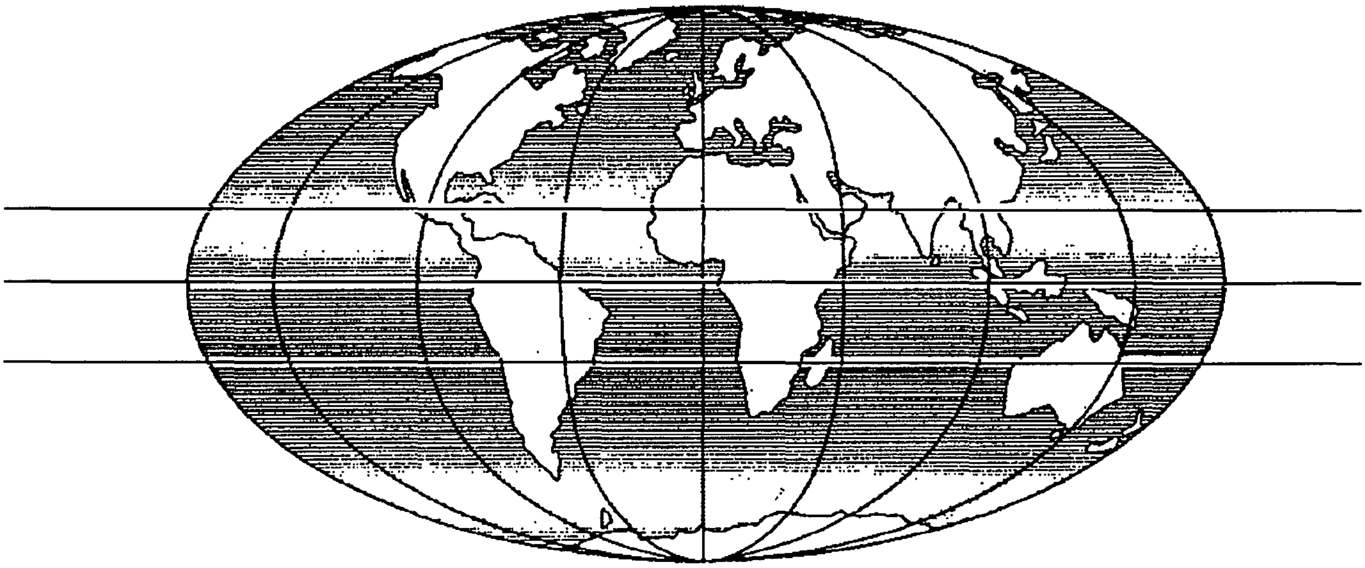
TRANSPORT RESEARCH LABORATORY

ODA

# Reprint

# TITLE Terrain evaluation and the use of remote sensing in civil engineering

by P J Beaven



Overseas Centre
Transport Research Laboratory
Crowthorne Berkshire United Kingdom

BEAVEN, P J (1994). Terrain evaluation and the use of remote sensing in civil engineering. In: *4th Symposium on Terrain Evaluation and Data Storage, Pretoria. 3-5 August 1994.*

# KEYNOTE ADDRESS

**P J BEAVEN**
**OVERSEAS RESOURCE CENTRE**
**TRANSPORT AND ROAD RESEARCH LABORATORY**
**UK**

I wish to thank the organisers of this Symposium for inviting a member from the UK Transport Research Laboratory to deliver this address. It gives me great pleasure to be able to re-establish links with colleagues in South Africa and I hope that this will only be the first in a series of contacts between us.

## INTRODUCTION

The previous Symposium in this series was held at Kyalami in 1975; the first two were in 1964 and 1965. Looking back it is now obvious that that decade was a major period of development for terrain evaluation in civil engineering. Since that time the number of papers on the subject has declined and the subject matter has tended to describe the results of the evaluation rather than the techniques involved. This reflects the change from academic study to practical implementation. However no subject stands still and several important developments have taken place since then and new practitioners have entered the scene with different ideas. Thus it is an appropriate time to review the development of terrain evaluation and to speculate on developments in the future.

### What is terrain evaluation?

Before we consider the subject of terrain evaluation it is necessary to agree what we are talking about. Everybody knows what terrain evaluation is; it is just that most people have a definition that is slightly, or very, different from that of the next person.

