Knowledge-Based GIS Techniques Applied to Geological Engineering

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ABSTRACT: Expert system techniques are being investigated to implement a set of rules for geological engineering map production that can handle a variety of input data sources and output classification schemes. The thesis is that a few common data sources such as bedrock geology, agricultural soils, and topography provide the essential data to generate a diverse set of geological engineering maps with a variety of classification schemes. A knowledge-based geographic information system (KBGIS) approach which requires development of a rule base for both GIS processing and for the geological engineering application has been implemented. The rule bases are implemented in the Goldworks expert system development shell interfaced to the Earth Resources Data Analysis System (ERDAS) raster-based GIS for input and output. GIS analysis procedures including recoding, intersection, and union are controlled by the rule base, and the geological engineering map product is generated by the expert system. The KBGIS has been used to generate a geological engineering map of Creve Coeur, Missouri. The computer-generated map compares favorably with a manually produced geological engineering map of the same area and indicates significant promise for KBGIS techniques.

INTRODUCTION

GEOGRAPHIC DATA BASES consisting of remotely sensed digital imagery, digital elevation models (DEMs), and digitized cartographic products can be created interactively with excellent spatial registration and resolution. Geographic information systems (GISs) currently are capable of manipulating such databases to aid in site location, environmental planning, resource management, and other types of decision-making (Tomlinson, 1987). These applications require that large multilayered, heterogeneous, spatially-indexed databases be queried about existence, location, and properties of a wide range of spatial objects (Peuquet, 1984; Smith *et al.*, 1987). While GIS software packages allow these databases to be integrated and manipulated through polygon overlay and other procedures, a comprehensive analysis from initial data entry through final map/product generation requires extensive user interaction and sequential processing steps.

One potential approach to mitigating the requirement for user interaction and sequential processing is to utilize expert knowledge in GIS processing (McKeown, 1987; Robinson and Frank, 1987; Usery *et al.*, 1988). A rule base can be implemented through an expert system inference engine to generate a knowledge-based geographic information system (KBGIS) (Smith and Pazner, 1984). Such a system can be used to solve the critical resource analysis problems of minimizing information management time and maximizing research and application time (Campbell and Roelofs, 1984). A KBGIS might be used to match cartographic representational requirements against a knowledge base concerning classification, symbol schemas, user visual responses, and domain specific knowledge to select the best and most efficient presentation of geographic phenomena (Smith, 1984; Ripple and Ulshoefer, 1987; Bossler *et al.*, 1988).

A research project has been designed to use a knowledge-based approach to solve the problem of generating geological engineering maps from basic Earth resource data. These maps, which usually show surficial and bedrock geologic patterns classified according to engineering suitability for urban development such as waste disposal and building and road construction, are currently produced by manual methods. While use of remote sensing techniques has improved the map production cycle, a system for production of geological engineering maps and tables still requires significant input and interpretation by a skilled geological engineer.

Numerous properties of Earth materials including attributes of soils, geology, hydrology, and topography are considered by a geological engineer when creating a geological engineering map (Varnes, 1974). These properties are usually acquired by field investigation. The amount of time spent in the field is directly reflected in the amount and quality of data collected. Although such information is useful, it may not be cost effective if similar results can be obtained using more basic, previously compiled information such as digitized soils and DEM data.

One objective of this research is to determine the minimum number of Earth resource data sets needed to make engineering judgments about areas in the Midwest. This objective will be accomplished in conjunction with the major project goal of creating a KBGIS that will allow manipulation of these Earth resource data sets to create a geological engineering thematic map. This paper details the preliminary system design with simulated results and the final developed system with actual results of a geologic engineering map generation process compared to a manually produced map.

