experience deep scour erosion during floods.

Main Causes and Consequences of Landslides

The daylighting of wet plastic interbeds dipping unfavourably with respect to the orientation of excavations and the placement of compacted fill over weak foundations or pre-existing slip planes often lead to slope failures. Typical examples of these types of failure are:

-Slope failure in the left abutment of Al-Mujib dam caused by the daylighting of a 0.4 to 1.0 m thick wet plastic mudstone layer overlain by porous loose colluvium that allowed the percolation of rainwater towards the mud layer that was dipping steeply towards the excavation (Figure 1).

-Failure of a 16 m high highway embankment on Amman-Jerash highway founded on thick layers of loose wet colluvial deposits that already existed in a critical state of stability (Figure 2).

-Four failures in Wadi Es-Sir Sewage Treatment Plant in the period from September 8,1993 to February 23,1997 in spite of the continuous flattening of cut slopes from 1V:2H to 1V:4H. The failures occurred along slippery planes of wet plastic clayey marl in an area that experienced many old landslides and is characterized by poor drainage conditions as shown in Figure 3 which shows the sliding plane of the failure that occurred on July10, 1995.

-Slope failure at pump station no.3 along the route of the pipeline of pumped water from Deir Alla (Jordan Valley) to Dabouq (west of Amman). The failure occurred due to the daylighting of 0.4 to 0.6m thick layer of wet plastic clayey marl dipping unfavourably towards the excavation (Figure 4).

-Slope failure in Ma'in SPA complex main entrance road due to the excavation at the toe of a steep slope composed of wet moderately plastic marl. The failure occurred 4 months after the first appearance of the cracks at the crest and the sides of failed slope (Figure 5).

(A)

(B)

Figure (1): A landslide on the left abutment of Al-Mujib dam
A) The escarpment of the slide in the talus material
B) The slickenslide surface in the underlying mud layer

-Failure of concrete retaining walls constructed nearWadi Zaid in Tafila.The failure is due to the low bearing capacity of the very wet plastic clay marls on which the retaining walls were founded. The problem was further exacerbated by the poor quality of backfill material and poor drainage conditions (Figure 6).

It has been noticed that most of the landslide areas are dominated by highly plastic marls and moderately plastic shales as shown in Figures 7 and 8. Most of the formations that contribute to landslides in Jordan belong to Ajloun Group of the U. Cretaceous and to the Kurnub Sandstone formation of the L. Cretaceous as shown in Figure 9. Also, most of the landslides occurred in the years that witnessed high rainfalls, particularly in the winter season of the years 1991/1992 when the total annual rainfall exceeded 900 to 1000 mm in the highlands of north and west Jordan as shown in Figure 10.

Leakage of water from pipelines and ground reservoirs, accumulation of surface runoff in depressions with slow but continuous deep percolation through ground strata and steep cutting of slopes often lead to slope failures as shown in Figures 11 and 12. In Figure 11, the construction activities at the toe of Jebel Jofeh involving excavations and removal of debris from a previous landslide and the leakage of water from corroded pipelines resulted in reactivation of slide and failure of the above retaining wall and the street behind it. Figure 12 shows slope failure on Amman-Jerash highway due to the poor drainage conditions and daylighting of wet plastic marls due to nearby deep steep excavation. These failures resulted in the closure of a main road in Jebel Jofeh, destruction of many houses along Amman-Jerash highway and deportation of people from their damaged homes to safer ones. The placement of a thick embankment fill along Jordan road on a pre-existing slip plane in an area that suffered from an old landslide resulted in a creep displacement that caused drop and cracking of the asphalt road. The only feasible solution was to shift this section of the road towards the hill side as shown in Figure 13.

Figure (2): Failure of a 16 m high highway embankment founded on a thick layer of colluvial deposits along Amman-Jerash highway at St. 38+600

Figure (3): The sliding surface at the top of clayey marl bed in Wadi Es-Sir Sewage Treatment Plant. Note the jointed cliff of the limestone overlying the marl that belongs to Naur Formation (A1/2)

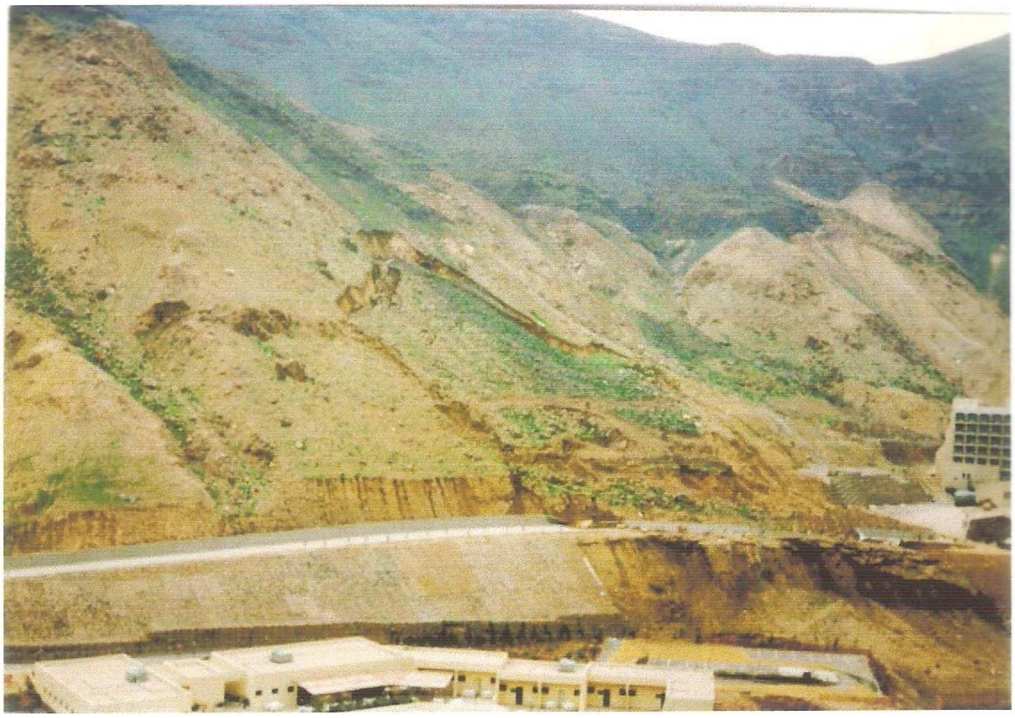
(A)