This problem was recognised by the Geological Society Working Group who published a report on the subject in 1982[1]. They considered that the varied use of ‘Land Classification’, ‘Terrain Evaluation’ and ‘Terrain Analysis’ had created confusion and led to misunderstandings. They used the term Land Surface Evaluation for their report which was defined as:

> ‘The evaluation and interpretation of land surface features and recorded surface data using one or a combination of the ground mapping, interpretation, classification and visual remote sensing techniques outlined in the report’ They explained this definition with a rider that ‘the object is to provide information about ground conditions likely to be of significance’

Looking at the papers from the previous Symposium, there are several statements equating terrain evaluation with soils engineering mapping. TRH 2[2] is the local reference for terrain evaluation but its title is ‘The Production of Soil Engineering Maps for Roads and the Storage of Materials Data’. It contains a definition of terms used in a terrain evaluation and also sets out what it should attempt to achieve.

A definition that I think gets closer to the thinking of engineers is given by Kantey[3]: 'The function of terrain evaluation is to provide the Engineer with a reliable estimate of the effect of the terrain on his proposed activity or project.' If you change the word 'Engineer' to 'user' this would provide an all purpose definition for planners and scientists in a wide variety of subjects, ranging from agriculture to zoology by way of forestry, geology and urban development.

Having set out a simple definition the next stage is to consider why there has been so much variety of opinion on the practice and aims of terrain evaluation. Most practitioners would agree on the main components required for a complete study. In summary these are collection of data, leading to *classification,* which would be the basis of any *mapping* or data storage exercise, leading to the *evaluation* which is the interpretation and assessment of data for a practical purpose.

## Types of classification

The major differences between alternative solutions to this strategy are shown in the type of classification used, which in turn reflects the purpose of the evaluation and the background of the user. One of the sources of difference between classifications is that some users were trying to predict conditions in unknown areas while other users were trying to classify the results of detailed ground investigations. The purpose of any classification is to group similar objects together and to separate them from those with different properties. The long history of research has produced many different alternatives to the classification of terrain.

One of the major challenges in terrain mapping is to devise a classification that can accommodate the variability and variation of the ground. Soil samples taken over a small area will give different results in any form of physical test due to the natural variability that occurs in any material. This can be defined by the normal statistical measures of variance, although it is too often overlooked. A more difficult concept to map is the way soils change in property both horizontally and vertically. The use of a soil profile to describe vertical changes at a point is standard practice and it is possible to attach such a profile to a terrain classification. The fact that the different layers vary in thickness is recognised in borrow pit surveys, where it has a direct effect on the use of the material. The idea that thickness of other soil layers can vary in a consistent manner, eg downslope, and is therefore predictable, is less often recorded.

There have been two very different approaches to the provision of a terrain classification. The method developed jointly by several organisations[4] is based on the identification of landscape patterns as seen in remote sensing imagery. The theoretical basis of this approach is that a change in landscape pattern is normally caused by a change in one or more of the landscape forming factors: climate, topography or geology. As these are the same factors that control soil formation a classification of landscape can be used as a surrogate for soil and its use. This thesis has been widely tested in many disciplines and the method has been widely used for many different types of terrain evaluation.

The alternative form of terrain classification is based on identification and mapping of the individual factors that affect the intended land use. For civil engineering these would include factors such as soil type, soil condition, slope angle etc. Combinations of these factors are used to identify areas of land having very closely defined properties.

This type of mapping would give more detailed results but has not been widely used, mainly because of the effort required to gather the data before the map can be established. This has made it very difficult to use the technique to predict conditions in unknown areas. However it can be seen that the methodology involved would be easily implemented on a Geographical Information System (GIS). Global sets of climatic, topographic and geological data now exist in computer format, albeit at small scale, and satellite imagery could be used to provide further information. However a considerable amount of expert interpretation would be needed to process this information to obtain a useful product.

The mapping of a single factor would produce a thematic map such as a geological or soils map. These could be considered a specialised form of terrain evaluation, but the term is usually used for a classification that encompasses all aspects of the terrain including shape of the ground surface, soil type, hydrological features and vegetation. Different types of geomorphological mapping have also been used for engineering projects and the relation of these to terrain evaluation is discussed below.

