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Application of SINMAP Terrain Stability Model Along Amman-Jerash-Irbid Highway, North Jordan

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Abstract The landslides have been occurred along the major highways in Jordan, one of these highways is Amman-Jerash-Irbid highway. SINMAP (Stability Index MAPping) is an ArcView GIS extension that facilitates the assessment of landslide potential at the watershed scale.

The study area was divided into four main sections, where the stability mapping of the first three sections were analyzed using SINMAP model while the fourth section cannot be analyzed as there are no landslides recorded in this section. A Digital Elevation Model (DEM) was prepared for the entire study area. Landslides locations have been recorded using GPS to establish landslide source areas inventory.

Several grid themes were resulted from the SINMAP analysis containing saturation themes and stability index themes for each section. The statistical and analytical results indicated that the "Unstable" stability class encountered in the three sections of the highway includes 39 landslides or 79% of the total inventory. At the same time, this class comprises 233 km² or 81.3% of the total area.

Key words: SINMAP model, Landslides, GIS, slope stability, DEM, Jordan.

Introduction

There are many approaches to assessing slope stability and landslide hazards (Sidle et al., 1985; Dietrich et al., 1986; Montgomery and Dietrich, 1988; Montgomery and Dietrich, 1989; Carrera et al., 1991; Dietrich et al., 1992; Sidle, 1992; Dietrich et al., 1993; Montgomery and Dietrich, 1994; Pack, 1995). The most widely used include (Montgomery and Dietrich, 1994): (a) field inspection using a check list to identify sites susceptible to landslides; (b) projection of future patterns of instability from analysis of landslide inventories; (c) multivariate analysis of factors characterizing observed sites of slope instability; (d) stability ranking based on criteria such as slope, lithology, land form, or geologic structure; and (e) failure probability analysis based on slope stability models with stochastic hydrologic simulations.

Recently, growing availability of GIS (Geographic Information System) systems and popularity of data in form of Digital Elevation Models (DEM), along with tools for their processing and analyzing, collecting terrain topography data that are essential for slope stability analysis purposes, has became considerably easier and less time-consuming. Possibility of integrating spatial data into GIS systems and their
subsequent universal analyses allows to extent analysis to practically unlimited range of considered variables.

This paper attempted to use integrated remote sensing and Geographic Information System (GIS) techniques to identify the areas prone to landsliding as well as to produce landslide hazard zonation map along Amman-Jerash-Irbid Highway. A landslide zonation map divides the land surface in zones of varying degrees of stability, based on an estimated significance of causative factors inducing instability. The landslide hazard maps identify and delineate unstable hazard prone areas to help planners to choose favorable locations for locating development schemes, such as road construction.

The slope stability model used to assess the instability conditions and to establish a landslide hazard zonation map along the highway is called Stability INdex MAPping (SINMAP), which developed by Pack et al. (1998). SINMAP approach applies to shallow translational landsliding phenomena controlled by shallow groundwater flow convergence (Dietrich et al., 1986; Montgomery and Deitrech, 1989). It does not apply to deep-seated instability including deep earth flow and rotational slumps. The data required to implement the theory include soil and climate properties that can be highly variable in both space and time. Stability indices output by the analysis should be interpreted as numerically precise and are most appropriately interpreted in terms of relative hazards.

**Description of study area**

The study area covers the rout of Amman-Jerash-Irbid highway north of Jordan (Figure 1), which about 394 km² divided into four sections. The study area is a part of the northern highlands, varies in elevation from about 160 m above sea level (a.s.l.) at Wadi Er Rumman in the central western part of section II, to 1098 m a.s.l. at Marqab Hittine area near Al Mirba’a area, about 4 km northwest of Thagrat Asfur.

The area is characterized by the presence of three distinctive topographic zones, the low relief topography which form Al Baq’a depression in the southern parts of the study area, the high rugged and steep mountainous area which dominate the majority of the western, and central parts, and the northeastern plateau, which forms part of Irbid plain.