(B)

Figure (4): The slide at pump station no. 3

A) Wide and deep cracks extending to more than 30m beyond the crest of the slope

B) The main scarp and failed benches



(A)

(B)

Figure (5): (A) The cracks on the crest and the sides of the slope overlooking the approach road to the main hotel at Ma'in SPA complex before failure
(B) The smooth sliding surface in the clay marl after failure

(A)

(B)

Figure (6): (A) The displacement and overturning of retaining wall on Wadi Zaid in Tafila
(B) The displacement of slope material beyond the failed wall

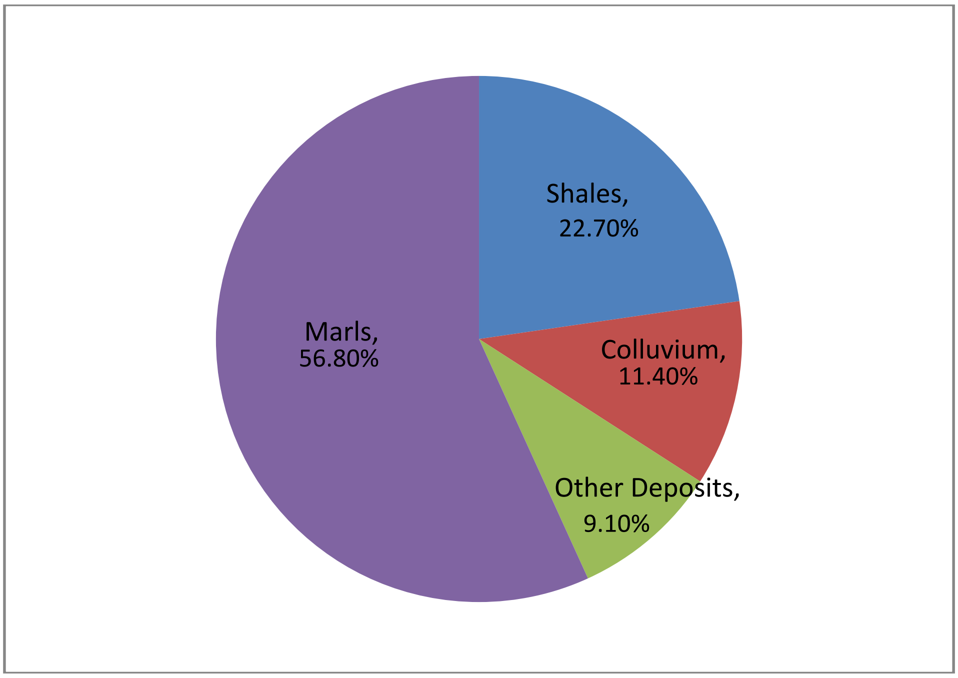


Figure (7): Frequency distribution of the dominating materials in 44 landslide areas

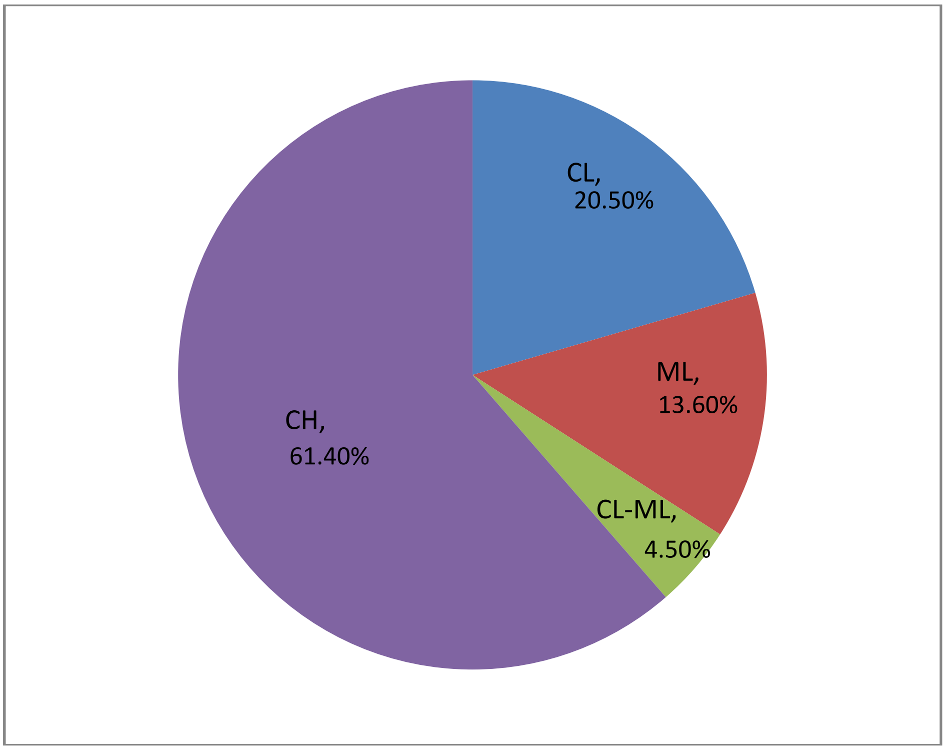


Figure (8): Frequency distribution of 64 samples from the landslide areas according to the unified soil classification system

