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An engineering geological GIS data base for mountainous terrain

Une base de données SIG de géologie de l'ingénieur pour des terrains montagneux

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ABSTRACT: Within the framework of two international research projects a method was designed for the application of geographic information systems in the construction of an engineering geological data base at a scale of 1:10.000. The method was applied to a mountainous area: the city of Manizales, in central Colombia. The major problem encountered in heterogeneous, mountainous, areas is the extrapolation of point information. Emphasis was given to the use of geomorphological, topographical and geological information which allowed, in combination with boreholes and outcrop data, to model the layer sequences spatially. Different maps were made for the spatial distribution of each material type. The depth of these materials was obtained by modelling material thicknesses as a function of other parameters. The resulting Engineering Geological data base was used as the main input in hydrological models and slope stability calculations.

RESUMÉ: Dans le cadre de deux projets internationaux de recherche, une méthode a été developpée pour construer une base de données de géologie de l'ingénieur à l'échelle de 1/10000, utilisant SIG. Cette méthode a été appliquée en terrain montagneux, a Manizales, en Colombie centrale. Dans les terrains montagneux hétérogènes, le problème majeur serait l'extrapolation de l'information de point. L'accent a été mis sur l'usage de l'information géographique, topographique et géologique qui en combinaison avec les données de sondages et affleurements a permis de modeler spatialement les séquences du sous-sol. Différentes cartes ont été produites pour la distribution spatiale de chaque type de matériel. La profondeur de ces matériaux a été obtenue en utilisant un modèle de profondeur de matériel définie en fonction de quelques autres paramètres. Le resultat, est une base de données de géologie de l'ingénieur qui a été utilisée comme entrée principale des modèles hydrologiques, ainsi que le calcul de stabilité de la pente.

1 INTRODUCTION

In the framework of two international research projects, financed by EEC, UNESCO and the Netherlands government, a methodology was developed for the use of GIS in landslide hazard zonation (Van Westen et al, 1993). An important aspect in landslide hazard analysis is the scale on which the data are collected and on which the final map will be presented.

The scale required for hazard maps is determined by the use which is made of the maps in the process of planning and decision making at site investigation, municipal, departmental or national level. In accordance with the scales used in engineering projects (IAEG, 1976) the following scales have been differentiated for landslide hazard zonation:

- Regional scale (1 : 100,000)
- Medium scale (1 : 25,000 to 1 : 50,000)
- Large scale (> 1:10,000)

Basically four different approaches in landslide hazard analysis can be differentiated: inventory, heuristic approach, statistical and deterministic approach (Hansen, 1984). Not all methods are equally applicable at each scale of analysis. Some require very detailed input data, which can only be collected for small areas. This paper describes the methodology developed at the 1:10,000 scale.

The objective of a large scale landslide hazard analysis is to produce a hazard map according to Varnes' definition (Varnes, 1984): a map displaying the probability of occurrence of landslides within a given time period, and for a specific area, which can be used to make risk maps for cities. Such an *absolute hazard map* can be made using so-called *deterministic models*. Such models aim to calculate the slope stability and express it as a Safety Factor, which is the ratio of the forces which contribute to instability and those that prevent it.

The GIS based stability model, which has been developed, allows for the calculation of slope stability using different scenarios, with respect to groundwater levels and seismic accelerations. The most important factors for stability calculation are slope angle, material sequence, material strength, groundwater depth and seismic acceleration.

In the method for deterministic slope stability analysis the following steps are taken:

- Groundwater modelling,
- Calculation of maximum horizontal seismic accelerations,
- Slope stability calculations using different scenarios for groundwater levels and seismic accelerations,
- Calculations of maximum failure probability within a 20 year period.

In nearly all of these steps the engineering geological data base is playing a crucial role. Therefore, much emphasis was put on the development of a method for the construction of such a data base.

2 STUDY AREA

The study area which was selected for the development of the methodology is located in the department of Caldas, central Colombia, surrounding the city of Manizales (figure 1). Manizales (300.000 inhabitants) is located at an altitude of 2000 m on the steep slopes of the western flank of the Cordillera Central, near the Nevado del Ruiz volcano. Due to its unfavourable topographic location, large parts of the city are built over steep slopes, which are mostly modified by cuts and (hydraulic) fills to provide adequate terrain for housing.

Manizales has suffered strongly from landslide problems. In the period 1960 - 1992 approximately 250 persons were killed by landslides, and around 1600 houses were damaged. The landslides are a result of the geological and geomorphological setting of the area and the wet climate (more than 2000 mm precipitation per year).