A major, approximately NS trending, watershed can be recognized from Safut to northwest of Husun area. Along this line numerous deeply incised wadies can be seen mainly draining toward the west-northwest and east-northeast.
Fig.1: Location map of the study area.
Previous Studies

Different geological and geotechnical studies have been carried out since the commencement of several landslides that took place along different sections of the highway (Toukan and Saket, 1983). Dames and Moor International (1993) prepared a detailed investigation of the Amman-Jerash-Irbid highway. They concluded that slope stability problems of this highway is attributed to the presence of a very weak friable nature of some of the interbedded sediments and their sensitivity to fluctuations in water content. Mansour (1994) evaluated the stability of the slope along Amman-Irbid-Jerash highway on the basis of geological and geotechnical data and concluded that the area is favorable to sliding. Al Basha (1996) has studied four landslide sites along the highway and he 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 instabilities of slopes along the highway and he suggested some of remedial treatments to failed areas. Malkawi et al., (2000), used remote sensing and GIS to create a mass movement hazard zoning map along Amman-Jerash-Irbid highway depending on Landsat TM (Thematic Mapper) images.

Geology of the study area

During the Mesozoic and Early Cenozoic, sedimentation was controlled by the oscillating movements of the Tethys Ocean to the northwest of Jordan and the eustatic movement of the Arabian-Nubian Shield and its Palaeozoic cover rocks in the south. The study area incorporates good exposures of sedimentary rocks including limestone, marl, sandstone, chalk and chert, of Jurassic and cretaceous ages (Figure 2).

Due to pre-Jurassic tectonics, the Azab Group, the oldest exposed strata in the study area, unconformably overlies the Triassic sequence. This group is unconformably overlain by Early Cretaceous sandstone of the Kurnub Sandstone Group (KS).

A thick sequence of limestone and marls of Ajlun Group (Cenomanian-Turonian) is unconformably overlies the Kurnub Sandstone Group. It is subdivided into five formations; Na’ur Limestone (A1/2), Fuheis (A3), Hummar (A4), Shuyab (A5/6) and Wadi As Sir Limestone (A7).

The Wadi Umm Ghudran Chalk (B1), Amman Silicified Limestone (B2a) and Al Hisa Phosphorite (B2b) formations (Coniacian-Campanian) of the Belqa Group cover considerable areas in the northern parts. A few poorly outcrops of the Muwaqqar Chalk Marl Formation (B3) (Maastrichtian-Palaeocene) are present in the northwestern parts of the study area. The Quaternary sediments in the study area are represented by soil, plateau gravels, alluvium, wadi sediments and calcrite.

The structure of the area is dominated by two major fault trends; northeast-southwest and east-west faults, possibly of Late Tertiary age (Abdelhamid, 1995). The majority of folds are ranging in trend from east-northeast and northeast to west-northwest.
Fig. 2: (A) Geological map of the study area, (B) Generalized cross section of the stratigraphic units exposed in the study area (Modified after Abdelhamid, 1993 and Sawariah and Barjous, 1993)
Instability problems along Amman-Jerash-Irbid Highway

The highway is located within an area of generally fine grained, horizontally bedded marine sediments of Cretaceous age. The dominate cause of slope stability problems is clearly the very weak and/or friable nature of some of interbedded sediments and their sensitivity to fluctuations in water content. Unfavorable structural conditions within competent rock is responsible for only a very small proportion of the presence of colluvial deposits on the side of the hills (Dames and Moor, 1993).

During the field investigations that carried out along the highway, several classes of slopes were identified: (1) Moderately strong limestone and marl slopes, (2) Weak Nodular and structurally fractured marly limestone slopes, (3) Weak marl- shale slopes, (4) Very weak clay-marl slopes, (5) Friable sandstone and shale slopes, (6) Soil slopes.

The highway exhibits a variety of mass wasting types, which summarized in Table 1. These variations of mass movements refers to variations of; materials involved, slope properties (i.e. slope height and angle), vegetation cover and human activities.