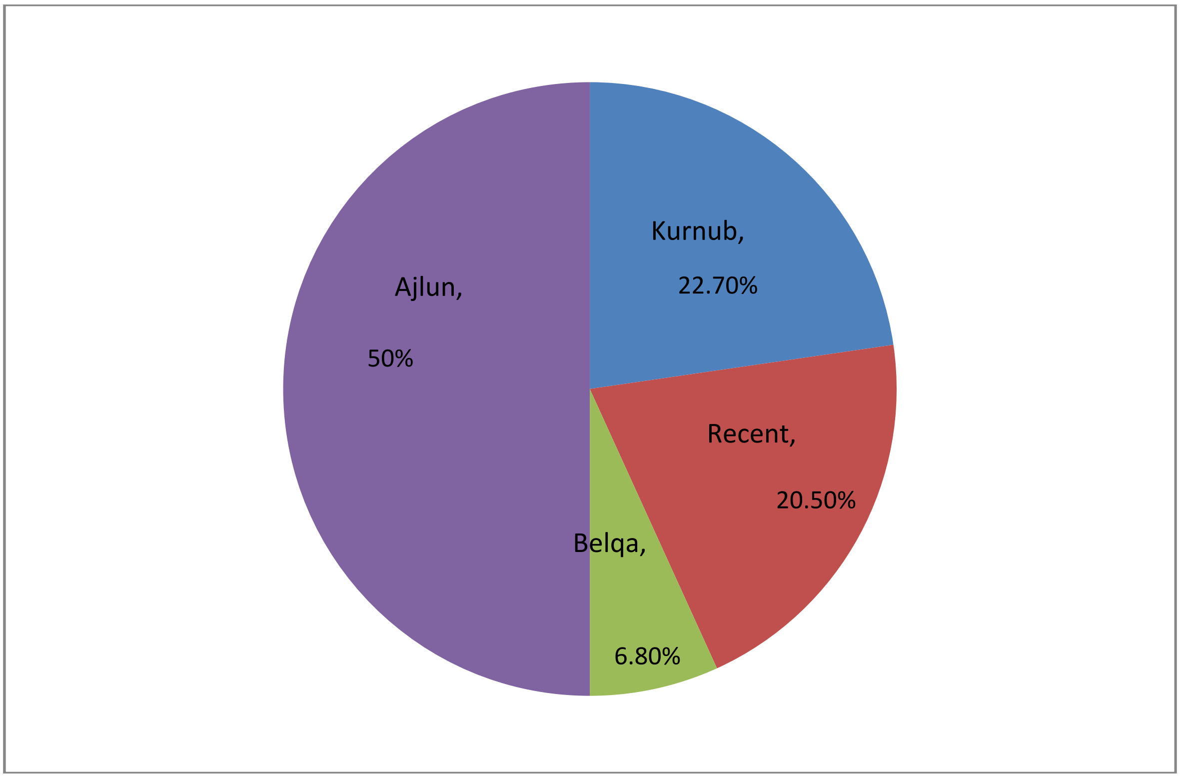


Figure (9): Frequency distribution of the geological formations in 44 landslide areas

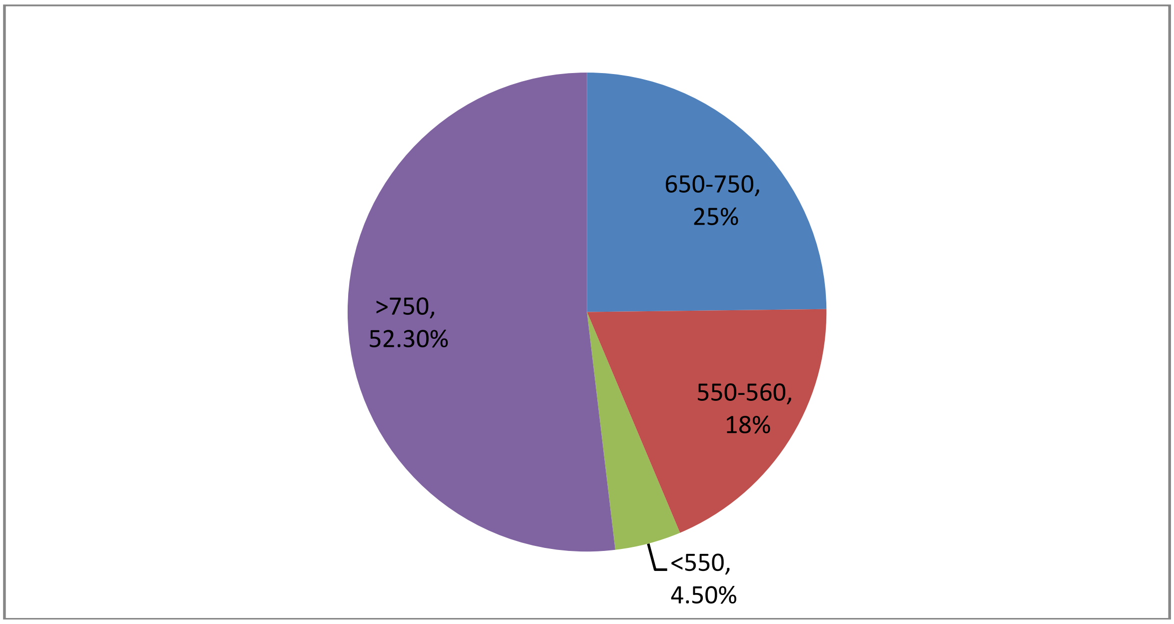


Figure (10): Frequency distribution of 44 landslides according to the total annual rainfall (mm) in the years of their occurrence

Figure (11): The construction activities at the toe of Jebel Jofeh that led to slope failure and closure of the upper road

The daylighting of a layer of a disturbed reworked plastic clayey marl under a succession of limestone and marly limestone beds at Station 56+600 along Amman-Jerash highway resulted in a major landslide exceeding 120,000 m^3. This resulted in the adoption of a split-level design of the highway. Inspite of the construction of gabions at the toe of the sliding mass continuous creep of this mass resulted in the last 18 years in excessive distortion of the gabions and the asphalt road as well (Figure14).

At Kufranja dam (under construction), a landslide occurred in the spillway chute on March17, 2012. The investigation showed that the slide was initiated in a plastic clayey marl near the middle of the spillway chute that was recently excavated due to the absorption of moisture from the preceding rainy months. The percolated water through the poor jointed rock mass near the top of the spillway excavation affected the colluvial deposits in the lower zone of the spillway chute. The colluvium was much thicker than what was anticipated and the geologic conditions were also worse than what was assumed in the design. Figure 15 shows the spillway chute excavated area after the landslide. The landslide resulted in both a delay of construction and an increase in the cost of the project.