## DEVELOPMENT OF TERRAIN EVALUATION

The use of the expression terrain evaluation became common forty years ago but the concept has a much longer history. One of the earliest uses in modern civil engineering was recorded at the beginning of the nineteenth century when engineers were building canals in many parts of southern England. William Smith noticed that the cuttings in different areas had the same lithology which was marked by the same inclusions (fossils) and also had the same engineering problems. This led to the publication of the first geological map of England in 1815, which could also be considered to be the first published terrain evaluation.

The modern phase grew out of the development of air photo interpretation which made it possible to survey large areas rapidly and economically. This coincided with a period when large new areas were being surveyed to assess their development potential and plans were prepared to implement these schemes. Field workers in many different areas were developing similar techniques to organise the collection and collation of data. A representative group of these workers published a report in 1966[4] proposing a terrain classification and describing a data storage system based on it. A more accessible paper[5] describes this joint study.

> "The underlying principles (of classification) were common to all, namely:
>
> (1) Terrain patterns of one kind or another are almost universal.
> (2) They can be subdivided into recurring homogeneous units.
> (3) They and their component units can be recognised and mapped using air photographs.
> (4) They can be used for the economical collection, indexing and retrieval of information on land resources."

In the original description of this system four higher classes were suggested: land zones; land divisions; land provinces and land regions. Land regions are formed from the three lower classes of land systems, land facets and land elements.

Very little use has been made of the three highest classes of this hierarchy: recent work at TRL suggests that an extra level may be needed to complete the sequence. These units are only of value at a very broad (international) scale of planning such as the Trans African Highway[6].

Land regions have been used as a preliminary stage in the development of a terrain analysis. The terrain patterns are on a larger scale and so can be identified from thematic maps as well as remote sensing imagery. Work in Asia[7] in areas of dense vegetation suggests that terrain classification may not be able to subdivide beyond the land region in areas where it is not possible to see the ground surface.

Land systems, land facets and land elements are the three lowest (smallest) of seven orders of terrain unit that comprise the land system method of terrain classification. In practice these are the three levels used, because only at this scale is terrain described in sufficient detail to enable design decisions to be taken on the basis of information they provide. The units at each level are made up of units at the next lower level, ie land systems are made up of associations of land facets and land facets are made up of associations of land elements.

Land system.

A land system is a large area with a recurring pattern of land forms, soils and hydrological regimes. Its physical attributes give it a distinctive, unified character, recognisable on the ground but more especially from the air or space, when the regular arrangement of surface features is very apparent. On the ground the character of a land system is expressed most obviously by its slope profiles and vegetation and land use practices, which are closely allied to the landscape. A land system is recognised and mapped by its pattern of streams, land forms and vegetation. A substantial change in any of these indicates a new land system. Vegetation, although an important factor in the recognition of land systems (being a major contributor to air photo patterns), is not used in the definition of land systems. This is because vegetation can be temporary, especially in areas of marginal habitability, and can be destroyed or modified by such events as fire, successive years of drought, changes in agricultural activity, overgrazing, and deforestation.

A land system is actually defined on the complement of land forms that makes up the terrain pattern, and is demarcated by the geographical extent of that association. These land forms, including the streams and rivers that constitute the drainage pattern, are developed on an underlying parent material as a series of characteristic slope components. The slope components are known as land facets.

A land system possesses the following characteristics:

1. It usually extends over an area of at least 100km$^2$, and is mappable at about 1:250,000 - 1:1,000,000 scale.

2. The climate is uniform.

3. It is developed on a parent material that is either uniform, or consists of several closely related rock types, or contains a range of rock types whose individual

members are too thin to be mapped at land system scale, eg a sequence of bedded sandstones and mudstones.

4. A recurrent land pattern that is clearly defined as seen in aerial photographs is a good indication of consistent land forming processes, and hence of uniform ground conditions.

5. Land systems are contiguous: there are no gaps of unclassified land between systems.

A land system is named after a town or village that occurs within it. The name is simply a label. The land system may occur in several places but each occurrence carries the same name, indicating that they are all the same terrain type consisting of a particular association of land facets.