<table>
<thead>
<tr>
<th>Mass wasting movement</th>
<th>Materials involved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock slides</td>
<td>Limestone and marly limestone</td>
</tr>
<tr>
<td>Toppling</td>
<td>High slopes of sandstone and limestone</td>
</tr>
<tr>
<td>Slumping</td>
<td>Weak marl and clay</td>
</tr>
<tr>
<td>Earth flow</td>
<td>Soil, alluvium and colluviums</td>
</tr>
<tr>
<td>Rock spreads</td>
<td>Highly fractured limestone and marl</td>
</tr>
</tbody>
</table>

Theoretical Background

Characteristics of SINMAP model

**SINMAP** is an ArcView extension that implements the computation and mapping of a slope stability index based upon geographic information in the form of digital elevation data. The model uses the GIS functionality implemented in ArcView for the data input and organization as well as for output and presentation of results.

The model is a slope stability predictive tool, within which is a hydrologic flow modeling component. It uses the surface topography to route flow downslope, assuming that the subsurface hydrologic boundary parallels the surface, and soil thickness and hydraulic conductivity are uniform. The flow model predicts relative levels of groundwater across a watershed area. This prediction is then used to assess slope stability.

The model requires three groups of input data

1. terrain topography in a DEM grid format;
2. soil mechanical and hydraulic properties in a grid or polygon vector format;
3. landslide source areas inventory in a point vector format.

Topographic data in DEM format are preprocessed by a built-in pit-filling module. The next step is to compute the required topographic parameters, such as slope and specific catchment area.

The model requires the following soil properties data:

- range of cohesion values;
- soil density value;
- range of internal friction angle values;
- range of R/T ratio.

For calibration purposes the landslides inventory map is needed, obtained from aerial or satellite orthophotos.

The output data are presented in a form of the following maps:

- stability probability expressed as stability index divided into six classes;
- topographic wetness index divided into five classes;
- graph of landslide occurrence in fields of slope and specific catchment area;
- summary table.

By adopting suitable ranges for variables it is possible to calibrate and group the majority of observed landslides into the smallest SI classes (Table 2)

**Table 2**: The definition of slope stability index SI classes.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Class</th>
<th>Predicted State</th>
<th>Parameter Range</th>
<th>Possible Influence of Factors not Modeled</th>
</tr>
</thead>
<tbody>
<tr>
<td>SI &gt; 1.5</td>
<td>1</td>
<td>Stable slope zone</td>
<td>Range cannot model instability</td>
<td>Significant destabilizing factors are required for instability</td>
</tr>
<tr>
<td>1.5&gt; SI &gt; 1.25</td>
<td>2</td>
<td>Moderately stable zone</td>
<td>Range cannot model instability</td>
<td>Moderate destabilizing factors are required for instability</td>
</tr>
<tr>
<td>1.25&gt; SI &gt; 1.0</td>
<td>3</td>
<td>Quasi-stable slope zone</td>
<td>Range cannot model instability</td>
<td>Minor destabilizing factors could lead to instability</td>
</tr>
<tr>
<td>1.0&gt; SI &gt; 0.5</td>
<td>4</td>
<td>Lower threshold slope zone</td>
<td>Pessimistic half of range required for stability</td>
<td>Destabilizing factors are not required for instability</td>
</tr>
<tr>
<td>0.5&gt; SI &gt; 0.0</td>
<td>5</td>
<td>Upper threshold slope zone</td>
<td>Optimistic half of range required for stability</td>
<td>Stabilizing factors may be responsible for stability</td>
</tr>
</tbody>
</table>
Slope stability theory

The **SINMAP** methodology is based upon the infinite slope stability model (e.g. Hammond *et al.*, 1992) that balances the destabilizing components of gravity and the restoring components of friction and cohesion on a failure plane parallel to the ground surface with edge effects neglected.

**SINMAP** uses the formula for the factor of safety (FS) for the infinite slope stability model (ratio of stabilizing to destabilizing forces) developed by Hammond *et al*. (1992). Based on the above assumptions and through mathematical manipulations, (presented in detail in the user manual - Pack *et al.*, 1998), the FS is expressed as:

\[
FS = \frac{C + \cos \theta \left[ 1 - \min \left( \frac{R}{T \sin \theta}, 1 \right) \right] \tan \phi}{\sin \theta}
\]

where

- \( C = (C_r + C_s) / (h \rho_s g) \) is the combined (root and soil) cohesion made dimensionless relative to the perpendicular soil thickness.
- \( h = D \cos \theta \) soil thickness, perpendicular to the slope.
- \( r = \rho_w / \rho_s \) is the water to soil density ratio.