Rock falls, although few, are not uncommon in steep hilly areas, particularly along road and highway routes like Amman-Jerash and Amman-Naur-Dead Sea highways, and in the towns of Ajlun, Kufranja, Salt, Wadi Es-Sir, Tafila and Wadi Mousa, and in the abandoned quarries bordering the outskirts and the downtown of Amman. These rock falls pose serious threat to people, properties, traffic and other facilities like power lines, tracks and pipelines. Rock falls are often triggered by intense rain and snow falls, earthquakes and human activities like blasting and excavations. Figure 16 shows an area, studied by the author in Yemen, that was seriously affected by rockfalls. Rockfall incidents claimed the lives of many people in Yemen, particulary those in houses built very close to the rocky cliffs.

Figure (12): Failure along Amman-Jerash-Irbid highway due to the daylighting of the wet plastic clayey marl that resulted in the collapse of the houses near the edge of the excavation

Figure 17 shows the crash of an empty car by a large rock boulder that rolled down from a steep slope in the town of Jerash, north of the capital, Amman.

According to Petley (2012), the death toll from the 2620 rainfall-induced landslides amounts to more than 32000 in the seven-year period (2004-2010) worldwide. If the earthquake-induced landslides are considered, the death toll rises to more than 80 000.

Most of the landslides and rock falls with disastrous consequences occur in densely populated hilly and mountainous areas after intense rainfalls or earthquakes.

Landslides and rock falls may sometimes cause the cancellation of projects like the frequent landslides in Hisban Dam project which led to the termination of the project.

In addition to their adverse impact on the environment, landslides often result in a substantial increase in the cost of the projects and delay in their completion.

Figure (13): Shifting of a section of Jordan Road due to a continuous creep movement of the road embankment constructed in an area that suffered from an old landslide

Observation and Monitoring

It is of a paramount importance to observe and record any unusual features that may affect the cut slopes in the project area. Such features may be detected at an early stage by field inspection, periodic survey measurements or by the examination of aerial photographs taken at different periods of time.

Among the features that may give an early indication of instability are:

1- Emergence or disappearance of springs.
2- Tilting of objects like trunks of trees, electric or telephone poles or metallic fences.
3- Development of tension cracks on the slope face or near its crest.
4- Cracking of civil engineering structures like buildings, box culverts, concrete retaining walls… etc. on or near the cut slope.
5- Sudden loss of liquids in septic tanks, pits or pools on or near the cut slope .
6- Any distortion in the surface or alignment of roads passing within or close to the project site.
7- Any unexpected change in the alignment of water pipelines or leakage from these pipelines within the project area.
8- Any displacement of retaining structures within the site manifested by, for example, tilting of the walls and widening of their expansion joints or the bulging of gabions and the breaking down of their wire meshes.
9- Rapid increase in stream flow and its turbidity.
10- Sticking doors and windows and distortion in ground and wall tiles.

(A)

(B)

Figure (14): (A) Severe damage in the gabions and the asphalt of Amman-Jerash highway due to the creep displacement of the failed slope along the wet plastic marl sliding surface at St. 56+600 (B) Satellite image of the landslide

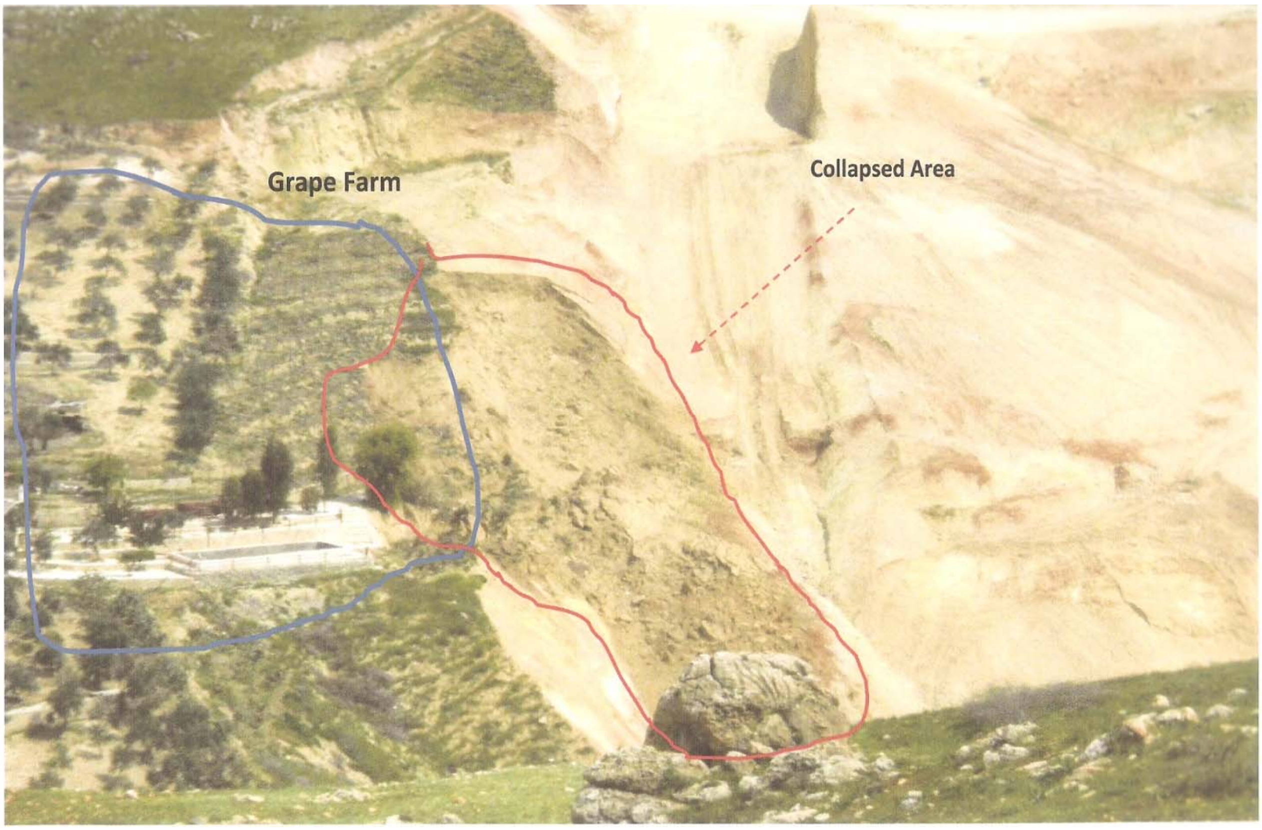


Figure (15): Kufranja dam-excavation of spillway, chute and flip Bucket (31/03/2012)

A simple warning system for rainfall–induced landslides can be established by developing a reliable relationship between rainfall and earth movements and recording rainfall intensities by installing rainfall gauges in the landslide-prone areas.