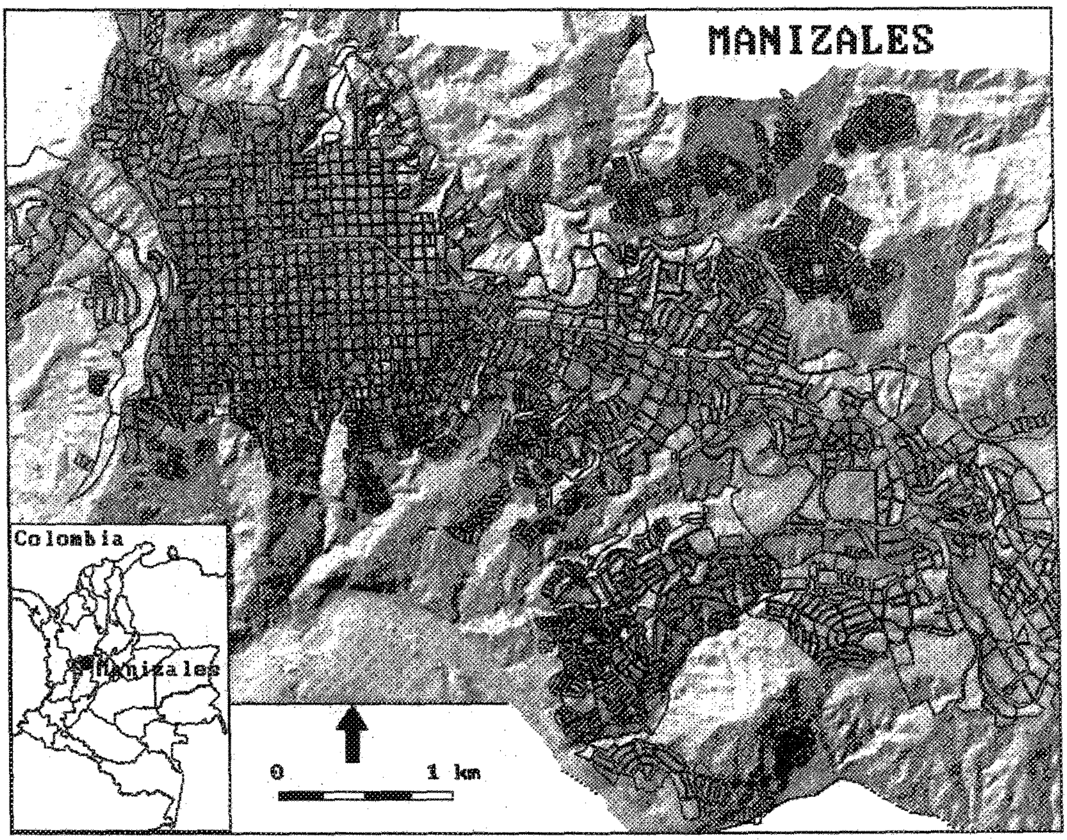


Figure 1: The study area

The area is located in a seismically active region, in one of the major fault zones of Colombia (Romeral fault zone). The geology of the area consists of metasedimentary rocks from the Quebradagrande formation of Cretaceous age and igneous rocks from the Quaternary. The city is located on Quaternary fluvio-volcanic sediments from the Manizales and Casabianca Formations. Most of the area is covered by recent pyroclastic fall deposits (Naranjo and Rios, 1989). The thickness of the ashes varies from 15 meters on the flat hilltops to 1 meter or less on very steep slopes. The ash deposits contain layers with textures ranging from very fine (<63µm) to very coarse (>5000 µm) (Van Westen et al, 1993). These changes in texture cause perched watertables in the ashes, which can trigger soilslips, soil avalanches and translational slides. The deepseated slides and flowslides which are also found in the area are caused by high groundwater levels on top of the impermeable schists of the Quebradagrande Formation. Since the residual soil has a lower strength than the ashes the failure surfaces of the deep landslides are located often on the contact between residual soils and ashes.