The variables \( a \) and \( \theta \) are the specific catchment area and slope respectively and are derived from the topography. \( C \) is the dimensionless cohesion of the soil and tree roots combined, \( \tan \phi \) is the soil friction angle, \( r \) is the water/soil density ratio, and \( R/T \) is the water recharge divided by the soil transmissivity. These last four parameters are manually input into the model. We treat the density ratio \( r \) as essentially constant (with a value of 0.5) but allow uncertainty in the other three quantities through the specification of lower and upper bounds. Formally these bounds define uniform probability distributions over which these quantities are assumed to vary at random. We denote \( R/T = x \), \( \tan \phi = t \), and the uniform distributions with lower and upper bounds as: (Pack *et al.*, 2001)

\[
C \sim U(C1, C2); \quad x \sim U(x1, x2); \quad t \sim U(t1, t2)
\]

The smallest \( C \) and \( t \), (i.e. \( C1 \) and \( t1 \)) together with the largest \( x \) (i.e. \( x2 \)) defines the worst case (most conservative) scenario under this assumed uncertainty (variability) in the parameters. Areas where under this worst case scenario FS is greater than 1 are in terms of this model, unconditionally stable and we define: (Pack *et al.*, 2001)
For areas where the minimum factor of safety is less than 1, there is a possibility (probability) of failure. This is a spatial probability due to the uncertainty (spatial variability) in C, tan φ and T. This probability does have a temporal element in that R characterizes a wetness that may vary with time. Therefore the uncertainty in x combines both spatial and temporal probabilities. In these regions (with FSmin < 1) we define: (Pack et al., 2001)

\[ SI = Prob(FS > 1) \]

over the distributions of C, x, and t (Equations, 10). The best case scenario is when C=C2, x=x1, and t=t2, which leads to:

\[ FS_{\text{max}} = \frac{C_2 + \cos \theta \left[1 - \min \left( x_1 \frac{a}{\sin \theta}, 1 \right) \right] r_2}{\sin \theta} \]

In the case that FS_{\text{max}} < 1, then

\[ SI = Prob(FS > 1) = 0 \]

Regions with SI > 1 (FS_{\text{min}} > 1), 0 < SI < 1 and SI = 0 (FS_{\text{max}} < 1) are illustrated in Figure 3 in a space defined in terms of slope (tan θ) and specific catchment area. This provides a useful visualization medium for understanding this approach.

Fig.3: Stability Index defined in Area-Slope space.
Data Processing

In order to apply the SINMAP methodology to establish a slope stability map for the highway, several steps were accomplished starting from input data, which depends on the previous data inventory and ending by the final product, which is a grid theme called “Stability Index” that divides the study area into several zones depending on the factor of safety (Figure 4).

Input data

Processing of Digital elevation model (DEM) Data

DEM data were created from the digitizing of topographic maps that cover the rout of the highway. This rout is covered by two topographic sheets of scale 1: 50,000, which are Sweileh and Jerash, each topographic sheet was scanned, cropped and divided into two sections. After that, each section was entered to the Arcview software as an image theme in order to create a point theme that represents the elevations, this theme was converted to DEM using Nearest Neighborhood methodology.

Fig. 4: Flowchart of SINMAP methodology.
Landslides locations theme

A field investigation has been carried out after the winter of 2004/2005, in order to locate all landslides that occurred along the highway route. About 23 landslides were located using a GPS and 1:50,000 topographic maps (Table 3).

A point theme was created consisting the distribution of all landslides in each section except section IV, because there are no recordings of any landslide within it, so the SINMAP model can not be applied to this section. Form the landslides recordings it can be seen that the maximum density of landslides appears in section II, which contains 16 landslides. In addition to these landslides occurrences, other landslides have been added from previous studies (e.g. Dames and Moor, 1993).

Creation of calibration regions theme

The calibration regions are areas within which single lower bound and upper bound calibration parameters values can represent transmissivity/recharge ratio (T/R), dimensionless cohesion (C), and friction angle (ϕ).