Land facet

The land facet is the basic unit of the classification, the 'building block' that makes up land systems. A land facet is a terrain unit of uniform slope, parent material, soils, and hydrological conditions. In concept it is sufficiently homogeneous to be considered uniform for most practical purposes. In engineering terms the same road design and construction cost would be applicable over the whole extent of a land facet. Land facets have the following characteristics.

1. The land facets of a land system are geomorphologically related to each other, ie the evolution of one is influenced by the evolution of surrounding facets. This means that facets always occur in the same relationship to each other: if facet 1 occurs upslope of facet 2 at one location, it cannot occur downslope of facet 2 at another. This concept forms the basis of recognition of land facets; an engineer can identify a given land facet by its position in the landscape, as well as by its shape.

2. Non related facets can occur, in most cases caused by local geological features such as an inlier or intrusion. As they are not part of the typical sequence they can not be predicted, although they can be recognised in a land system description and mapped in practice.

3. Facets are normally mappable at scales between 1:10,000 and 1:100,000.

4. The hydrological characteristics are consistent for all occurrences of the same facet within a land system.

5. Parent material can vary in the same manner as for a land system, although the total range of variation within a facet would normally be much smaller than variation of parent material within a land system. Ideally it is uniform.

6. Land facets are named after the land form that they comprise, eg 'plateau top', 'footslope', 'river terrace'. These simple names are not of course unique; many land systems have river terraces. Thus the properties that relate to a 'river terrace' land facet apply only to the occurrences of that facet within a single land system. The river terraces of another land system may have quite different properties.

7. Land facets are contiguous; there are no gaps of unclassified land between facets.

## Land element

The land element is the smallest unit of the classification. A land element is a sub-division of a land facet, although it has no specified minimum size. Land facets can contain minor features too small to be called facets in themselves, often too small to be mapped at any practicable scale, yet of significance to a project. Examples are ox-bow lakes, beach ridges, small rock outcrops, volcanic dykes.

## Extent of terrain units

All the higher land units, from land zone down to land system, are given a type name which is linked to some locality. Some land systems may extend for hundreds of kilometres but if the pattern of facets is the same the area is classified under the same name. In the original concept of the classification it was proposed that local systems separated by a considerable distance could be grouped together as an "abstract land system". In practice this idea has rarely been used.

Facets and elements are classified as numbered sub units of a land system. An individual facet, eg a river terrace, could appear in neighbouring, ie different, land systems and thus it would be possible to build up a catalogue of facet types. The ability to identify different facets is the basis of predicting terrain conditions in new areas. However little progress has been made in defining 'abstract' facets and prediction outside an existing land system still depends on the experience of the interpreter.

## Alternatives to land system mapping

Attempts have been made to classify facets using inherent characteristics. The system developed for engineering use in Australia[8] does not use local names to identify the provinces, patterns (land systems), units (facets) or components (elements). The provinces are defined as groups of patterns on a common rock type and given a code based on the features in Table 1.

Some of the codes are based on measured parameters such as drainage density and some are based on expert interpretation eg topographic class. This system has not been widely used outside Australia; the use of numeric codes, instead of local names, is difficult to understand by the occasional user. The list of units would probably need extensive revision if it were to be used in a more complex landscape. A development of this system, and its use in Papua New Guinea, has been described by Speight[9]. It is a form of the morphometric mapping described below.

**Table I** Classification features of PUCE

| Land Unit | Classification feature | No. of classes |
|---|---|---|
| Province | Rock age | 19 |
| | Reference number | Serial up to 999 |
| Pattern | Amplitude of local relief | 9 |
| | Drainage density | 9 |
| Unit | Topography | 54 |
| | Soil | 9 |
| | Vegetation | 9 |
| Component | Slope profile | 9 |
| | Slope angle | 9+9 |
| | Soil profile | 15 |
| | Land use/cover | Serial numbering |
| | Vegetation | Serial numbering |

## Geomorphological mapping

As mentioned above, the use of geomorphological classification is inherent in the use of terrain mapping units for the prediction of properties in unknown areas. Thus it is logical to consider the use of geomorphological mapping as the basis of engineering surveys directly. Where existing geomorphological maps exist they can of course be re-interpreted for engineering use. However very few geomorphological maps have been produced and so the decision is whether a geomorphological map will provide the best solution.