A low-cost simple early warning system was proposed by Uchimura and Towhata (2009) which could indicate that failure would occur 30 minutes before its occurrence. It is very suitable for use in hilly areas susceptible to frequent small landslides.

Masannat (2011) suggested a parameter called slope stability index, SSI, for the evaluation of the relative stability of natural slopes. According to this parameter, the slopes were classified within 5 groups ranging from slopes of high stability with SSI greater than 81 to unstable landslide-prone slopes with SSI less than 20, where an early warning system could be needed.

The significant role of early warning systems stems from the fact that the number of fatalities due to natural hazards is much lower in the developed countries which use adequate monitoring and warning systems than in the underdeveloped ones which lack such systems (Figure 18).

Due to the exponential growth of population who seek settlement in the major cities located in the hilly and rugged terrains, landslide and rock fall hazards continuously increase. Prevention of all landslides and rock falls often entails prohibitive costs that many countries cannot afford. Some minor slides could be tolerated depending on their probability of occurrence and the associated magnitude of loss as shown in Figure 19.

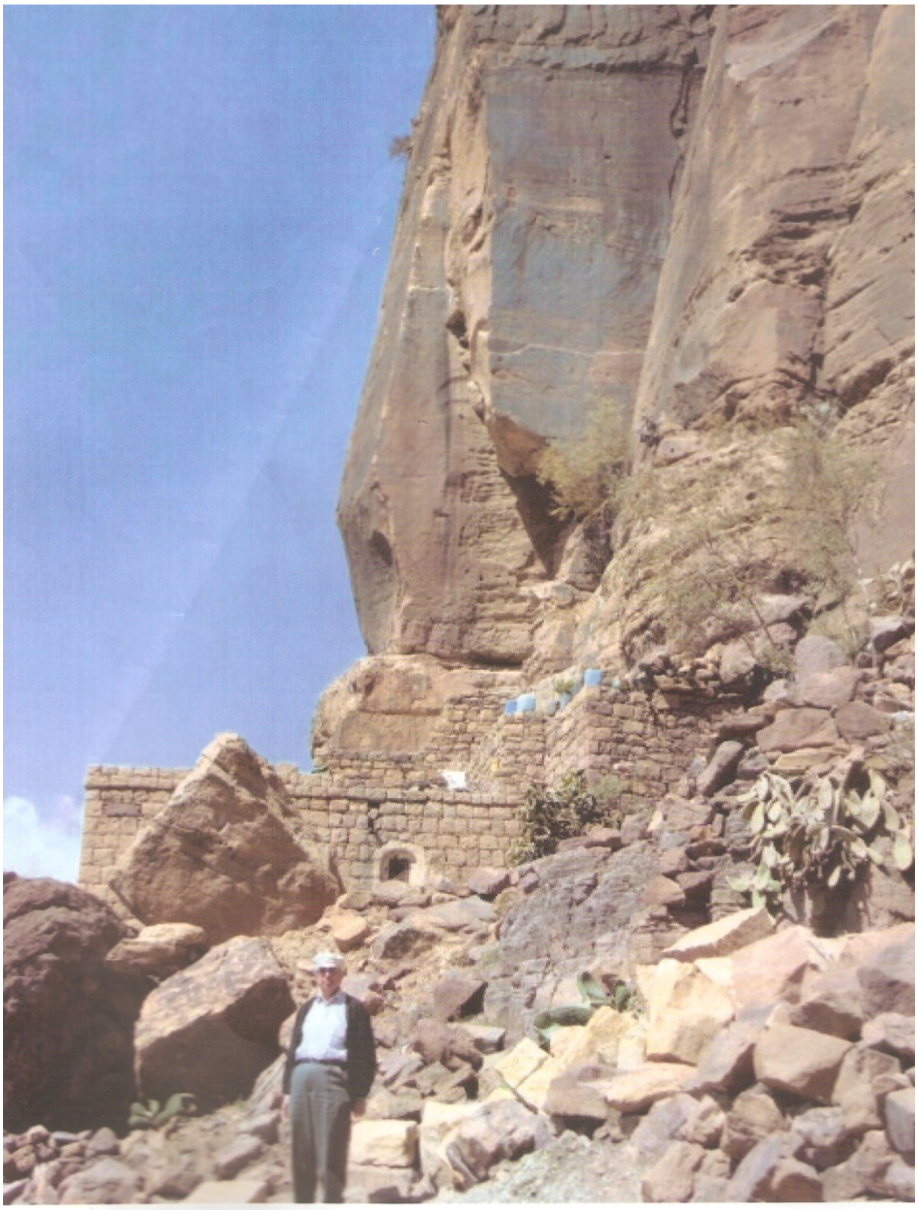


Figure (16): High rocky cliffs and rock falls threatening the houses built at their toes

In landslide-prone areas with high geotechnical uncertainties, an adequate instrumentation and monitoring system should be installed by experienced contractors and monitored and analyzed by qualified geotechnical engineers.

In such areas, staged design and construction approach could be adopted whereby the rate of construction and the design features could be adapted to the new site conditions as manifested by the readings of the instrumentation system .

This approach is applicable to landslide-prone areas along Amman-Jerash and Amman - Naur - Dead Sea highways and Jordan Road as well as to dam projects like the Arab Potash dikes on the Dead Sea and Kufranja Dam.

