Developing a Geoinformatic-engineering Stability Modeling Method, using Field Data and GIS Environment: A Case Study from Al Qarara Area in Wadi Musa, Jordan

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Abstract - By applying detailed geological field surveys, the spatial factors affecting geo-engineering stability were used to develop a geo-engineering stability modeling method to identify areas under potential threat of landsliding. The factors affecting geo-engineering stability in Al Qarara area in Petra-Jordan were studied and given assumed rates of importance, where optimization process was run by lag iterations; the produced spatial layers of the different factors were gathered and modeled using GIS; a final stability map was produced using an optimized equation. The produced map was validated qualitatively and quantitatively, where a comparison was made between the reality in the field and several maps of different equation. The modeling method which was developed in the context of this study proved to be suitable to produce micro-zonation maps of areas having landslide risk. Further applications on the method in other areas suffering landslides will further improve it.

Keywords: geo-engineering stability, landslide, developing modeling method, GIS, spatial modeling, field mapping

Introduction

In Jordan, landslides affect many main roads and residential areas, especially during or after periods of heavy rain and snow falls or melts; clayey-marly formations with topographic differences in the country lead to that. Wadi Musa is located to the southern part of Jordan City, where to the eastern part of the city, the worldwide well known Petra Archaeological Park (PAP) occurs. Accelerating growth of population in this city which is due to the improvement of economic situations leads to increasing demand on lands for building and residential expansion.

Increasing residential and different land use expansion, made the Petra Development and Tourism Region Authority (PDTRA) through the Directorate of Studies and Planning, to investigate the area of Al Qarara according to its geo-engineering stability. Commissioner of Local Community Development and Environment (correspondent author, geologist) headed the technical committee and the team of the study in its different phases. PDTRA was in a crucial need to develop a geoinformatic-engineering stability modeling method, using field data and GIS environment, which can be used for similar investigations in the future.

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Geological outcrops in the city are mainly composed of carbonate rocks mixed in with different ratios of clays. Beds of clayey limestone, marl, clayey marl, and marly limestone are dominant in the different rock units of the area, where fractures, fissures, and joints are internal structures distinguishing the rocks.

Landslides can be natural or man-made and may be formed by addition of material on top soil during the construction of earth dams and embankment, or by removal of material, like excavation during road and railway constructions, and/or any civil construction (Sharpe, 1938).

Slopes in their final state should remain stable, but they are usually dynamic-evolving systems. Materials on non-stable slopes are constantly moving down the slope at rates that vary from unnoticeable creep of soil and sediments to landslides and rock falls that move at tremendous speeds. According to Sharpe (1938), the main factors that contribute to mass movements along slopes are: thickness and type of soil cover vegetations, type of exposed rocks, influence of surface and subsurface water, nature of stratifications, structural conditions, weathering processes, seismic activity, and man-made excavations.

Down slope movements of soils and rocks under the action of gravity are of special concern as these may affect man-made structures and natural features such as drainage systems (Attenwell and Taylor, 1984). However, human activities can lead to either an increase in some of these phenomena, such as landslides or hillside development, or the reduction of the possibility of landslides by means of stabilizing structures or techniques on naturally sensitive slopes.

In recent years, the assessment of landslide hazard and risk became a topic of major interest for both geoscientists and engineering professionals as well as for community and local administration in many parts of the world (Aleotti and Chowdhury, 1999). The main elements of risk assessment system are presented in Figure 1.

Landslides
Causes of landslides

Rainfall contributes to increase in pore water pressure, which increases shear stress. During intense rainfall events, the variations in pore water pressures distributed within the soil are highly variable depending on the hydraulic conductivity, topography, degree of weathering, and fracturing of the soil. Increase in pore water pressure may be directly related to rainfall infiltration and percolation or may be the result of the build-up of a perched or groundwater table (Terlien, 1998). In low-permeability soils slope failures are caused
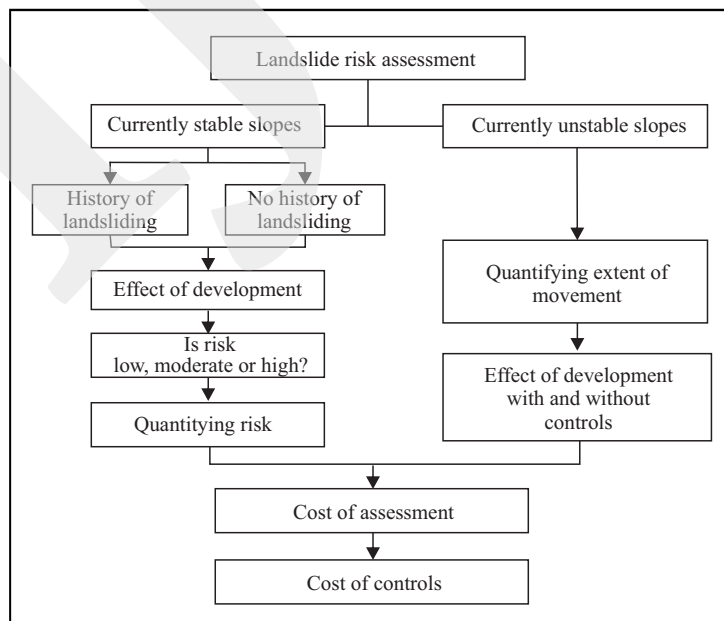

Figure 1. Flowchart showing the main elements of the risk assessment system (after Aleotti and Chowdhury, 1999).

by long duration-moderate intensity rainfall events. In fact, the reduction in soil suction and the increase in pore water pressures due to antecedent rainfall is considered to be a necessary condition for landslide occurrence (Sanderson *et al.*, 1996; Wieczorek, 1987). In addition, there are other factors triggering land sliding *e.g.*, the presence of fractures, undercutting of weak materials, and the presence of marly materials that causes rotational movement.

Human activities *e. g.* removing the lateral support such as cut for roads and canals, as well as removing trees and vegetation are participating in landslides.

Classification of landslides

Gravity produces a component of stress, directed downwards on the material in every natural or artificial slope. Slope processes are down slope movements of solid earth materials in response to stresses produced by the geometry of a slope and the force of gravity. These processes have been called Mass Wasting or Mass Movement by geomorphologists, or more popularly, landslides. These terms can be confusing if they are not fully defined each time they are used.

Varnes (1972) suggested that slope movement can be used as a comprehensive term for any down slope movement of earth materials.

Slope movement classification systems can be based on many features or characteristics, such as type of material moved, geometry of the failure, mechanics of deformation, type of movement, rate of movement, or a combination of the above. Each of these features or characteristics can be related to the prediction, prevention, and control of slope movements.

Varnes (1978), developed a classification system of landslides based on the type of movement, in addition to the type of material which is used as a secondary classification tool. This system has the advantage that the features used to classify slope movements are preserved, thereby making classification of past events possible. In addition, classification based on type of movement also establishes the characteristics of the mechanism of deformation, which is important in the analysis of slope stability.

Chowdhury (1978) classified slides according to their causes into:
1. Landslide arising from exceptional causes such as earthquake, exceptional precipitation, severe flooding, accelerated erosion from wave action, and liquefaction.
2. Ordinary landslides, or landslides resulting from known or usual causes which can be explained by traditional theories.
3. Landslides which occur without any apparent cause.

Geographic Information System is software for managing, processing, and analyzing the spatial data (including map-related picture, image, text, and data), used in different fields. Recently, this tool with a lot of options was improved. GIS can be simply used for memorizing, visualizing, querying and overlaying of maps, also for combining various analyses, comparing various attribute data and therefore solving problems which are difficult (Longley *et al.*, 2001). GIS is important in assessing landslide hazard maps where the probability, location, and frequency of expected landslide can be predicted (Zolfaghari and Heath, 2008).

Previous Studies

Different geological and geotechnical studies have been carried out covering different parts of Jordan. Several landslides studies took place along different sections of the Old Jerash-Irbid highway. Dames and Moore (1993) investigated the Amman- Jerash- Irbid highway and concluded that the slope stability problems along this highway are attributed to the presence of a very weak and friable interbedded sediments and their sensitivity to fluctuations in water content. Abderahman (1994) presented the effect of geological structures on the stability of slopes and rock falls in the Zarqa River Valley. Mansour (1994) evaluated the stability of slopes along the Amman- Jerash- Irbid highway on the basis of geological and geotechnical data. He concluded that the studied slopes are prone to sliding. Abderahman (1996) carried out a detailed study of landslides along Jerash-Amman highway. Al Basha (1996) studied four landslide sites along the highway and concluded that the

studied slopes are unstable to partially stable and may have many wedge failures.