3 INPUT DATA

The following data were used in the construction of the engineering geological data base:

- a detailed geomorphological map,
- landslide distribution maps,
- a geological map,
- digital elevation models,
- slope maps,
- soil and rock descriptions,
- laboratory data

3.1 Maps

The geomorphological map of the study area was made by aerial photo interpretation using recent 1:10,000-scale aerial photos, followed by a detailed fieldwork. During photo-interpretation, a legend structure for the geomorphological map was defined, using various levels of detail. Geomorphological subunits (GSs) are the smallest sections of the terrain that can be presented on a 1:10,000-scale map. A GS consists of one landform, for which the genesis, together with morphographical characteristics is given, for example a short fault related slope with convex form. Much emphasis is placed on the delineation of subunits caused by human activity (see table 1). Digitizing the geomorphological map, with approximately 8000 segments and 2800 polygons, took three weeks.

Three detailed landslide maps were made on the basis of photo-interpretation and fieldwork: for the 1940's, 1960's and 1980's.

Table 1: Anthropogeneous units distinguished in the geomorphological map

Code	Description
90	Levelled hilltop
91	Levelled slope
92	Levelled ridge
93	Levelled niche
94	In-filled valley
95	Hydraulic fill
96	Material dump on slope
97	Cut slope
98	Stabilized slope
99	Quarry

During the photo-interpretation use was made of a photo checklist. Each landslide was mapped as a polygon, with a unique identifier, which was linked with a data base containing information on the landslide type, subtype, activity, vegetation, depth and presence of scarp and accumulation area. During fieldwork most of the landslides were checked and described with more detailed field checklists.

The geological map was digitized after careful revision of the existing geological map (Naranjo and Rios, 1989).

For the construction of digital terrain models for the Manizales area, 20 maps sheets at 1:2,000 scale from 1990, with 10-m contour interval, were digitized. In order to obtain the terrain situation before the major earth displacements, 12 map sheets at scale 1:2,000 from 1949 were also digitized. The various topo sheets were merged together and two DTM's were made: one from 1949 and one from 1990. For both periods a slope map was calculated on the basis of the DTM's.

3.2 Material descriptions

During fieldwork, data were collected to characterize various soil and rock materials. Material descriptions focused on the following aspects:

- Collection of data on material sequences via profile descriptions,
- Description of the different material types with a number of simple variables.

The method for soil description is based on the procedures developed at ITC for large-scale engineering geological mapping (Rengers et al., 1990). Prior to the fieldwork, a list of all materials occurring in the Manizales area was prepared. This list was based on geomorphological photo-interpretation, existing geological maps and reports, and the general overview of the area obtained during a first walk-over field survey. The list is given in table 2. The list contains all material types, including rocks and soils. The different rock types are grouped according to their origin (sedimentary, metamorphic, etc.) and classified as residual soil, weathered rock, and fresh rock. The base of weathering grade IV (above which more than 50% of the rock is decomposed and/or disintegrated into soil) is taken as the limit between soil and rock. The transported soils were divided into volcanic ashes, alluvial materials, slope deposits, urban land fill and hydraulic land fill.

For the soil observations, a checklist was designed in accordance with the data base structure (figure 2). The variables for field description of soils are described in Cooke and Doornkamp (1990), Dackombe and Gardiner (1983), and Selby (1982). Most of these data are obtained by direct measurement or observation. Others, such as permeability or grain size percentage were obtained by estimation. These field estimations proved to be very difficult, and differed greatly from the values measured in the laboratory. Some of the parameters, such as bulk density, soil strength, plasticity, porosity, grain-size distribution, and mineralogy, were tested in the laboratory on a limited number of samples. For each soil outcrop (with a unique code for OP, observation point), a separate soil observation sheet was filled in.

The first step in soil description is to divide the soil outcrop into a number of different layers. Each layer is assigned a unique identifier, entered as LN (layer number) in the checklist, starting from the top of the profile. For each layer, the depth (in cm) below the terrain surface of the top and the bottom of the layer were entered into the columns TOP and BOTTOM, and the descriptive parameters were filled in. Pocket penetrometer and shear vane test results were made if the soil material allowed it. In outcrops with coarse materials, grain-size estimations of the coarser fraction were performed by line counting.

4 MODELLING MATERIAL THICKNESSES

Due to the very heterogeneous nature of the surficial materials in Manizales, its rugged topography and the small amount of drillhole information, the engineering geological data base could not be obtained from interpolation of material depths derived from drillholes and outcrops. Therefore, another method was developed, based on the use of logic reasoning in GIS. Combining the different maps using conditional statements in GIS made it possible to produce the engineering geological data base.