APPROACH

To create a KBGIS to support engineering geologic mapping requires a thorough understanding of both the concepts of engineering geology and the map generation process. An approach was developed to analyze the basic logic a geological engineer uses in map generation and to transfer that knowledge to an expert system (Figure 1). This expert system approach is being implemented as a series of steps: (1) determine the basic Earth resource information required for production of geological engineering maps, (2) determine the common elements in classification schemes, (3) develop a set of rules for map production, (4) implement the rules in an expert system that will use

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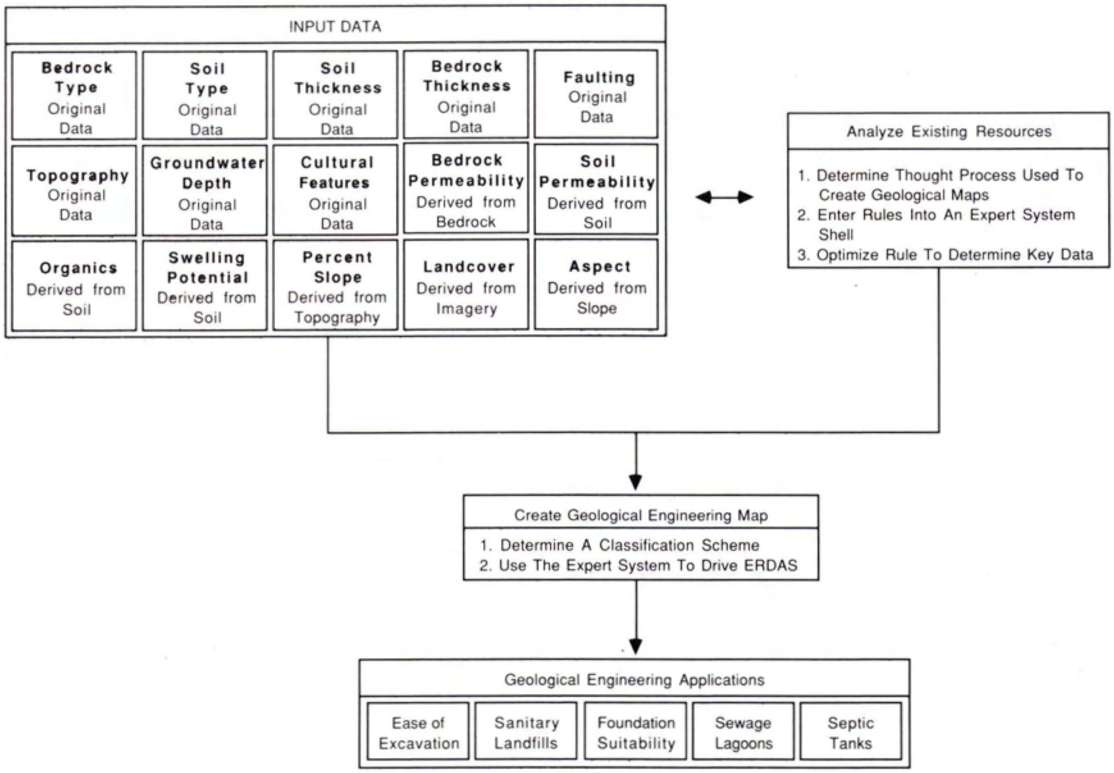

FIG. 1. The approach used to enter the basic logic of geological engineering map production.

the basic Earth resource information to generate various thematic maps, and (5) validate the function of the expert system in a prototype study area.

DEVELOPMENT OF GEOLOGICAL ENGINEERING KNOWLEDGE BASE

To assess the basic information required for the creation of geological engineering themes, the maps in Table 1 were analyzed to determine the logic used in their construction. Information obtained from the different maps and their authors was entered into an expert system shell called 1st Class (Programs-In-Motion, 1987). Data are entered into 1st Class as examples comprised of various soil and rock properties called factors from which a decision tree is built (Figure 2). This type of structure makes 1st Class effective for analyzing different map products for the basic information used in their construction because it allows analysis based on properties instead of the mapped-unit classification.

Preliminary analyses indicate that the basic parameters of agricultural soils and topographic information are sufficient to create geological engineering themes used by field mapping experts. The decision tree aspect of 1st Class minimizes the search involved by considering only those factors which are needed to produce distinct results. In Figure 3, the decision tree uses information from soil surveys, including the plasticity index, knowledge of the presence of karst, flooding potential, and topographic information, with the controlling factor being plasticity index.