There are two methods to create calibration regions:
1. Creating single calibration region for each section of the study area.
2. Creating multi-region calibration theme, which can be used if we have a polygon coverage (shape file) or grid theme of calibration regions.

The single calibration method was used in this study and that refers to two main reasons; the first is lack of hydrological data covers the entire study area and the second is the difficulty of assigning polygons that have specific engineering parameters (C and ϕ), which arise from the heterogeneity of the materials cover the study area. So, every studied section was treated as a single unit and have its own single calibration region.

Previous engineering data inventory has been completed for the subject area by Dames and Moor International (1993). These data were refined to choose the upper and lower bounds of engineering properties (C, ϕ) for each section (Table 4).

Preparatory Grid Processing

A major part of the SINMAP is the creation of several derivative grids from the DEM grid. These grids are derived solely from the DEM grid and require no other parameters for their construction. The processes for creating these several grids are initiated by selecting menu items in the third group of the SinMap menu. The grids and associated grid themes that are created by the grid processing steps are:

- **Pit-Filled DEM**: contains the pit-corrected data of elevation
- **Flow Direction**: Each cell in this grid represents the compass direction for water flow within the cell down the slope of the steepest triangular facet draining from the cell.
- **Slope**: Each cell in this grid represents the slope angle in degrees.
- **Contributing Area**: This is the specific catchment area and is equal to the upslope area draining to the cell per unit length of contour through which that area drains.
Table 3: Locations of landslide occurrences along Amman-Jearsh-Irbid highway.

<table>
<thead>
<tr>
<th>No.</th>
<th>Section #</th>
<th>Landslide coordinates</th>
<th>Slided material</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>I</td>
<td>32° 06' 50&quot; N, 35° 51' 15&quot; E</td>
<td>Highly fractured limestone</td>
</tr>
<tr>
<td>2</td>
<td>I</td>
<td>32° 07' 16&quot; N, 35° 51'20&quot; E</td>
<td>Highly fractured limestone</td>
</tr>
<tr>
<td>3</td>
<td>I</td>
<td>32° 09' 40&quot; N, 35° 50' 49&quot; E</td>
<td>Soft marl</td>
</tr>
<tr>
<td>4</td>
<td>I</td>
<td>32° 10' 57&quot; N, 35° 51' 00&quot; E</td>
<td>Soft marl</td>
</tr>
<tr>
<td>5</td>
<td>I</td>
<td>32° 11' 01&quot; N, 35° 50' 56&quot; E</td>
<td>Soft marl</td>
</tr>
<tr>
<td>6</td>
<td>I</td>
<td>32° 11' 10&quot; N, 35° 51' 01&quot; E</td>
<td>Marly limestone</td>
</tr>
<tr>
<td>7</td>
<td>I</td>
<td>32° 11' 30&quot; N, 35° 51' 32&quot; E</td>
<td>Marly limestone</td>
</tr>
<tr>
<td>8</td>
<td>I</td>
<td>32° 11' 34&quot; N, 35° 51' 50&quot; E</td>
<td>Marly limestone</td>
</tr>
<tr>
<td>9</td>
<td>I</td>
<td>32° 11' 39&quot; N, 35° 51' 52&quot; E</td>
<td>Soft marl</td>
</tr>
<tr>
<td>10</td>
<td>I</td>
<td>32° 12' 10&quot; N, 35° 52' 01&quot; E</td>
<td>Soil</td>
</tr>
<tr>
<td>11</td>
<td>I</td>
<td>32° 12' 16&quot; N, 35° 52' 10&quot; E</td>
<td>Soil and friable sandstone</td>
</tr>
<tr>
<td>12</td>
<td>I</td>
<td>32° 12' 17&quot; N, 35° 52' 27&quot; E</td>
<td>Soil and friable sandstone</td>
</tr>
<tr>
<td>13</td>
<td>I</td>
<td>32° 12' 49&quot; N, 35° 52' 46&quot; E</td>
<td>Soil</td>
</tr>
<tr>
<td>14</td>
<td>I</td>
<td>32° 12' 55&quot; N, 35° 53' 07&quot; E</td>
<td>Soil</td>
</tr>
<tr>
<td>15</td>
<td>I</td>
<td>32° 13' 20&quot; N, 35° 53' 24&quot; E</td>
<td>Soil</td>
</tr>
<tr>
<td>16</td>
<td>I</td>
<td>32° 13' 59&quot; N, 35° 53' 47&quot; E</td>
<td>Soil</td>
</tr>
<tr>
<td>17</td>
<td>I</td>
<td>32° 14' 07&quot; N, 35° 53' 41&quot; E</td>
<td>Soil and friable sandstone</td>
</tr>
<tr>
<td>18</td>
<td>I</td>
<td>32° 15' 13&quot; N, 35° 53' 39&quot; E</td>
<td>Friable sandstone and limestone</td>
</tr>
<tr>
<td>19</td>
<td>I</td>
<td>32° 17' 53&quot; N, 35° 54' 51&quot; E</td>
<td>Soil</td>
</tr>
<tr>
<td>20</td>
<td>I</td>
<td>32° 17' 53&quot; N, 35° 54' 51&quot; E</td>
<td>Soil</td>
</tr>
<tr>
<td>21</td>
<td>I</td>
<td>32° 19' 17&quot; N, 35° 55' 10&quot; E</td>
<td>Marly limestone</td>
</tr>
<tr>
<td>22</td>
<td>I</td>
<td>32° 17' 06&quot; N, 35° 54' 47&quot; E</td>
<td>Marly limestone</td>
</tr>
<tr>
<td>23</td>
<td>I</td>
<td>32° 17' 17&quot; N, 35° 54' 49&quot; E</td>
<td>Soil</td>
</tr>
</tbody>
</table>