Table 2: Material codes for the Manizales area

Mat	MATERIAL
10	Volcanic ash (undifferentiated)
11	• Silty ash
12	• Sandy/silty ash
13	• Coarse sandy ash
	Alluvial material
21	• From local source
22	• From main rivers
	Slope deposits
31	• Predominantly fines & sand
32	• With boulders & gravel
	Urban land fill
41	• from sedimentary rock
42	• from meta-sedimentary rocks
43	• from igneous rocks
	Hydraulic land fill
45	• from sedimentary rocks
46	• from meta-sedimentary rocks
47	• from igneous rocks
	Manizales Formation
51	• Residual soil
52	• Weathered rock
53	• Fresh rock
	Casabianca Formation
54	• Residual soil
55	• Weathered rock
56	• Fresh rock
	Black shales, schists
61	• Residual soil
62	• Weathered rock
63	• Fresh rock
	Cherts, grauwackes
64	• Residual soil
65	• Weathered rock
66	• Fresh rock
	Andesitic lavas
71	• Residual soil
72	• Weathered rock
73	• Fresh rock
	Gabbros
74	• Residual soil
75	• Weathered rock
76	• Fresh rock

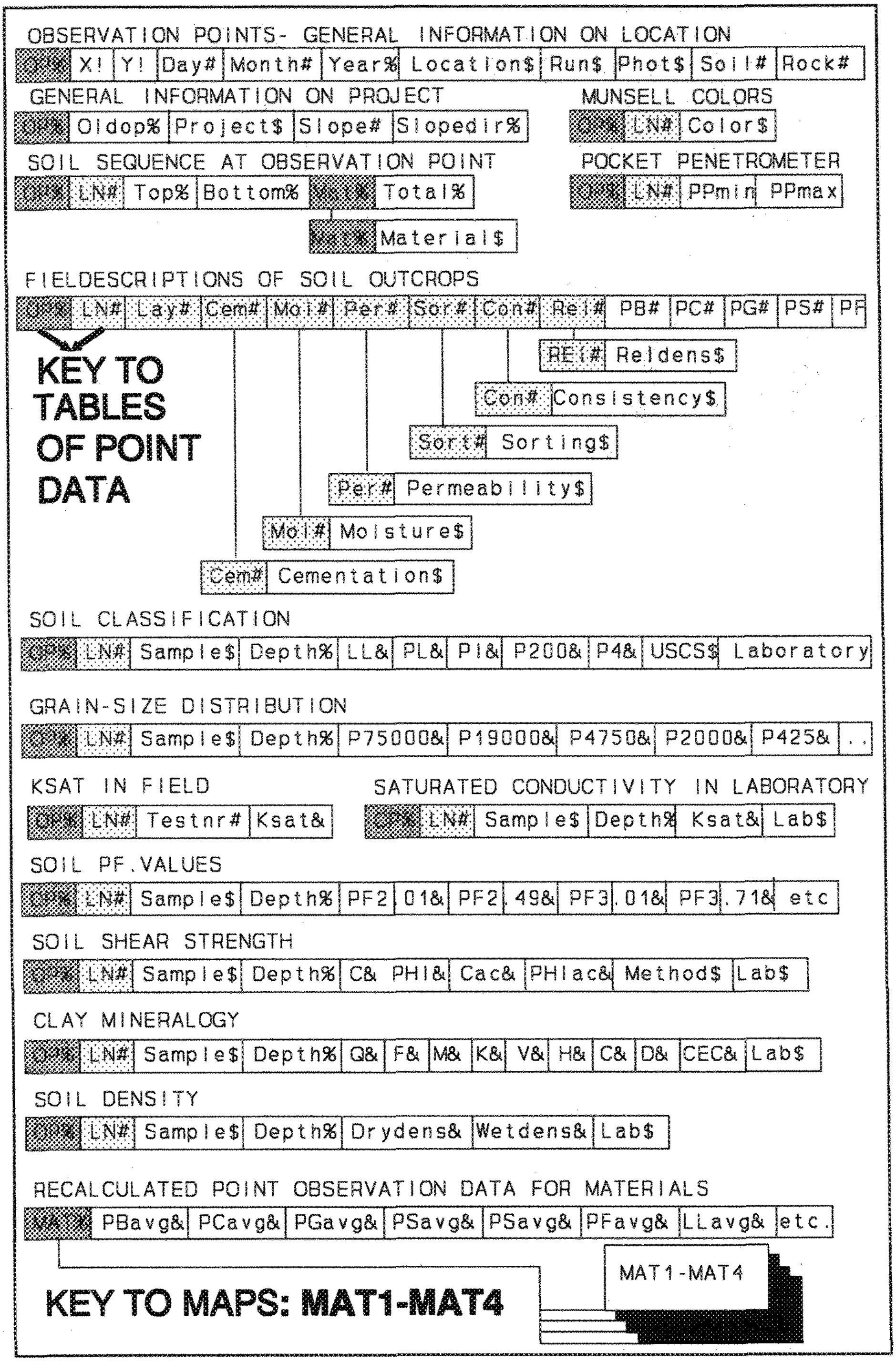


Figure 2: The engineering geological attribute data base

This data base describes the materials in three dimensions, showing both the spatial distribution of 4 basic material layers, and their thicknesses. As we are working with a 2-D GIS system this was done by separating the spatial information from the thickness information (see figure 3). In this way 8 different maps were used which provide the engineering geological information for any pixel if the maps are read simultaneously using a pixel-information program.

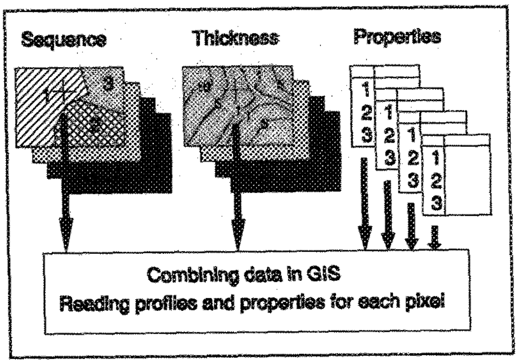


Figure 3: Schematic representation of the GIS data base

To derive at such a data base, distribution and thickness information should be available on the following aspects:

- Volcanic ash cover
- Slope deposits
- Land-fills

Furthermore we should know the depth of cuts in order to establish the material which is now outcropping.

4.1 Ash thickness modelling

A model was established for the calculation of maximum volcanic ash cover by means of multivariate statistical analysis, in which the ash thickness, derived from drillholes and outcrops, was used as the independent variable, and factors such as slope angle, slope direction, slope length, and distance to the volcanoes were used as dependent variables. From this analysis, only the slope angle turned out to be significant. A general function was derived relating ash thickness with slope angles.

Based on the information from the other maps, a series of conditional statements were used to construct the ash thickness map, first by excluding those areas where no ash cover could be expected, based on geomorphological, geological, landslide and slope information. Then for the remaining areas the basic relation between ash thickness and slope angles was applied (see figure 4).

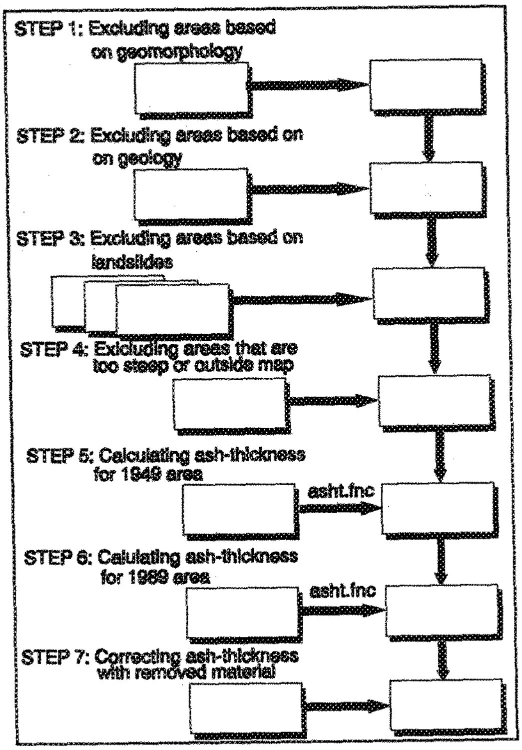


Figure 4: GIS based method for the creation of an ash-thickness map

4.2 Slope deposits modelling

For the modelling of the distribution and thicknesses of slope deposits, use was made of the three landslide distribution maps, made for different periods. From the accompanying attribute data base it was possible to find out those landslide types which do not lead to a deposition of slope material (such as debris avalanches). Also a good estimation of the thickness of slope deposits could be obtained from the information on landslide depth in the attribute tables.