Al- Homoud *et al.* (1999) studied the effect of rainfall on the instabilities of slopes along the highway and suggested some of remedial treatments. Malkawi *et al.* (2000) used remote sensing and GIS techniques to create a mass-movement hazard zoning map along the Amman-Jerash-Irbid highway depending on landsat images TM (Thematic Mapper). El-Naqa (2006) made a SINMAP terrain stability model along Amman-Jerash-Irbid highway. Muhaidat (2010) conducted stability analysis of slopes along As-Salt Wadi Shueib Road and suggested corrective measures to support the stability of non-stable slopes in the area.

Al Farajat (2002) derived microzonation map of the city of Aqaba for its groundwater pollution vulnerability using GIS for landuse planning purposes. He mapped and digitized natural geological settings of the city to build the data base, where different vulnerability indexes were used.

In 2008, Al Farajat used GIS in building microzonation map of the hills of the secondary industrial gypsum wastes for its stability hazard in the industrial area of Aqaba, the produced geophysical results were modeled using GIS. A combined seismic refraction and geomagnetic surveys were used.

Studied Area

In 2000, Petra Region Authority (former name of PDTRA) planned land use units of the city of Wadi Musa, Dar Al Handasah Consultants (the firm which developed the plans) classified the area of Al Qarara as a free area, and this was attributed to the presence of potential landslide risk, but the study presented no further details.

Al Qarara is located in the central part of Wadi Musa, at the end of Wadi Zurraba catchment area, which extends along more than 8 km in a northeast-southwest direction. The area of the interest is 0.142 km^2. Al Qarara drains a catchment area which reaches to around 30 km^2, and witness flash floods in winter when thunder storms forms; this exposes some parts of the area for potential risks of landslide as the drainage path is toward it (Figure 2).
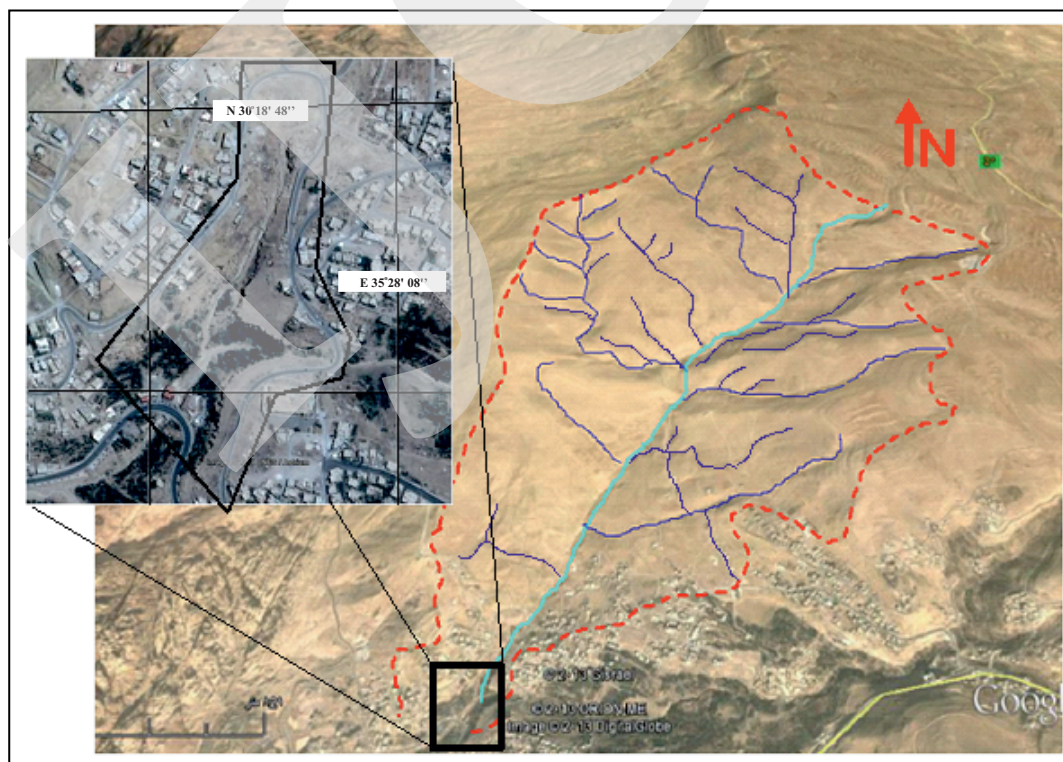

Figure 2. Locality map of the studied Al Qarara area (black lines), and Wadi Zurraba catchment area (red dashed lines) with its drainage pattern (blue lines).

Methodology

In this study, the authors attempted to use GIS techniques along with field data to develop a landslide hazard identifying method, and to produce hazard microzonation map of this hazard in the studied area. The method will identify and delineate unstable areas, to help planners to choose favorable locations in locating development schemes.

Detailed geologic field surveys and direct measurements on the beds, besides the available geological reports on the area and the high resolution digital elevation models (DEM), will assist in building the spatial data of the studied area.

The team of the study evaluated the geology of the studied area due to its different aspects; stratigraphy, lithology, structures, dip of the layers, and topographic slopes. These aspects were digitized, given coordinates using GPS, tabulated and exported into GIS environment, where spatial layers were produced from them using GIS modeling. Each layer was reclassified using assumed weights, where optimization process was run by lag iterations, and the layers were gathered by an optimized multiplication formula, and at the end the stability map was produced. The produced map was validated qualitatively and quantitatively, where a comparison was made between the reality in the field and several maps of different equation.

Geology

Stratigraphy

The outcropping rocks in the study area are related to the Upper Cretaceous rocks. Quennell (1951) divided the Upper Cretaceous into two groups; involving the Ajlun Group (lower part) and the Belqa Group (upper part).

Those outcropping rocks of the area belong to the Ajlun Group, consisting mainly of carbonate rocks. The thickness of the sequence which is ranging in age from Cenomanian to Turonian is over 800 m in north Jordan and Azraq Basin and decreases toward southeast. The Ajlun Group is sub-divided into the following formations (from bottom to top):

1. Na'ur Formation
2. Fuheis Formation
3. Hummar Formation
4. Shueib Formation
5. Wadi As-Sir Formation

From the detailed field survey and the aid of the available geological maps and reports and using GIS, it was possible to produce a geological map of the study area with a scale of 1:2000 (Figure 3).

Na'ur Limestone Formation (Cenomanian)

This is the oldest formation which outcrops in the area; and reaches a thickness of about 60 - 75 m. It consists of two massive carbonate units up to 15m thick, which comprise massive, nodular, light grey, brown dolomitic limestone, with abundant *Thalassinioides* burrows and oyster bivalves. The strata interbedded between these unit comprise alternating thin beds of yellow-buff algal laminated micrite green-grey, pink marl, grey buff, nodular dolomite and sandstone; corals, echionoids, bivalves, gastropods are common. The transitional beds and the overlying carbonate platform indicate a change from a restricted shallow-marine to full marine, subtidal environment of deposition (Powell, 1989).

In the studied area, this formation outcrops with a thickness of 15 m in the close wadis. The beds of the upper parts of this formation are outcropping in some parts of the wadis in the studied area; and they tend to be composed of clayey marl. The upper parts of the formation are mechanically brittle and inflexible, and they are highly affected by rocks overlaying them. After precipitation events, the rocks tend to swell and then to be shrink when the water leaks out. With the presence of structural deformations and effect of gravity, the upper parts of this formation in the studied area are fractured and jointed, forming zones of risk at the limps of the wadis and steep slopes, that led to toppling and rock fall phenomena (Figure 4).