The purpose of a geomorphological map is to explain how the existing terrain was produced and to record its features. In engineering surveys it is usual to use a variant of geomorphological mapping called morphological mapping which concentrates on recording the shape of the ground to which the interpretation of geomorphological process can be added. Morphological mapping records changes of slope and steepness; morphographical maps identify landform units eg fan. The difference between these and morphochronological or morphogenetic maps is illustrated in the Geological Society report[1]. Geomorphological mapping has been usually associated with projects where slope stability is a major feature. It has also been used for detailed studies where geomorphological evolution has a direct influence on the problem being studied eg gravel resources in glacial areas.

## Parametric classification

Morphological mapping, where the extent of one particular feature is recorded, is one form of parametric classification. This is the opposite approach to land pattern analysis, which identifies a large feature in the landscape and subdivides it. The land pattern method of classification has caused dissatisfaction with some users with its physiographic bias, qualitative framework and use of subjective analysis. The alternative landscape analyses proposed to reduce the effect of such biases have not been widely adopted. The parametric approach aims to devise a classification from quantifiable elements of the terrain.

The first problem in setting up a classification of this type is to choose the attributes to be mapped and to define the limits of the various classes. The intended use of the evaluation should determine these choices but practical considerations of data gathering may also influence the decisions.

The effort required to establish such a mapping system was described by Benn & Grabau[10]. To develop an Airfield Construction Effort (ACE) model an equation was set up relating construction effort to five variables: volume of grading; difficulty of grading; rock volume; difficulty of providing drainage; clearing of vegetation. For each of these variables one or more equations were developed, based on field work, relating them to an appropriate parameter such as slope or soil type. The subdivision into classes is based on an analysis of these equations to produce break points that are significant to the overall model.

The effort required for such a system means that it has not been adopted for civilian engineering, particularly as such systems are designed to be application specific. However the increasing availability of data in computer format, including satellite derived data, together with the increasing use of Geographic Information Systems (GIS), means that parametric classifications will become of increasing importance.

## MAPPING SYSTEMS

The second stage of terrain evaluation is to identify the different mapping units on the ground. The scale and the extent of the mapping will be determined by the intended use ie the evaluation stage. National surveys of land systems or regions are typically at scales between 1:1M and 1:250,000. Many countries have prepared national or regional maps of this type, usually for planning development, and the extent of this coverage for Africa is shown in Fig 1. More detailed project surveys at the facet or element level use scales of the order of 1:10,000. The objective of any mapping exercise is to identify all features of interest to the user and to describe them. The techniques outlined below are described in more detail in the Terrain Evaluation Manual.[11]

The main source of information for terrain evaluation mapping has always been the stereoscopic aerial photograph. The scale is chosen according to the level of detail required, usually being between 1:5,000 and 1:40,000. Colour photography is not essential but is being used more now that the price differential is not so large. The stereoscopic image is essential when defining the facets and elements of the system.

Air photo mosaics or uncontrolled print lay-downs were very useful when identifying landscape patterns. The pattern could then be examined and defined on the corresponding stereo pairs. Landsat satellite imagery has been available for over twenty years now and has been used to extend existing mapping into neighbouring areas and also has provided the basis of preliminary terrain analyses. The earlier MSS imagery was of moderate resolution but seven band TM imagery with a resolution of 30 metres is available for most areas now. The highest resolution imagery generally available at present is the panchromatic SPOT imagery with a ground resolution of 10-13 metres. In addition to the panchromatic imagery SPOT data can be collected at a lower resolution (20-27m) in three bands. Both are potentially available as stereoscopic images as the camera can be tilted to the side to record the same area from different angles on different days.

`Land system mapping in Africa`

Few comparisons have been made of the advantages of different types of imagery for terrain analysis. A recent study of a humid tropical region[12] concluded that SPOT stereoscopic imagery could be used to map land systems with 90 per cent accuracy. However this could mean that a small significant unit could be completely missed. The area studied was covered by heavy vegetation and the high humidity meant that it was difficult to obtain stereo cover; because of haze the best images were from the infra red band.