4.3 Modelling cut-and-fill

Manizales is constructed over very rugged terrain, and construction of most parts of the city required large volumes of material to be moved to create smooth topography on which housing construction could take place. Evaluating the volume of earth moved is important in preparing the engineering geological map. In areas from which material has been removed, it is important to know the total thickness of soil material excavated, in order to predict which material is exposed after cutting. When the total thickness of moved material was low, ash may still be present. Otherwise, residual soil underlying the ash will be exposed. For the areas where material was deposited it is important to know the thickness of fill. In this evaluation, DTMs from different years can play an important role. Two DTMs (one of 1949 and one of 1989) were subtracted yielding the change in topography for each pixel. Differences smaller than 1 m were not taken into account, as they are within the accuracy of the procedure followed. The amount of cut or fill for those parts of the city which already existed in 1949 could not be calculated.

5 MAP COMBINATION

For the construction of the engineering geological data base, the maps that have been presented earlier will have to be combined. The first step in the analysis is the determination of the main material types that can be found, either at or below the surface. On the basis of borehole and field information eight possible materials were differentiated (table 3).

Table 3: Main material types in the study area

MAT	MATERIAL
1	Volcanic ash
2	Residual soil
3	Weathered rock
4	Fresh rock
5	Slope deposits
6	Alluvial deposits
7	Urban land fill
8	Hydraulic fill

At this stage of the analysis, no distinction was made between materials from different geological formations. For each of the material maps presented in figure 3 (which are named: MAT1 to MAT4) the legend of table 3 was used. The procedure for creating the maps MAT1 to MAT4 is given schematically in figure 5.

The maps displaying the distribution and thickness of ash, slope deposits and fill are used, as well as the slope map and the geomorphological map. The surface material map (MAT1) is made using the following steps:

- The geomorphological map is renumbered using an attribute called MATNR, indicating the most probable material type (table 3) on the basis of geomorphological information.
- Those pixels which have fill material (FILL>0) are classified as urban land fill (7) or hydraulic fill (8), depending on the geomorphological information.
- Those pixels which have slope deposits (COL>0) are classified as slope deposits, if they were not yet classified in the first step.
- Those pixels which have alluvial deposits are classified as such.
- Those pixels that have volcanic ash (ASH>0) are classified as ash if they had not been classified as such earlier.
- The remaining unclassified pixels are classified as residual soil (2) when the slope angle is less than 60°, and as weathered rock if the slope is steeper.

Based on the information from the surface layer (MAT1) and the various maps, also the second layer can be modelled, using the following steps:

- Those pixels classified in MAT1 as urban fill or hydraulic fill and which have underlying slope deposits (COL>0) are classified as slope deposits (5). If this is not the case, but they have ashes underneath (ASH>0) they are classified as ashes, and otherwise as residual soil.
- Those pixels classified as slope deposits in MAT1 are classified as residual soil in MAT2, taking into account that most landslides remove the ash cover.
- Pixels classified as alluvial material in MAT1 are classified as weathered rock in MAT2.
- Ash in MAT1 is assumed to be underlain by residual soil in MAT2.
- Residual soil in MAT1 is assumed to be underlain by weathered rock in MAT2.
- Weathered rock in MAT1 is assumed to be underlain fresh rock in MAT2.

Analogous steps are followed for the construction of maps MAT3 and MAT4. The last map consists almost completely of fresh rock.

The maps that have been created sofar can now be read simultaneously using a pixel-information program in the GIS, resulting in a sequence for each pixels, consisting of the values of the maps MAT1 to MAT4, and the thickness information from the maps ASH, FILL and COL (see figure 6).

The engineering geological maps presented sofar cannot be directly connected to the geotechnical attribute data base. In order to make this possible, the 8 material types should be subdivided on the basis of geology, so that the material codes of table 2 can be used. In order to do so the maps MAP1 to MAP4 are combined with the geological map using a so-called two-dimensional table in GIS (table 4). Using this table the residual soils, weathered rocks, fresh rocks, slope deposits, urban fills and hydraulic fills can be subdivided in units related to lithology. The numbers in table 4 relate to the material codes used in table 2, which are also the keys used in the engineering geological data base. All relevant geotechnical data can be retrieved from the tables containing the recalculated point observations.