Table 4: The upper and lower bounds of calibration engineering parameters (Dames and Moor, 1993).

<table>
<thead>
<tr>
<th>Section #</th>
<th>Dimensionless cohesion $C$</th>
<th>Friction angle $\varphi$ (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Minimum</td>
<td>Maximum</td>
</tr>
<tr>
<td>1</td>
<td>0.2</td>
<td>0.6</td>
</tr>
<tr>
<td>2</td>
<td>0.4</td>
<td>0.7</td>
</tr>
<tr>
<td>3</td>
<td>0.1</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Note: $C = (C_r + C_s) / (h \rho g)$

The hydrological data were obtained from the data bank of Water Authority of Jordan, (WAJ, 2004) (Table 5).

Table 5: Hydrological parameters used in calibration region themes (WAJ, 2004).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmissivity (m²/hr)</td>
<td>1</td>
<td>28</td>
</tr>
<tr>
<td>Recharge (m/hr)</td>
<td>2.99×10⁻⁴</td>
<td>3.5×10⁻⁴</td>
</tr>
<tr>
<td>$T/R$</td>
<td>2857</td>
<td>9364</td>
</tr>
</tbody>
</table>
Output themes

Saturation Grid Theme

SINMAP model uses the following equation to calculate the relative wetness \( w \) (Pack et al. 1998):

\[
    w = \min \left( \frac{R}{a} \frac{1}{T \sin \theta}, 1 \right)
\]

Where: \( R \): is the recharge (m/hr), \( a \): specific catchement area \( T \): is soil transmissivity (m²/hr). The values of \( R \) and \( T \) are used to assign alues to each grid cell in the saturation theme.

Stability Index Grid Theme

Stability index values are 0.0 or greater, with values greater than 1.0 indicating some level of stability. For display purposes, the Stability Index theme is grouped into four classifications. Each grid cell contains the actual calculated SI value, which may be determined by clicking on the cell with the Identify tool. (Figure 5) illustrates the stability index themes of sections I, II and III.

Slop-Area Plot Chart (SA)

The SA Plot provides a view of study data in slope-area space—not in geographic space. The data in the plot are derived from a feature table, which points to a dbase file created by SINMAP (Pack et al., 1998). The file is created by extracting data from the slope theme, contributing area theme, and the landslides theme, (Figure 6) illustrates the SA plots for sections I, II and III of the study area.