This study also assessed the accuracy of identification of sub units. Because of the problems mentioned above the accuracy in this case was not high enough for mapping although it was recommended that the imagery should be used as a high quality base to record the results of air photo interpretation. Higher resolution imagery is required for this level of mapping.

Until quite recently it seemed unlikely that higher resolution satellite imagery would become available on the civilian market. This has now changed with the release of digitised satellite photography from the CIS and the announcement of new high resolution commercial satellites. The Russian imagery comes from a variety of sources with different resolution and scale. Images digitised to two metre resolution are available now and it is possible that one metre resolution will be released soon. Quality and delivery have been problems in the past but the situation is improving. A panchromatic image of an area 21 km square would cost $4000. Some stereoscopic imagery is available.

Commercial imagery is also due to improve beyond the existing panchromatic SPOT limit of 10 metres. SPOT 4, due in 1997, is planned to have 5 metre resolution imagery and the

American government has licensed three companies to launch satellites with up to one metre resolution. One company plans to launch a satellite next year with a 2048 pixel array focused to give a three metre pixel. The suggested cost of an image is £300-400. The Lockheed company plans to launch a satellite with one metre resolution within three years. Plans for these satellites also allow for stereoscopic viewing and so the potential for terrain mapping, in areas where air photography has been difficult to obtain, is due to be greatly extended.

## EVALUATION

The classification and mapping stages are only means to the end of collecting the required data so that an evaluation can be prepared. The choice of classification, and the data collected, must be influenced by the eventual way it will be used. For this purpose it must be decided at an early stage whether the exercise is only intended to satisfy an immediate goal or whether the information gathered will be used at later stages of the development or will be used for other purposes as well.

The data that are collected fall into two broad categories

1) Descriptive
2) Measurements

All field surveys contain some descriptive information. The classic case is the driller's log which contains some factual information, such as depth, but mainly consists of text. Many data base systems hold this information as a copy of the field sheet.

Wherever possible it is preferable to standardise field surveys by preparing proformas where the required information is entered as a class. This makes entry into a database easier but has the added advantages of helping the field surveyor consider the range that exists for each factor and also reminds him to collect the complete set. However not all data sets can be treated in this way and most field survey sheets contain a section for Remarks, recognising that it is not possible to design the ideal form that can record every piece of significant information.

The second type of information recorded is the physical measurements. This includes measurements made in the field, such as thickness of soil or slope of the ground and also the results of tests on samples taken from a known position in the terrain. The variability of data has been mentioned previously; this takes two forms. Experimental error is the difference observed between repeated tests on the same sample. It also includes variation in results that does occur between different laboratories (these can be surprisingly large for some tests). In addition to this is the variation in test results that occurs in samples from nominally the same material.

The variability of a material is a property which can, and should be, recorded. Another property of the data that should also be recorded is its validity. There are two aspects to this: the reliability of the measurement, which is a function of the way it has been made; the level of verification or checking of the data which has been recorded.