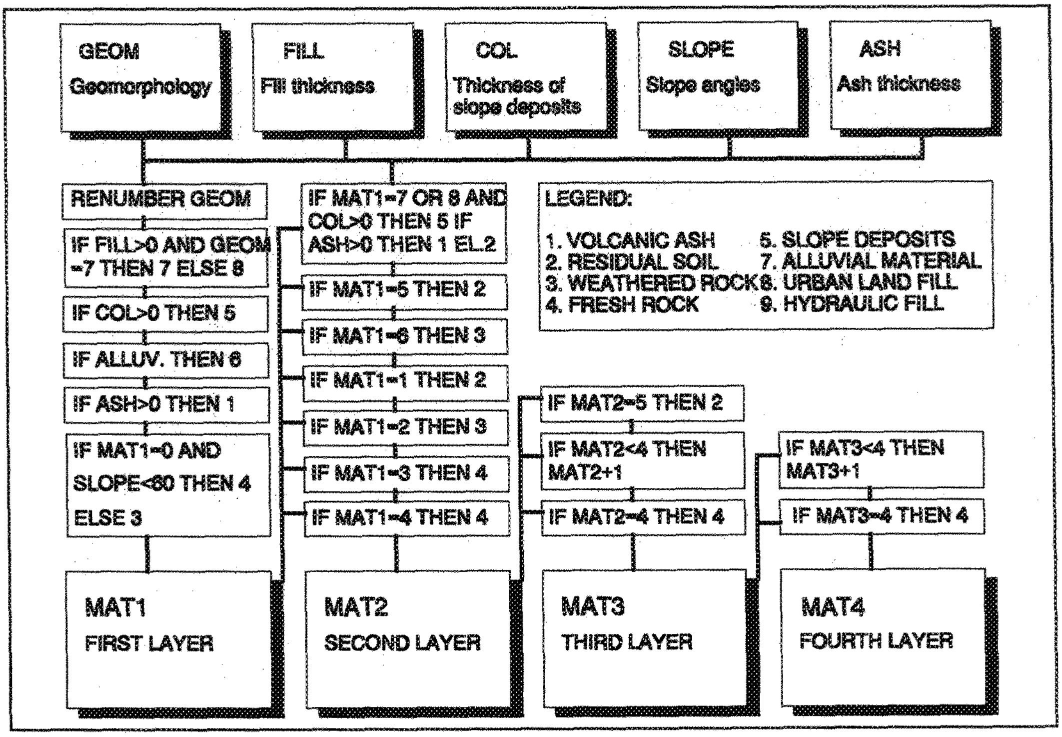


Figure 5: Flow-chart for the construction of the engineering geological data base

Table 4: Combination of geological map with material types from maps MAT1-MAT4

	Units from maps MAT1 - MAT4							
Units from geological map	Material types (table 2)							
	1	2	3	4	5	6	7	8
Manizales F.	10	51	52	53	31	21	41	45
Casabianca F.	10	54	55	56	31	21	41	45
Black shales	10	61	62	63	32	21	42	46
Grauwackes	10	64	65	66	32	22	42	46
Lavas	10	71	72	73	32	22	43	47
Gabbros	10	74	75	76	32	22	43	47