Fuhays/ Hummar/ Shu'ayb (Undifferentiated) (Cenomanian-Early Turonian)

This formation is about 80 m thick; it consists of greyish green, pink, red calcareous siltstone-
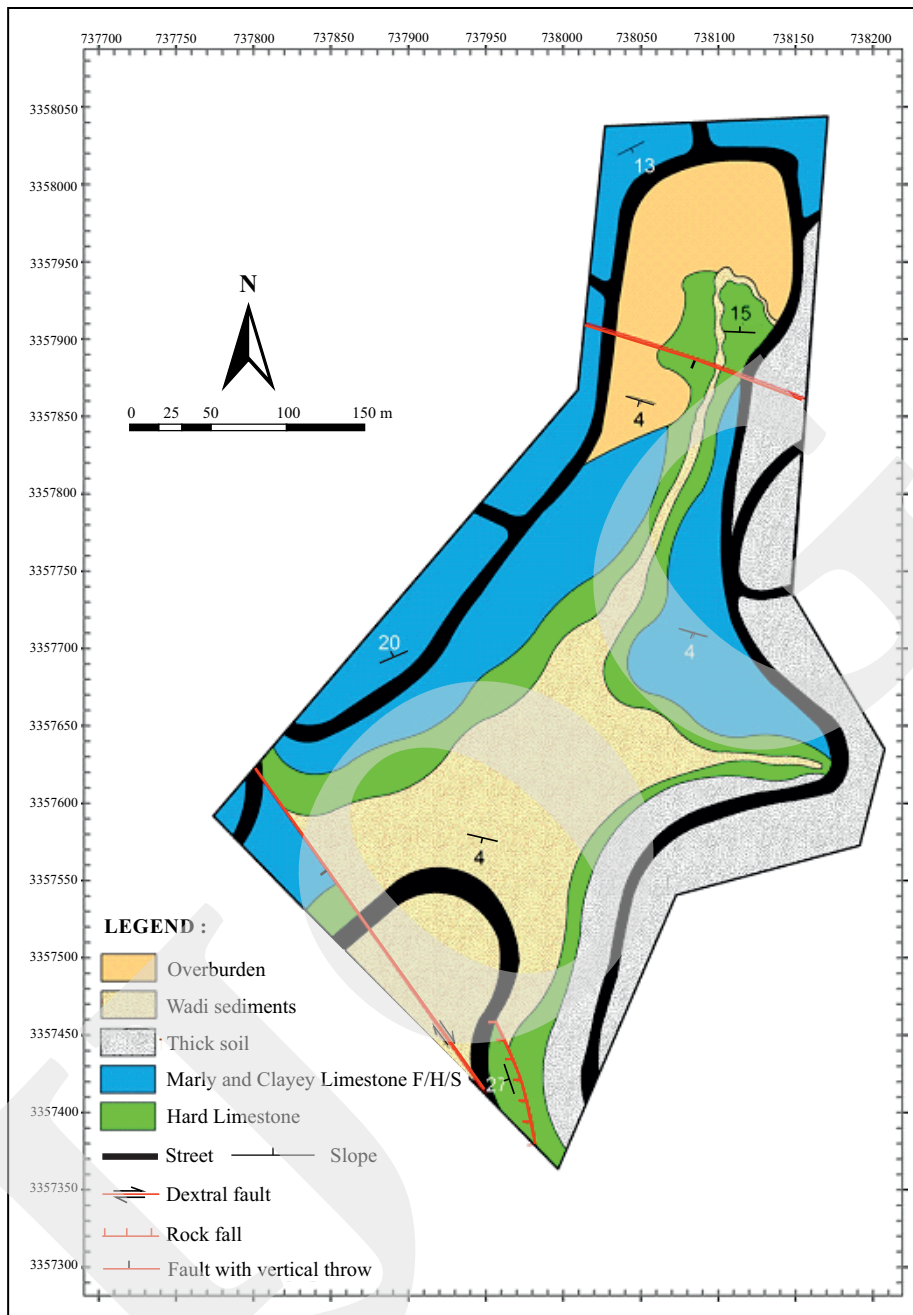
Figure 3. Geological map of the studied area showing the different stratigraphic units and structures, with a scale of 1:2000 using GIS modeling.

mudstone, thin bedded yellow-buff fossiliferous marl, marly limestone, banded gypsum with green and red mudstone, and multicoloured sandstone beds. The depositional environment ranges from open marine to supratidal (Powell, 1989).

The formation tends to swell with the presence of water, and to be shrink when the water leaks out. The majority of the buildings of the studied area are extended over this formation.

Because of its ability of swelling and shrinking, the houses and structures are exposed to cracking, where some displacements or creeping took place, especially with structures of weak foundations.

Holocene Sediments

The thick soil layers covering-different rock units, especially Fuhis/Hummar/Shuaib, are Holocene sediments, and they are found in the

Figure 4. Toppling and rock falls in the studied area.

eastern part of the studied area, and they are composed of clay/carbonate-marl soil fragments, containing small pieces of rocks with different sizes. These sediments found in the lower parts of the studied area, were derived from the higher ones. While the streams and wadis contain recent beds of mixed gravel, sand, and clay, with bad sorting. Under rainfall conditions, some landslides and erosions can occur in the streets and roads (Figure 5). In addition to the natural deposited recent sediments, there are man-made sediments resulted from cutting/filling processes, digging, and overburden (Figure 6).

Geological Structures

Geological structures play a dominant role in the behavior of slopes; therefore, they are of primary importance for engineering geologists and geotechnical engineers. Especially in sedimentary rocks; the succession, thickness, and attitude of beds, other major and minor structural features such as folds, faults, and joints are of direct relevance to cause potential instability. These features also help in understanding slope development processes, formation of valleys, escarpments, and the development of residual soils.

It is assumed that a fault is induced when deviatoric tectonic stresses produce a shear stress that exceeds the shear strength on a particular plane in the rock mass (Kersten, 1990). Shear and tension joints are frequently associated with major faults and when formed along a fault they are frequently referred to as feather joints because of their appearance. Intraformational shears that are, zones of shearing parallel to bedding, are also associated with faulting. Their presence means that the strength of the rock along the shear zone has been reduced to its residual value (Bell, 1993).

Faults are most prominent in the harder rocks, which yield to stresses by fracturing, in contrast to soft rocks which yield by deformation. In some cases, where a fault runs parallel to the wall of cutting, the rocks up to the fault can be removed, and the fault surface left as the final slope face (Blyth, 1946).

Goodman (1980) defined joints as regularly recurring fracture surfaces, usually planar, cutting across the rock with constant orientation and mean spacing from as little as centimeters to as much as several meters. Bell (1993) also defined joints as fractures along which no displacement has occurred and they are present within all types of rock. Joints are present in all competent rocks within the surface, at all orientations. Joints are many thousands of times more frequent than faults. Indeed, it is rare to find cubic meter of rock that does not contain any joint.

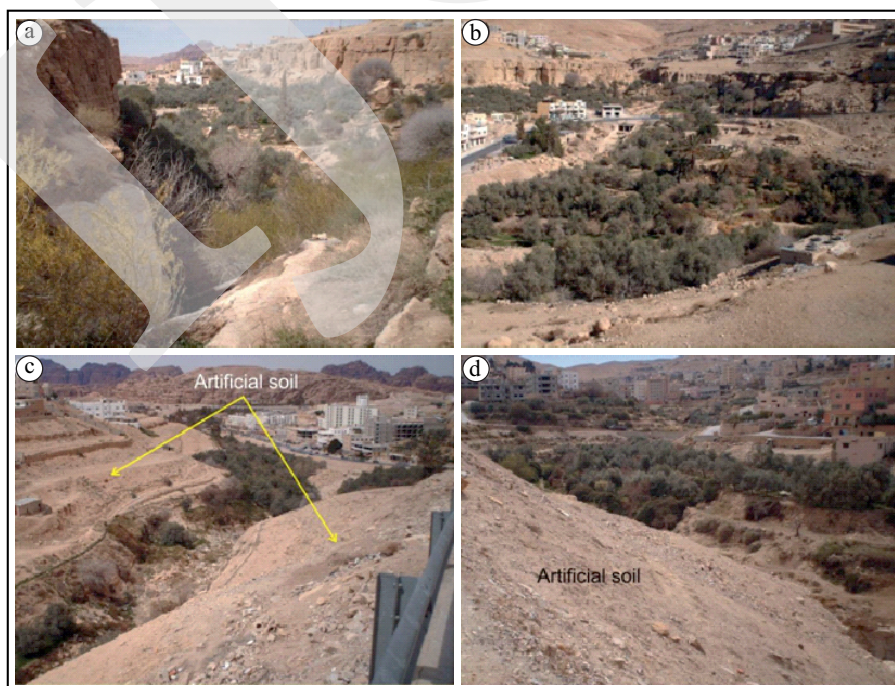Figure 5. Registered landslides (a, c) and erosions (b, d) in the streets and roads of the studied area.