Analytical Results

Using the DEM and landslide inventory data, the SINMAP model was used to derive a stability index map comprising sections I, II and III of Amman-Jerash-Irbid highway. As mentioned previously that the SINMAP model can not be applied to section 4 of the study area because there are no landslides occurrences were took place. The Statistical results that obtained fro the slope-area plot charts for the three sections of the highway are shown in Table 6.
Table 6: Summary of the analytical data resulted from SINMAP analysis for the three sections

<table>
<thead>
<tr>
<th>Section No.</th>
<th>Stability</th>
<th>Stable</th>
<th>Moderately stable</th>
<th>Quasi stable</th>
<th>Unstable</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Area (km²)</td>
<td>21.00</td>
<td>5.25</td>
<td>5.25</td>
<td>57.75</td>
</tr>
<tr>
<td>I</td>
<td>% of area</td>
<td>23.6</td>
<td>5.8</td>
<td>5.8</td>
<td>64.8</td>
</tr>
<tr>
<td>I</td>
<td>Number of landslides</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>I</td>
<td>% of landslides</td>
<td>0.0</td>
<td>0.0</td>
<td>20</td>
<td>80</td>
</tr>
</tbody>
</table>

| II         | Area (km²)       | 4.57   | 0.00              | 4.57         | 77.72    |
| II         | % of area        | 5.2    | 0.0               | 5.2          | 88.6     |
| II         | Number of landslides | 0      | 0                 | 2            | 13       |
| II         | % of landslides  | 0.0    | 0.0               | 13.3         | 86.6     |

| III        | Area (km²)       | 9.33   | 0.00              | 4.67         | 97.98    |
| III        | % of area        | 8.3    | 0.0               | 4.2          | 87.5     |
| III        | Number of landslides | 2      | 0                 | 0            | 22       |
| III        | % of landslides  | 23     | 0.0               | 0.0          | 91.7     |

| Total      | Area (km²)       | 34.9   | 5.25              | 14.49        | 233.45   |
| Total      | % of area        | 12.1   | 1.82              | 5.03         | 81.03    |
| Total      | Number of landslides | 2      | 0                 | 3            | 39       |
| Total      | % of landslides  | 4.5    | 0                 | 6.8          | 89       |
Fig. 5: Saturation and stability themes of the three sections of the highway
Fig. 6: Slope-Area plot charts for section 1, 2 and 3 (squares stand for landslides and black dots refer to nonslided area).
Conclusions

The SINMAP model was used for assessment of landslide hazards along Amman-Jerash-Irbid highway. This highway route subjected to severe landslides since the road cut began. The most serious landslides incidence occurred during the snowy and very wet winter of 1991/1992 and 2004/2005.

The slope-area plot charts represent the distribution of the contributing areas within the different classes of stability shows that some of landslides are located within an areas classified as stable and quasi-stable zones. This refers to the impact of human activities in the area, where these zones are naturally stable but the road cuts reduce the stabilizing forces of the slopes leading to landslides.

The analytical results of a SINMAP analysis indicated that the percentage of the areas that have stability index value < 1.0 estimated to be 64.8% in section I, 88.6% in section II and 87.5% in section II, therefore, section I can be considered the most stable section of the highway whereas section II is the most unstable. This refers to the effect of topography and geological setting beside the intensity of landslides included in each section.

In the light of the current study the SINMAP methodology does a good job of delineating areas that appear to be susceptible to landsliding which accounts for 81% of study area having a stability index value of less than one. It can be assumed that section IV of the study area is quite stable because it is characterized by low relief topography and moderately homogeneous geological cover.

According to the analytical results and conclusions, the current study suggests the following recommendations. It is highly recommended to reassess the stability conditions by SINMAP methodology using more accurate DEM and high resolution data focusing on sections II and III because they considered the most complicated sections of the study area. Secondly, Remedial procedures should be taken to minimize the risk at areas that have stability index less than one, such as slope reduction by reducing the slope angel and place additional supporting materials at the foot of the slope to prevent a slide or flow at the base of the slope. In addition to construction of retaining walls and chain-link fencing draped over the slope.

References