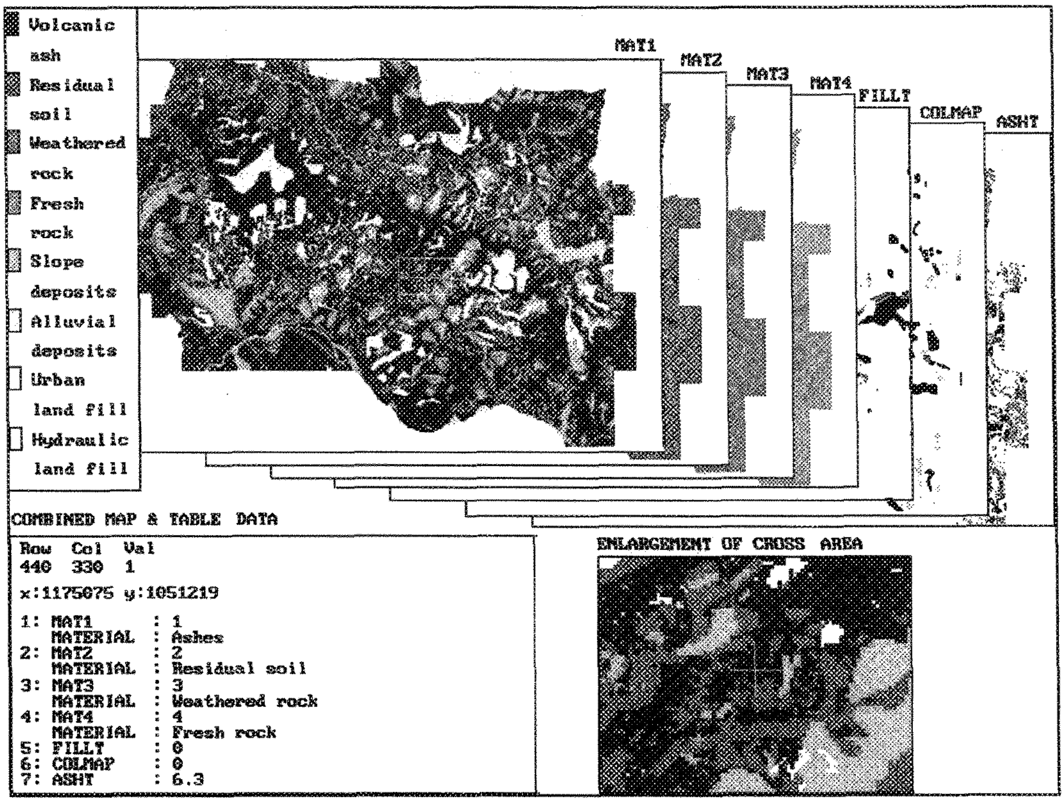
6 CONCLUSIONS

This study resulted in a method for generating an engineering geological data base with GIS for mountainous areas, where only a limited number of drillhole data is available.

The method, however, also has a series of drawbacks, which should be studied more in detail in the future:

- The data base which was constructed gives a general overview of the most important material types which can be found in the area. For very heterogeneous terrain conditions, which is the case in most cities located in mountainous terrain, the detail of such a data base should be increased, to achieve reliable results in subsequent slope instability analysis. Many landslides in Manizales occurred in small patches of slope deposits or rubble, which were too small to model.
- The most difficult part in the study was the modelling of volcanic ash thicknesses. Although there was a general relationship between slope angles and ash thicknesses, many exceptions to the rule remained. More research should be undertaken to be able to model ash-thicknesses in more detail.
- Due to the heterogeneity of the volcanic ashes, the spatial variability of the ash material could not be included in this study. Therefore, no subdivision was made between the different types of ashes given in table 2.

The data base presented here resulted to be very useful in the use of groundwater models, the calculation of seismic accelerations and safety factors (Van Westen et al, 1993).



```
COMBINED MAP & TABLE DATA
Row  Col  Val
440  330  1

x:1175075 y:1051219

1: MAT1         : 1
   MATERIAL     : Ashes
2: MAT2         : 2
   MATERIAL     : Residual soil
3: MAT3         : 3
   MATERIAL     : Weathered rock
4: MAT4         : 4
   MATERIAL     : Fresh rock
5: FILLT        : 0
6: COLMAP       : 0
7: ASHT         : 6.3
```

Figure 6: Reading the engineering geological maps in GIS

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1993, 28 cm, 304 pp., Hfl.165 / $95.00 / £61
35 papers, each with a practical orientation, detailing the problems of building man's structures on karst terrane: why and how to fix it, and how to avoid the problem next time. Keynote addresses; Geology of karst areas; Groundwater contamination in karst terrane; Geophysical investigations of karst; Karst hydrology; Engineering designs in karst areas; Remedial engineering in karst terrane; etc.

Novosad, S. & P. Wagner (eds.) 90 5410 302 7
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1993, 25 cm, 324 pp., Hfl.165 / $95.00 / £55
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1993, 25 cm, 210 pp., Hfl.95 / $55.00 / £35
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Rock slope stability analysis
1992, 25 cm, 374 pp., Hfl.135 / $75.00 / £50
Up-to-date information in a new form dealing with the geomechanical problems of rock engineering design. Starting from geological surveys and discontinuity data collections it describes a number of procedures to assess the shear behaviour of joints and rock masses and the methods to model groundwater flow. The input data, required for a slope analysis, are completed by the description of the methods used to build a geomechanical model. Methods used to assess the stability degree of a rock slope are described as well as provisional techniques for the movement of unstable rocks. Rockfall models, toppling and buckling analysis; etc. Author: Politech.Torino.

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5 general and 5 specialist themes. The general themes include landslide investigations, stability analysis techniques, stabilisation measures, hazard assessment, and monitoring and instrumenstation. The specialist themes are seismicity and landslides, landslides and reservoirs, open-pit mine slopes, slope stability in tropical areas, and landslides in Australasia. Editor: Univ. Canterbury, Christchurch, New Zealand.

Plotnikov, L.M. 90 5410 220 9
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