Figure 6. Digging (a, b) and overburden (c, d) engineering operations in the studied area.

Geologists and engineering geologists believe that studying joints and their origins can provide valuable clues to the history of tectonic processes in near-surface rocks and also to understand slope stability problems (Priest, 1993).

Joints originate from extension strain (stretching) and from shear. In the latter case, each joint is like a minor fault in the rock, and for some reasons the offset that might have occurred on one or several surfaces was dispersed on hundreds or thousands of years. Shear joints tend to be closed, whereas the extension joints are opened (Muhaidat, 2010).

These openings are often filled with gouge or detrital material or chemical cements. The influence of filling material on the shear strength of a joint depends on the thickness of the filling materials (Goodman, 1993), where the shear strength is continuously reduced with the increase in filling thickness. Once the filling thickness exceeds the amplitude of the surface projections, the strength of the joint is controlled by the strength of the filling material. Additionally, the presence of fill-

ing material in discontinuities may hinder natural drainage because of the presence of a significant proportion of fine clayey material, of an extremely low permeability, which results in building up of pore water pressures (Muhaidat, 2010).

Thus stability is decreased due to two reasons (Chowdhury, 1978), those are:
1. Reduced strength along discontinuities due to the presence of filling material.
2. High pore water pressures due to decreased natural drainage.

RESULTS

The studied area lies within the highlands to the east of the southern segment of the Dead Sea Transform (DST). The southern segment of the DST is the Wadi Araba active strike-slip fault. It extends from the southeastern corner of the Dead Sea to the Gulf of Aqaba with a general N-S trend (Figure 7). The DST is 1100 km long and connects the Gulf of Aqaba-Red Sea
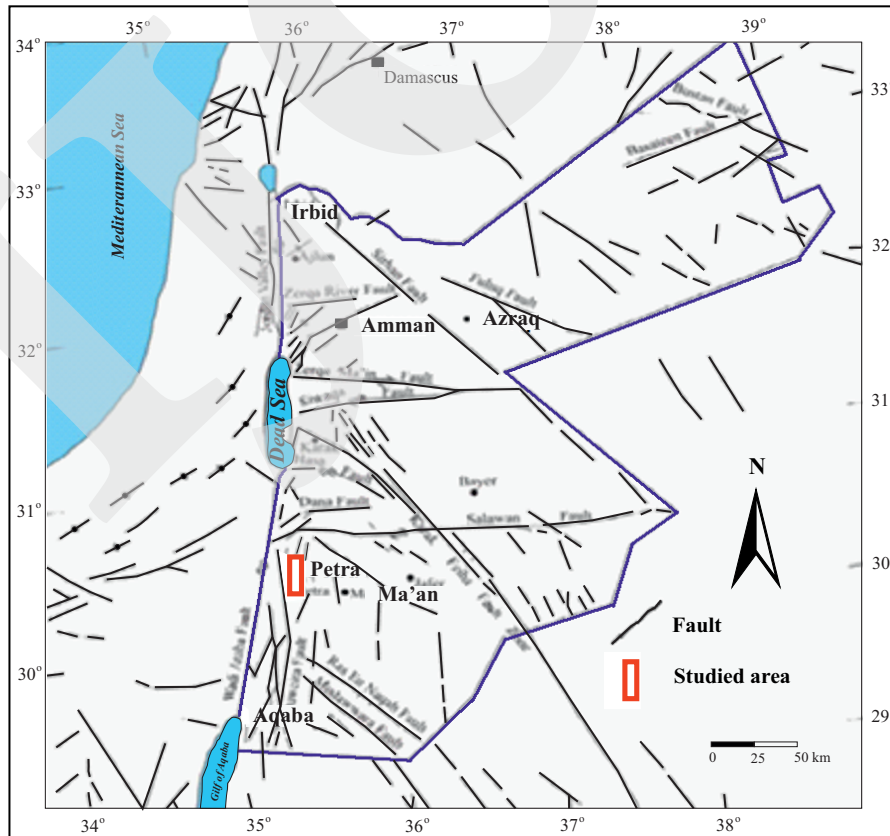

Figure 7. Structural pattern map of Jordan (Diabat and Masri, 2005).

spreading system to the convergence zone in the Taurus – Zagros Mountain. The DST is the major tectonic feature controlling the geological and geomorphological evolution of the region since the Miocene (Garfunkel, 1981). The DST was formed as a result of the northward sinistral movement of the Arabian plate associated with the opening of the Red Sea (Garfunkel *et al.*, 1981). The movement started in the Miocene and is still active in the present times (Quennell, 1959; Eyal , 1996) . This fault system is responsible for the formation of different structures in Jordan and the studied area. Because of its key position in the geology of the region, the Dead Sea and its margins have been the subject of many detailed mapping and regional structural studies (*e.g*. Quennel, 1951, 1958, 1959,1983; Bender, 1968; Freund *et al.*, 1968; Garfunkel, 1981; Kashai and Croker, 1987). Comprehensive structural studies were based on small-scales or mesostructures (*e.g*. Eyal and Reches, 1983; Ron and Eyal 1985; Eyal,1996; Atallah, 1996; Zain Eldeen *et al.*, 2002; Diabat, 1999, 2009, 2013; Diabat *et al.*, 2004).

The city of Wadi Musa overlooks Dead Sea Transform Fault System, which affected the topography of the area, and resulted in topographic difference in Wadi Musa with more than 500 m. Consequently, the outcrops of different rock formations from different ages are dominant in the city and its surrounds. Several structural features in Wadi Musa are a result of the transform fault system of the Dead Sea, and these include faults and folds of different forms, directions, and throws. Wadi Musa was affected by several main faults; the most important one is the Wadi Musa sinistral transform fault, which is extended northeast-southwest and is the result of the Dead Sea Transform Fault System. Then, the area of Wadi Musa was affected by two faults extended north-south to the eastern part from Wadi Musa Fault. All of the named faults are crossing Wadi Musa and they caused deformations in the different-rock units, affecting its stability. No main folding systems are dominant in Wadi Musa.

From the previous explanation, it is obvious that Wadi Musa City itself was formed as a result of mega landslide event, which in turn led to sublandslides. In Zuraba and Qarara areas, there have

been no main faults detected, but some secondary faults were registered with normal throws, one of them was accompanied with a vertical dextral movement, besides some rock slides.

Stability modeling

The factors which control geo-engineering stability in Al Qarara area were given assumed rates of importance; the produced spatial layers of the different factors were gathered and modeled using GIS. A final stability map was produced by gathering the layers of the factors using an assumed equation. To validate the results of the model with the reality in the field qualitatively and quantitatively, space image and direct field measurements were used.

Second phase of field survey was allocated for validation purposes, where the produced risk map was studied in the field by direct comparisons in the different parts of the studied area. Excellent correlation and fitting was found between what was on the map, and what was investigated in the field from an engineering point of view.

Lithology

Lithology was considered in this study as an essential factor for the stability of the rocks and their suitability for building and different engineering purposes. Four main types of rocks were found in the studied area, each type was given a rate.

Table 1 shows the method to which field data were processed and given rates (example on slope and lithological data), where optimization process was run by lag iterations to reach at these rates to simulate the study area in respect to its stability situation in the field.

Hard limestone rocks of the Naur Formation were considered suitable for different engineering purposes. For that, they were given high rate, while marly limestone and clayey limestone were considered as not suitable, and they need engineering processing before any construction. On the other hand, thick soil and wadi sediments were considered less suitable and were given lowest rate (Table 2, Figure 8).

Overburden and wadi sediments were excluded for their location in the studied area, which do not permit engineering construction on them.