For limited budgets, areas of critical stability should be prioritized for monitoring and detailed study based on well-defined criteria established by expert committees.

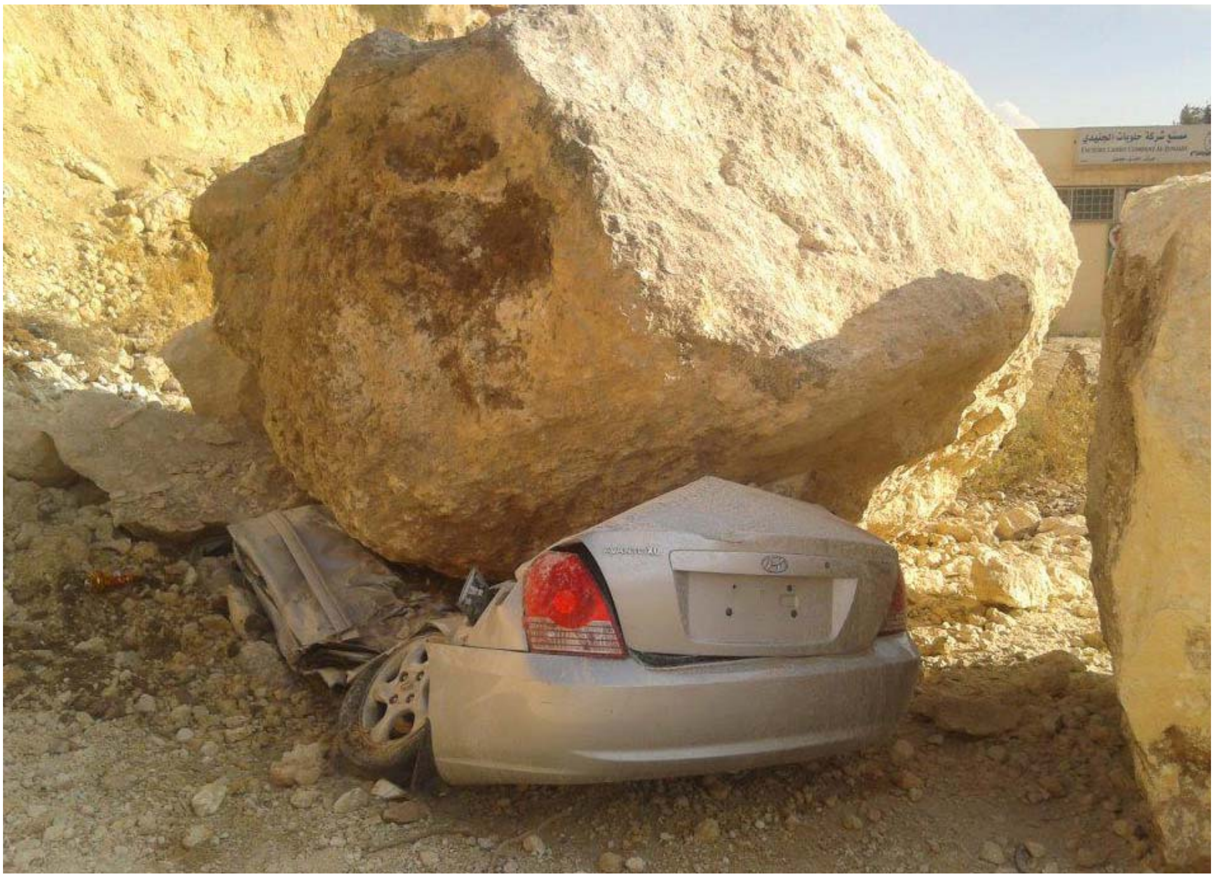


Figure (17): A large rock boulder that rolled down from a slope in Jerash town causing the crash of an empty car

The total cost of an engineering project is substantially influenced by the uniformity of ground conditions and the adequacy of site investigation. Figure 20 clearly shows that the increase in the cost of investigations often results in substantial savings, avoidance of unpleasant surprises and optimization in the design of the project and the monitoring system.

Stabilization and Control Measures

It is common that in some large projects, like highways, some minor landslides of limited effects are unavoidable. All efforts, in such cases, should be exerted as to minimize the adverse impact of such landslides. If major landslides are anticipated, then a drastic change in the design of the project or its location should be considered .

For landslides of limited extent, protection and stabilization measures should be thoroughly assessed technically and economically. However, best efforts should be exerted in avoiding building and construction of projects in landslide-prone areas.

The most common method for increasing the factor of safety against sliding is changing the geometry of slope by flattening, unloading and benching.

Fookes and Sweaney (1976) presented the common control measures and structural means to minimize the risks of rock falls. Ritchie (1963) illustrated the rock fall modes (roll, bounce and fall) and the common protection systems. The support measures commonly include concrete retaining walls, sheet piles, micro-piles, geogrid and geotextile reinforced retaining walls, gabions and others. Guniting and wire meshes are used to protect against rock falls.