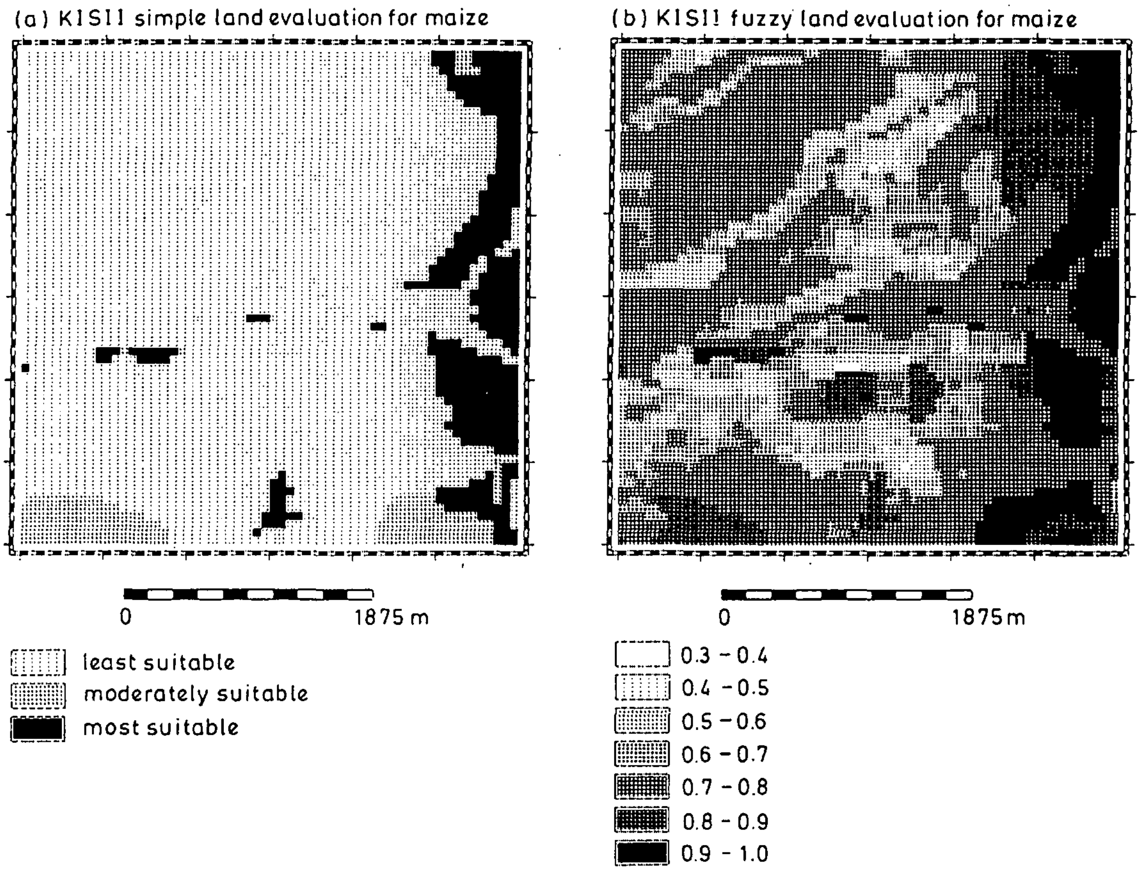
Information entered into a data base has an apparent authenticity which may not be fully justified. A record of slope angle may be based on an instrumented survey, a field estimate (possibly into a limited range of classes), an interpretation from contoured maps or an estimate from stereoscopic air photographs. Unless some indication of the origin of the data is recorded, subsequent analyses can only take it at face value.

A second aspect of the validity of data is the level to which it has, or can be, verified. Data which you have collected and recorded yourself (and checked!) is of the highest value. Data from other sources is of varying quality, depending on the amount of checking (QA) that has taken place. Where assistants are involved in collecting and recording data a procedure needs to be devised with cross checks to identify inconsistencies. When the information has been checked it should be flagged.

Having prepared reliable data the next problem is how store it in a way such that it can be manipulated and transferred to other users. The basic structure for computer storage of data is the table; this is similar in spreadsheets, databases or GIS (which normally use standard databases to hold such information). The transfer between computer packages is becoming fairly routine, and the main problem is now with data structure, such that the different system can recognise what the information represents. A first standard for geotechnical data has been recently published[13] and standards for maps are also being actively developed.

The concept of terrain evaluation is a natural candidate for GIS technology. From its earliest days the emphasis was on developing data storage structures that could support the requirements of the users. Card storage systems demonstrated the principles of the system but could not cope with the quantity of data generated. The rapid development of the PC and workstation means that affordable and effective systems are now available. However any new technology has its limitations which have to be recognised and allowed for in system design.

One of the commonest features of a GIS is the ability to associate an attribute ie terrain information, with an area which can be defined by a mapping boundary. The power of a GIS is its ability to overlay different data sets to identify where features coincide or meet a set of criteria and thus generate a new map. However the processes involved must be understood and the result checked in the field to prevent the production of results that do not coincide with reality.



An example of the improvements possible with the use of more advanced modelling is shown in Figure 2 showing the evaluation of an area of land for maize growing[14]. Both maps are based on the same data sets derived from soil maps and digital terrain models. From this information four data sets of land quality, such as water availability, were derived using three classes:limiting, moderately limiting and non limiting. Using simple Boolean logic to combine these data sets, Figure 2a is produced indicating that most of the area is unsuitable for maize production. Using a fuzzy set method of analysis on the same data produces a more subtle classification. It agrees with the first map on the best areas, but shows that a large part of the area falls within the 0.7-0.9 possibility of being suitable.