Table 1. The Method to Which Field Data were processed and given Weights (example on slope and lithological data)

OBJECT ID	FID Dip Slope	Weight	FID Structure	Weight 1	FID Litho	Lithology	Weight12	SHAPE Length	SHAPE Area	Final Weight
1	1	6	25	10	6	F/H/S	3	262.1015	2107.852	180
2	1	6	26	10	7	Soil	1	121.2814	7.179443	60
3	2	6	26	10	7	Soil	1	454.8537	3821.625	60
4	3	3	27	1	8	NL	10	177.2591	1082.773	30
5	4	6	28	10	9	F/H/S	3	292.5462	2714.635	180
6	11	6	35	10	16	Soil	1	220.5902	2376.339	60
7	12	6	36	10	17	Soil	1	893.3948	11336.09	60
8	19	6	49	3	8	NL	10	147.3271	1265.571	180
9	25	10	26	10	7	Soil	1	12.21932	1.437249	100
10	25	10	27	1	8	NL	10	1526.525	14909.58	100
11	25	10	27	1	19	F/H/S	3	249.3951	1390.59	30
12	25	10	29	10	10	F/H/S	3	364.9448	3135.387	300
13	25	10	30	10	11	F/H/S	3	237.7739	2727.872	300
15	25	10	32	10	13	F/H/S	3	213.5184	2117.002	300
16	25	10	32	10	15	NL	10	97.31339	612.4998	1000
17	25	10	33	10	14	F/H/S	3	89.1088	360.2782	300
19	25	10	38	10	19	F/H/S	3	598.9739	7865.341	300
20	25	10	39	10	20	F/H/S	3	719.9696	11880.22	300
21	25	10	43	1	32	NL	10	824.6052	6975.344	100
22	25	10	44	10	32	NL	10	215.1645	1879.678	1000
25	25	10	56	6	32	NL	10	128.7507	653.0229	600
26	27	6	30	10	11	F/H/S	3	237.4323	2282.032	180
27	3	3	27	1	8	NL	10	6.98771	0.000542	30
28	25	10	27	1	8	NL	10	6.98771	0.000542	100
29	0	0	0	0	0	Street	0	2951.865	12060.34	0
30	0	0	0	0	0	Street	0	534.8386	3008.504	0
31	0	0	0	0	0	Street	0	120.4162	481.0096	0
36	0	0	0	0	0	Street	0	534.8386	3008.504	0
37	0	0	0	0	0	Street	0	120.4162	481.0096	0

Table 2. The obtained Typical Rating Values of Each Factor after Lag Iterations

Lithology	Rate	Structural Condition	Rate	Slope/dip	Rate
Hard limestone	10	Low faulting	10	<10 °	10
Marly and clayey limestone	3	Medium faulting	6	10°-20°	6
Thick soil	1	faulted	3	20°-30 o	3
Wadis sediments and overburden	0	Highly faulted	1	>30°	1

From the table, it is obvious that there is no medium value between the hard limestone (which was given the highest rate), and the clayey marly limestone, which was given the lowest rate, and this is attributed to that there was no rocks in the studied area to have lithology of a hardness value middle between the two mentioned rock types.

Structural values

It is meant by structural settings for this study the extent to which the rocks got affected by faults, cracks, and joints, besides the rock fragility.

The blocks of the rocks of the studied area which are located close to the wadis have no
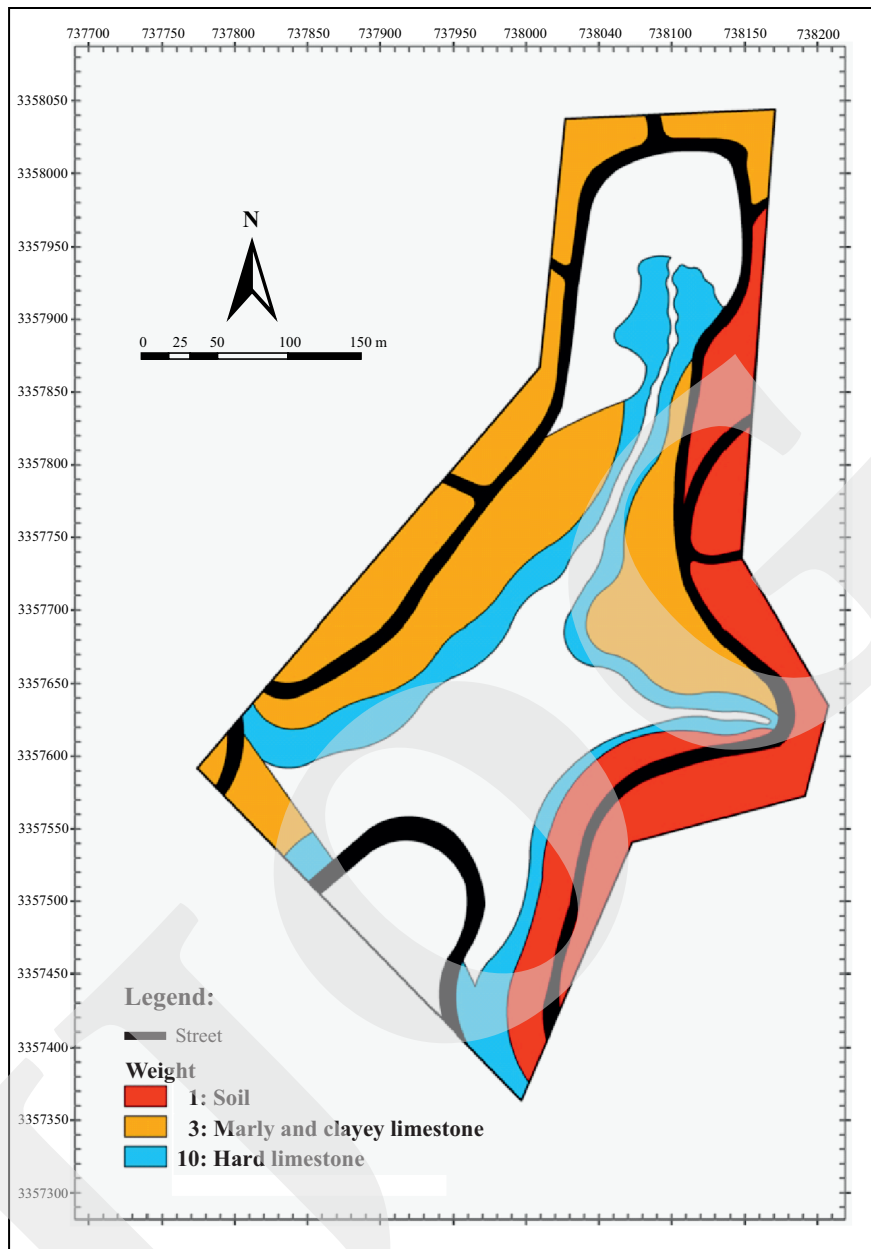
Figure 8. Produced map of the lithologically rating with a scale of 1:2000 using GIS modeling.

lateral support, for that they can show faulting, while the blocks of the rocks within beds of high dip values tend to have faults more than those within beds of low dip values (Table 2; Figure 9).

Topographic Slope and Dip Values

Topographic slope is the angle of the land surface forms with the horizon, while dip is the angle of the bed forms with the horizon. In this study, a high resolution digital elevation model (DEM) with 30 m grid resolution was used to visualize the area in 3-D, and to derive its slope. It was noticed that all values of the topographic slopes are in accordance with the dip values, and for that they were merged with each other. Highest and lowest slopes were measured, and accordingly weights were given (Table 2; Figures 10 and 11).