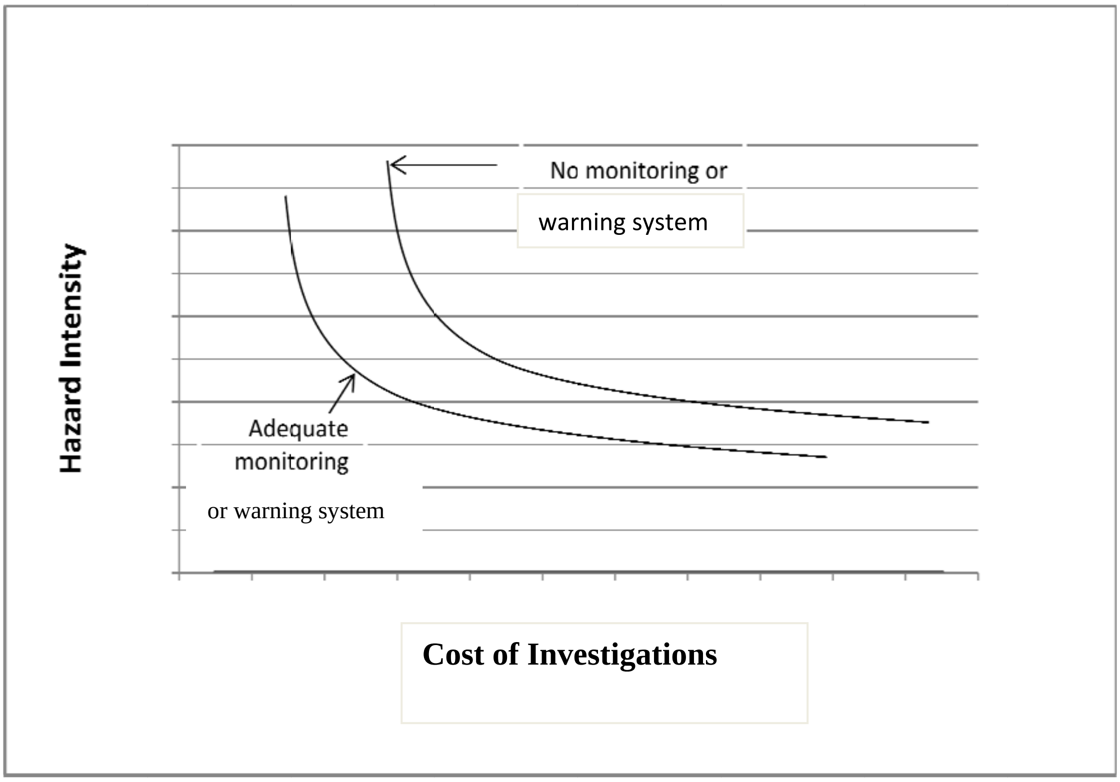


Figure (18): Cost of investgations *vs.* hazard intensity

Dowels, rock bolts, soil nailing and grouting are common methods for reinforcing slopes.

Rock trap ditches with or without fences are often used to protect traffic and passengers from rock falls.

In nearly all cut slopes, effective drainage systems are needed to decrease deep water percolation in the slope material and thus to prevent both surface erosion and build-up of pore pressures in soils and cleft water pressure in rock discontinuities. Strong vibrations from heavy machinery and blasting could trigger landslides.

Therefore, the selection of proper methods for excavation and proper construction equipment could help in minimizing the threats of landslides and rock falls. The protection of the outcrops of air-slaking materials like shales, marls and mudstones against variations in moisture content and weathering agents by, for example, mortared riprap or shotcreting with wire mesh would help in averting deterioration in slope stability with time.

LANDSLIDE RISK MANAGEMENT

Risk management comprises three major pre-disaster components: risk assessment, risk evaluation and decision-making. Risk assessment comprises identification of landslide-prone areas, type of earth movement, rate of ground displacement, probability of occurrence, volume of affected area, who and what will be affected (exposure) and consequences of slope failure. Risk evaluation comprises the vulnerability of the affected structures and facilities; i.e. their capability of withstanding the effects of the landslide or rock fall. This mainly depends on the form, quality and location of these structures and facilities. Risk evaluation comprises also the accepted level of risk based on the resilience of the community; i.e. its capacity of self-management and recovery and the preparedness measures. These measures include public awareness of risks and the mobilization of the efforts of all stakeholders to cope with the anticipated consequences of the probable landslides/rock falls.

The decision-making process depends on the risk reduction policies and emergency considerations. These generally include avoidance, prevention and mitigation measures based on the socio-economic and political considerations of the respective areas.

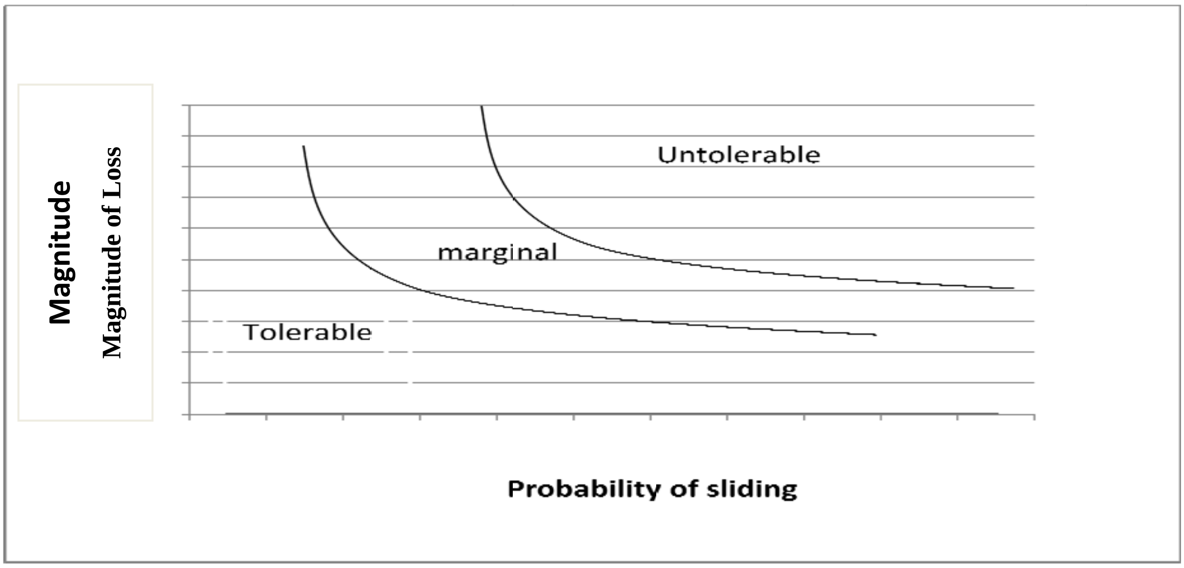


Figure (19): Effects of probability of sliding and magnitude of loss on the tolerance level of sliding

Decision – making Guidelines

The avoidance measures include the legislations that control and regulate the building and construction activities in the different areas on the basis of the level of landslide threat, types of structures and facilities in each area and their relative significance on the local and national levels .