This example is based on standard FAO land evaluation methodology where relationships have been established between measurable terrain properties and the evaluation required. This form of modelling is also required to convert terrain data into engineering evaluation. In some cases models of this type do exist; it is possible to predict soil strength from a knowledge of physical properties (Plastic Limit) and moisture content. The prediction of soil moisture content could be obtained from other models so in theory it would be possible to model soil strength. This approach was started by the military[10] but will need a great deal of effort if this technique is to become of widespread use in civil engineering.

## FUTURE ISSUES

Terrain evaluation can be said to have grown with the development of geological mapping and one of the basic dicta of geologists is that the past is the key to the present. This paper summarises the development of terrain evaluation and its application to present engineering practice. This Symposium contains many papers describing the use of terrain evaluation for many different purposes. One of the tasks before us is to identify common ground and the areas of potential development.

There are two broad areas where terrain evaluation has been used. The first was for the prediction of the properties of ground in unknown regions. Interpretation of stereoscopic air photography is the basis of all well established surveys and the land system method of classification is the most widely method of organising them. It has been used for many different types of evaluation, but mapping produced for one survey can be re-evaluated for a different end user.

The alternative approach to terrain evaluation has been the organisation of detailed survey data to produce an assessment of the ground in engineering terms. There is a wide variety of systems of this type ranging from traditional ground investigation to computer based data storage systems. These systems are not normally used for preliminary surveys and many of them are not suitable for predicting conditions outside the immediate survey area.

All systems depend on some form of modelling to make the connection between recordable data and the assessment the user requires. In the first case this was based on the experience of the interpreter and one of the main thrusts of system development has been to reduce that to standard forms. With ground based systems some modelling has been developed but a great deal still requires to be done.

The development of GIS presents the opportunity to organise data and relate it spatially. However GIS will not solve the problems; it provides more effective tools to manipulate the data. An understanding of the working of such a system is required if it is to be used in the first place but the hope for the future is that it will be able to combine the advantages of both approaches. To do this within the computer will require more effort devoted to the development of the models relating user requirements to measurable factors.

## REFERENCES

1 Geological Society. Land surface evaluation for engineering practice. Q J Engng Geol 15, 265-316 1982

2 National Institute for Road Research. Technical recommendation for highways. The production of soil engineering maps and the storage of materials data, TRH2. Pretoria, CSIR, 52pp

3 Kantey, B A. Planning and design requirement from terrain evaluation for roads and railways. Proc 3rd Symposium on Terrain Evaluation and Data Storage. S African Inst of Civil Engng, pp59-64, 1975

4 Brink, A B A et al. Report of the Working Group on land classification and data storage. MEXE Report 940 Christchurch UK 1966

5 Webster R and P H T Beckett. Terrain classification and evaluation using air photography: a review of recent work at Oxford. Photogrammetria, 26, pp51-75 1970

6 Beaven P J and C J Lawrance. The application of terrain evaluation to the Trans-African Highway project. Bull Ass int perm congr Route No 372 1972

7 Lawrance C J Terrain evaluation in West Malaysia. Part 1. Transport and Road Research Laboratory Report LR 506. 1972

8 Grant K. The PUCE programme for Terrain Evaluation for Engineering Purposes. Division of Applied Geomechanics Technical Paper 15. CSIRO, Australia. 1973

9 Speight , J G. Landform pattern description from Aerial photographs. Photogrammetria 32, pp161-182. 1977

10 Benn, B O and W E Grabau. Terrain evaluation as a function of user requirements. Land Evaluation ed G A Stewart. Macmillan of Australia. 1968

11 Lawrance, C J, R J Byard and P J Beaven Terrain evaluation manual. HMSO 1993

12 King R B. The value of ground resolution, spectral range and stereoscopy of satellite imagery for land system and land-use mapping of the humid tropics. Int J Remote Sensing 15, pp521-530. 1994

13 Association of Geotechnical Specialists. Electronic transfer of geotechnical data from ground investigations. 1992

14 Burrough P A Fuzzy mathematical methods for soil survey and land evaluation. J Soil Science 40, 477-492, 1989