Building the Risk Map of Landslide

Relative stability used here means the range of stability between the different sub-areas in the studied area, depending on the conditions
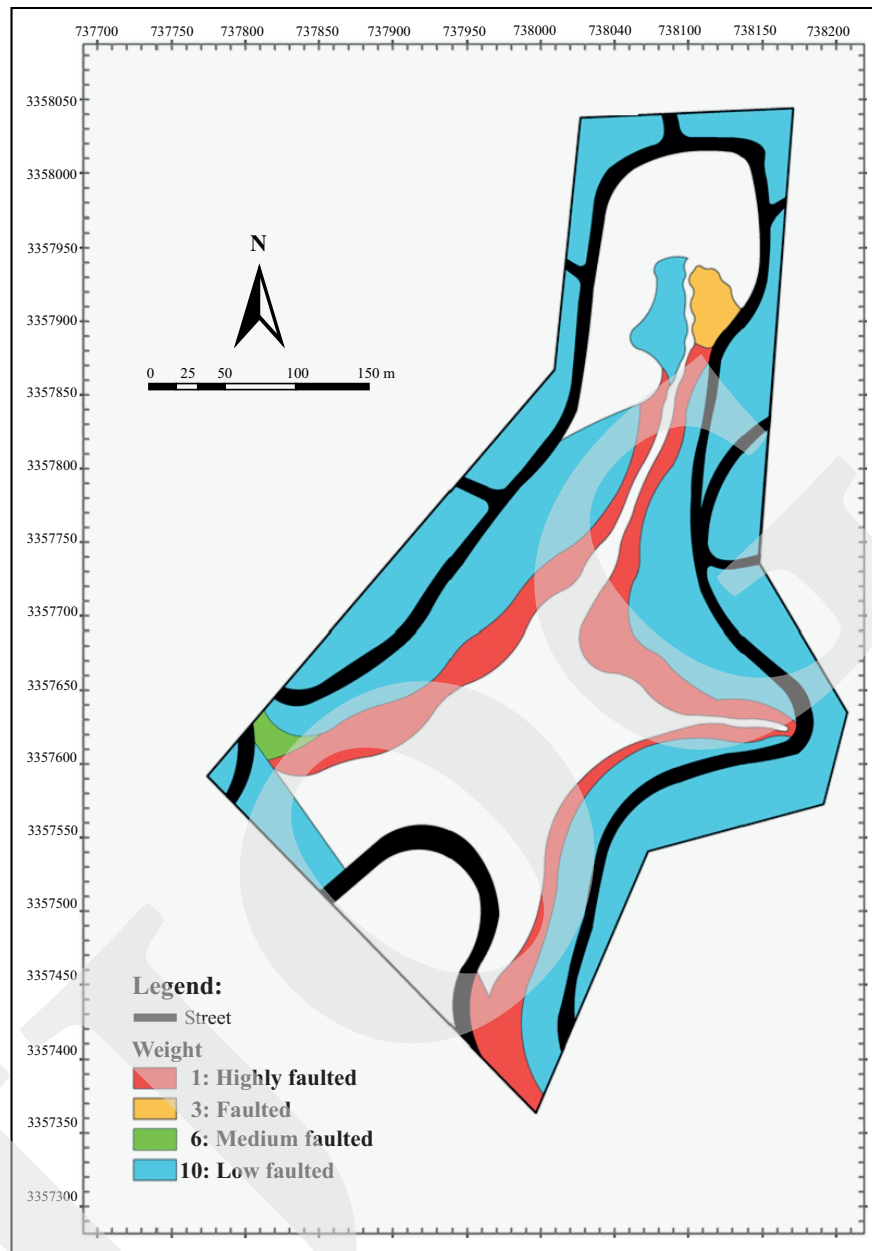
Figure 9. Produced map of the structural rating with a scale of 1:2000 using GIS modeling.

of the geo-stability factors mentioned before. After multiplication of the produced layers, areas found with stability products between 30 and 100 were classified as relatively unstable, while areas having values ranging between 180-1000 were classified as stable zones.

By multiplication of the maps produced from the different factors, the stability map was produced, which clarifies the range of relative stability of the studied area. The values of stability in the map (Table 3; Figures 12 and 13) were produced by multiplication of the assumed rates

of the different factors for each pixel in the map using GIS. Several iterations were applied using lag of values (of rates and risk classes) to reach at the models of the produced layers.

The produced map was validated qualitatively and quantitatively, where a comparison was made between the reality in the field and maps of different assumed equations (produced by several iterations using lag of values -of rates and risk classes-). Also overlying the produced risk model (transparent GIS colures) on satellite images of the area was useful.
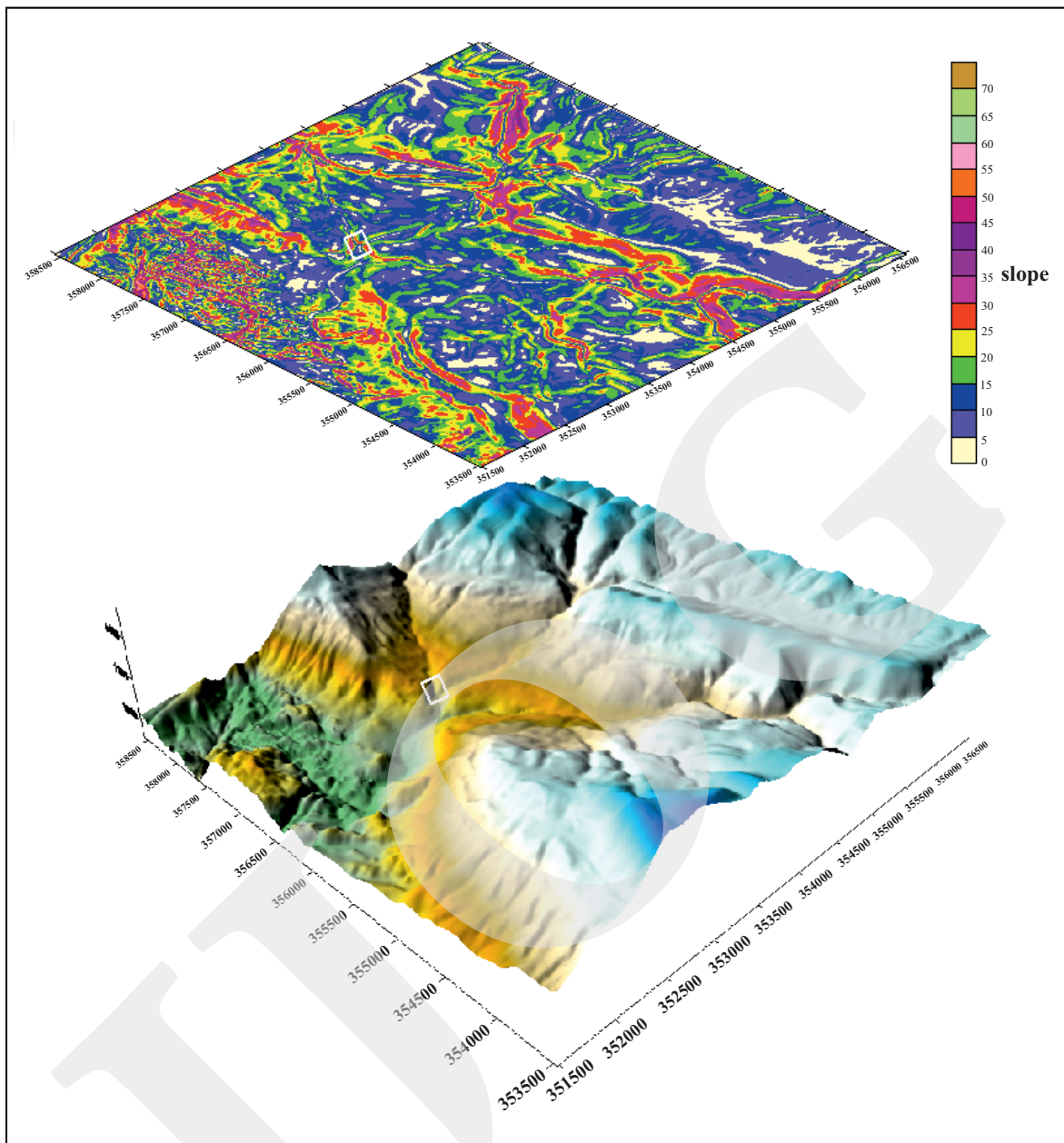
Figure 10. Produced map of 3-D topography of the studied area (bottom), and the derived slope model (top). The studied area is surrounded with white rectangle.

Discussion

The quality of a landslide hazard evaluation depends on the extent that the hazards are identified and how can be understood. Coping with land topography needs well geological and geo-morphological experience of landslide kinds and landslide behaviors, and judgment. To develop a dependable geotechnical mapping method and grasping, landslide mechanisms are of a paramount importance. This leads to that the

quality of evaluation is normally accompanied with the practical experience of the persons who implement the field-work and the time and efforts they spend to understand the risk.

Realistic quantifying of data based on experience, and understanding of the studied area, the regional hazards of the site in question, with good knowledge of the uncertainty leads to a good decision making.