These measures mainly aim at reducing landslide hazards to people, properties and facilities to the minimum. They also include regulations concerning the installation of monitoring and early warning systems at the existing landslide- prone areas, particularly along road and highway routes passing through metastable hilly areas These aim at reducing the cost of hazard reduction measures as shown in Figures 18, 19 and 20.

The risk is linked with the level of threat, vulnerability of people, structures and facilities, in addition to the resilience of the endangered community; i.e. its capacity of self-recovery.

Hazard zoning maps prepared by well-qualified and experienced teams of engineering geologists, geotechnical engineers, surveyors and photogeologists constitute an essential tool for the evaluation of the potential risk.

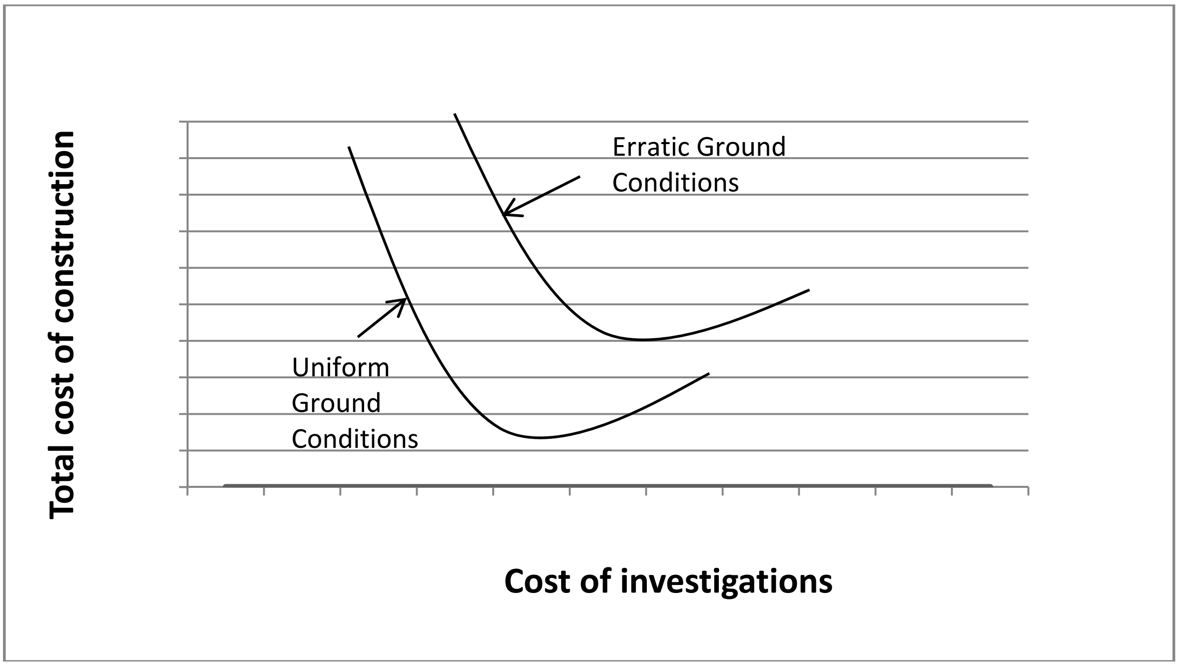


Figure (20): Effects of cost of site investigations on the total cost of construction

Any decision concerning the control of construction activities or the stabilization and mitigation measures in the vulnerable areas depends mainly on the level of risk and the cost of such measures. If the risk is rated as (1) low, (2) medium and (3) high and the cost is rated as (1) low, (2) medium and (3) high, then the product of the cost and risk (cost X risk), designated as CR, could be rated on a scale from 1 to 9. This parameter could be adopted as the main criterion for any management decision related to the construction and building activities in the vulnerable areas. These areas could be classified as follows in terms of regulations controlling building and construction activities:

A- Prohibitive areas if CR is greater than 6, where no construction activities are allowed.

B- Restricted areas if $3 \leq CR \leq 6$, where building or construction is allowed under the conditions of extreme necessity and after intensive investigations and with proper precautionary measures .

C- Regulated areas if CR is less than 3, where construction activities are allowed after conducting site investigations according to the national building code.

Local risk management groups formed from the people and experts residing in the vulnerable regulated and restricted areas can set the priorities for the preventive and mitigation measures.

Preparedness measures that include installation of monitoring and warning systems, evacuation plans, control and mitigation engineering works, training of rescue teams and provision of adequate rescue facilities are to be taken in each vulnerable area at a level commensurate with the estimated level of risk .In case of disastrous landslides or rock falls, the rapid exchange of reliable information during and shortly after the event is of a paramount importance. Raising awareness among all the stakeholders about the necessity of keeping the relief facilities and infrastructure services in good operational condition is an essential element in the preparedness measures.

If ever a damaging landslide or rock fall occurs, the well-trained crisis team should be ready to cope with the event in a well-organized and efficient manner.

Removal of debris and rescue of injured people and those trapped under the damaged structures should receive top priority. Local experts should start collecting data about the event shortly after its occurrence with the rapid exchange of information through effective communication means.

The rehabilitation activities aim at repairing the vital facilities, roads and equipment as soon as possible to minimize the disruption of the livelihood of affected people .

The reconstruction of buildings and infrastructure facilities is a top priority as well as the analysis of the event . The results of analysis must be integrated in the planning of the future development activities of the affected areas and in the review of the existing hazard-zoning maps. The efforts of the main concerned official bodies like the Natural Resources Authority, Ministry of Public Works and the Royal Scientific Society should be well coordinated with those of the researchers at the public and private universities in refining the landslide hazard-zoning maps. The establishment of a Natural Hazard Management Board directly linked with the Cabinet to be in charge of establishing the disaster risk management plans for Jordan should be seriously considered by the Government officials.

The natural hazards may include, in addition to landslides and rock falls, floods, sink holes linked with the continuous drop in the Dead Sea water level, earthquakes, failures of major structures like dams and depletion of groundwater resources or their contamination .

The proposed Board will also be responsible for building the capacities that are capable of dealing efficiently with all the matters connected with the anticipated natural hazards in an integrated and foresighted managerial approach .

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