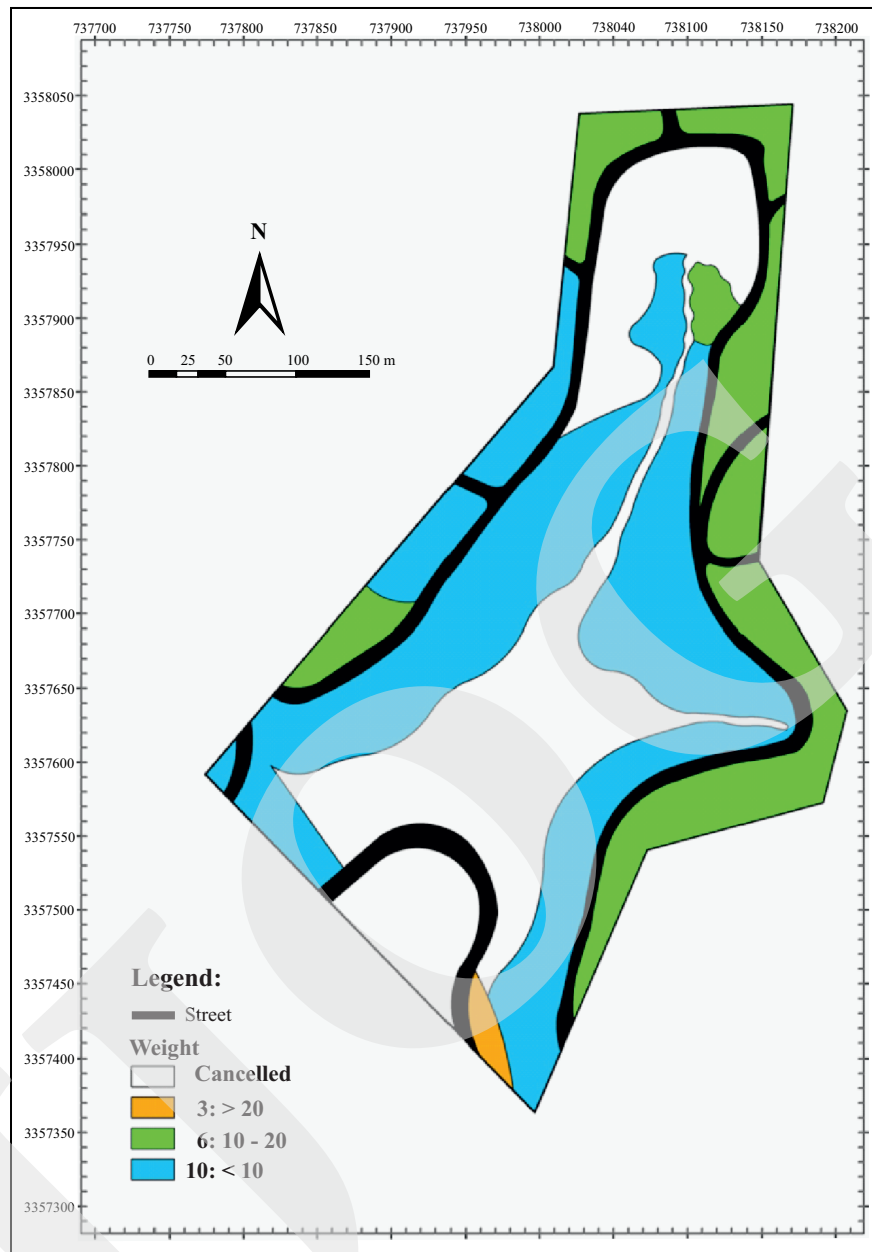Depending on the obtained geological information from the field survey on the area of

Figure 11. Produced map of topography/slope rating with a scale of 1:2000 using GIS modeling.

Table 3. The obtained Typical Values of Stability after Lag Iterations

Stability	Assumed classes
Anstable	30
	60
	100
Stable	180
	300
	600
	1000

Zuraba and Qarara, the range of relative stability was modeled using obtained data from the field using GIS. Several geological factors were taken into consideration to produce the stability map, including lithologial composition of the rocks, structural situation, and topographic slope of the beds. From these main factors on which the stability highly depends, assumed values (rates) were considered (from the field experience) to reach at the final stability map. Several iterations were applied using lag of values (of rates and risk classes) to reach at the models of the produced
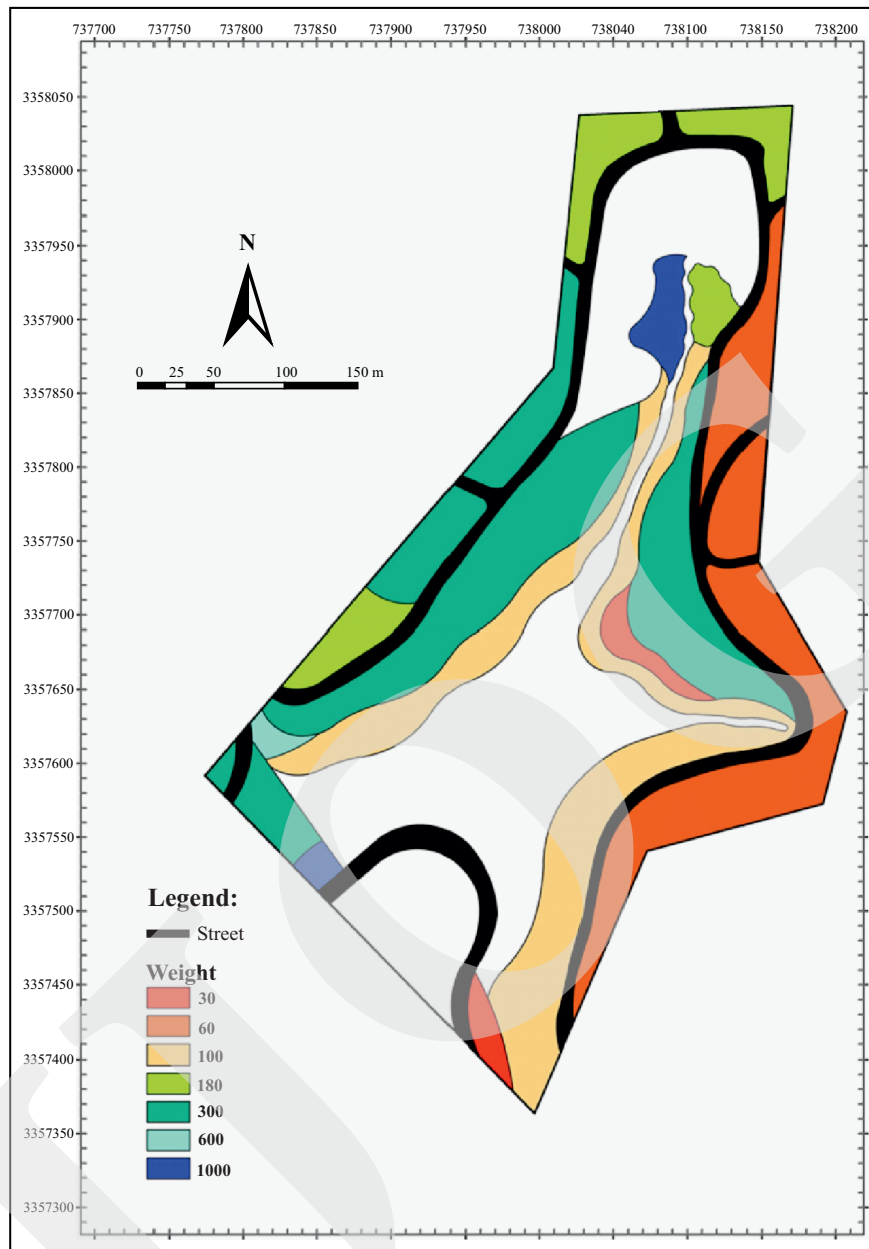
Figure 12. Produced map of stability with a scale of 1:2000 using GIS modeling.

layers, where the values used in this study were proved to be the type values, to represent the geo-stability layers, and the produced risk map.

Despite the small size of the studied area, the diversity and wide spectrum of the geological conditions led to a wide range of stabilities. Landslides in the studied area are a cause of several ways, where these were found to include saturation of sloped rocks with water from rainfall or leakage from sewerage nets, vibrations caused by previous seismic events, and undercutting of cliffs by man-made activities. The man made activities

in the area include:
1. removal of vegetation covers,
2. modifications on the natural drainage system,
3. main leaking water,
4. modification on slopes with the road structures, buildings on steep terrains, and
5. vibrations from traffic and displacement of rock blocks.

From the area of study, an area of 66% was found to be unstable, while stable areas form simple part of the area. Most registered landslides took place in the area, have been recorded
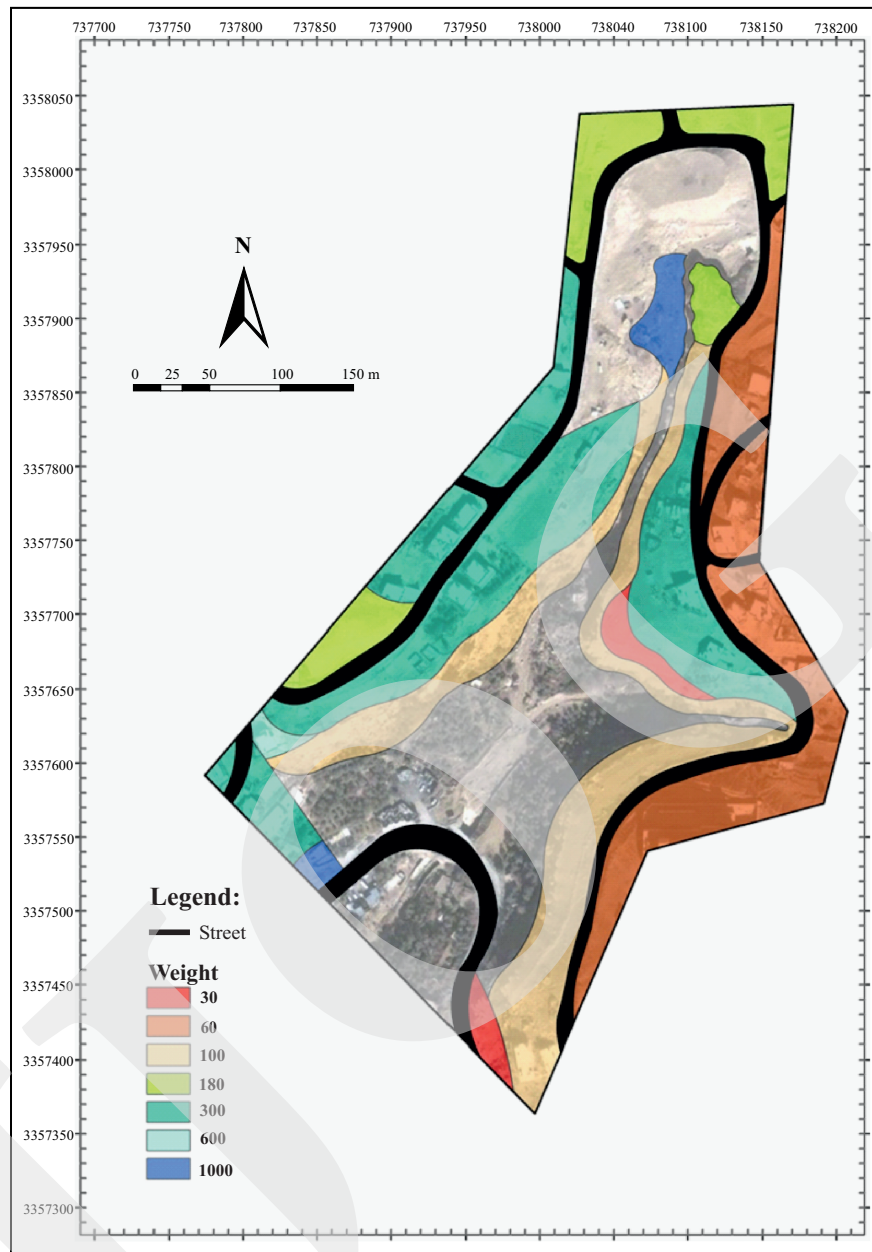
Figure 13. Map of stability on satellite image with a scale of 1:2000 using GIS modeling.

to take place in the rainy seasons, and mostly they were within Fuhis/Hummar/Shuaib, due to the presence of clayey limestone and marl. Thick soil layers with high slopes as in the higher part of the study area led to instability, even with the presence of supporting walls. Limps of the wadis in the study area were distinguished with rock blocks having deep vertical faults, where the wadi itself was considered as an area of high risk.

Due to the low stability values, PDTRA was advised not to license any building permits. The

study confirmed the old one done by Dar Al Handasah (2000), and it was advised that the area should be given permits for light uses like parks and gardens only.

After validating, the results of the model show that the modeling method has proved to assess areas under risk of instability, for areas of the same geology. Further applications on the same method in other areas suffering landslides are strongly recommended. Figure 14 illustrates the steps followed in modeling the stability of the studied area.
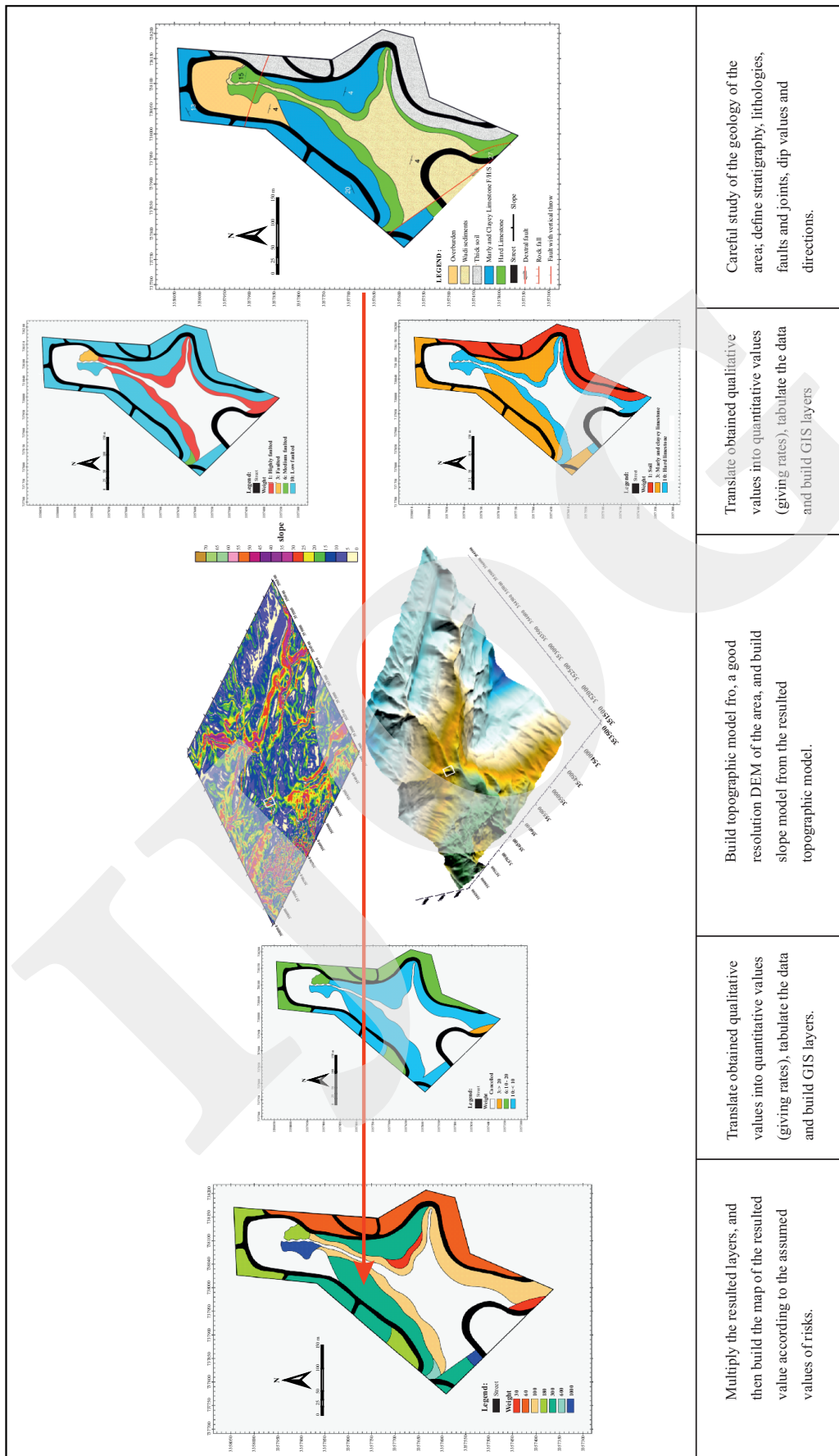
Figure 14. Chart illustrates the steps of process followed in modeling the stability of the studied area.

CONCLUSIONS

The following points are concluded:

1. Modeling of an area to produce microzonation maps of the landslide hazard needs a careful study of its micro-geological aspects (stratigraphy and structures).

2. Besides using the available geologic maps and Landsat images and DEMs, field survey is an essential and primary part of such studies.

3. GIS environment (ARCGIS) is of high importance in dealing with and building of the different layers of the stability factors and their optimized rates.

4. Despite the developed geo-informatic modeling method proved to be in place to produce microzonation maps of landslides hazard of the study area, it is still in need for more modification and development by applying it on other areas of different geology.

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