Two questions must be addressed when determining a classification scheme: (1) the basic properties to be considered and (2) the potential use to be made of the geological engineering map. It is desirable to have a classification scheme that will provide a standardized system which not only will show distinction between different units of a geological engineering

Topography	Geology	Plasticity Index	Flooding	Karst	Slope		Result
Flat-marsh	?	20	Frequent or Occasional	No	2		Ia
Low-relief	LS-DO	10	Frequent or Occasional	No	2		Ib
Low-relief	LS-DO	15	Rarely or Never	No	2		Ic
Low-relief	LS-DO	20	Rarely or Never	No	4		Id
Low-relief	LS-DO	27	Rarely or Never	No	2		Ie
Rugged	LS-DO	10	Rarely or Never	No	20		IIa
Rolling	LS-DO	40	Rarely or Never	No	9		IIb
Karst	LS-DO	20	Rarely or Never	Yes	25		IIc
Rugged	LS-DO	20	Rarely or Never	No	40		IId
Roll-rugged	LS-DO	18	Rarely or Never	No	20		IIIa
Roll-rugged	LS-DO	22	Rarely or Never	No	20	. . .	IIIb
Roll-rugged	LS-DO	20	Rarely or Never	No	20		IIIc
Rolling	LS-DO	40	Rarely or Never	Yes	9		IVa
Rugged	LS-DO	25	Rarely or Never	Yes	30		IVb
Rugged	LS-DO	24	Rarely or Never	Yes	30		IVc
Rugged	LS-DO	15	Rarely or Never	No	20		V
Roll-rugged	SH-SS-LS-ST	23	Rarely or Never	No	20		VI
Rugged	SS	12	Rarely or Never	No	30		VIII
Roll-rugged	SH	10	Rarely or Never	No	20		Xa
Gentl-Roll	SH	40	Rarely or Never	No	9		Xb
Low-relief	SH	54	Rarely or Never	No	5		Xc

LS=limestone, DO=dolomite, SH=shale, SS=sandstone, ST=siltstone

FIG. 2. Factors affecting engineering geology are entered as examples in the expert system shell 1st Class. Only 6 of 30 factors are shown.

TABLE 1. GEOLOGICAL ENGINEERING MAPS EXAMINED.

Map	Source
Engineering Geology of the Creve Coeur Quadrangle, Missouri	Rockaway and Lutzen, 1970
Map of Hillside Materials and Their Engineering Character of San Mateo County, California	Wentworth *et al.*, 1985
Engineering Geology of the Northeast Corridor, Washington, D.C., to Boston, Massachusetts	USGS, 1967
Engineering Geology of the Maxville Quadrangle, Jefferson and St. Louis Counties, Missouri	Lutzen, 1968
Engineering Geology of the St. Louis County Quadrangle, Missouri	Lutzen and Rockaway, 1971

```
- - - start of rule - - -
PI??
├ <19.00:PI??
│   ├ <12.50:Flood??
│   │   ├ Frequent or Occasional:―――――――――― Ib
│   │   └ Rarely or Never:――――――――――――――― Ic
│   └ ≥12.50:PI??
│       ├ <16.50:Slope??
│       │   ├ <20.00:――――――――――――――――――― V
│       │   └ ≥20.00:――――――――――――――――――― IIa
│       └ ≥16.50:――――――――――――――――――――――― III
└ ≥19.00:PI??
    ├ <22.50:Slope??
    │   ├ <3.50:―――――――――――――――――――――――― Ia
    │   └ ≥3.50:Karst??
    │       ├ Yes:―――――――――――――――――――――― VIb
    │       └ No:――――――――――――――――――――――― Id
    └ ≥22.50:PI??
        ├ <32.50:Karst??
        │   ├ Yes:―――――――――――――――――――――― VIa
        │   └ No:――――――――――――――――――――――― VIb
        └ ≥32.50:PI??
            ├ <48.00:――――――――――――――――――― IVa
            └ ≥48.00:――――――――――――――――――― IIb
- - - end of rule - -
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FIG. 3. A part of the decision tree created from the factors in Figure 2.

```
IF Flooding is Frequent or Occasional and
   Slope is <5% and
   Plasticity Index is 10 to 20 and
   Karst is No
THEN Class is Ia

IF Flooding is Frequent or Occasional and
   Slope is <5% and
   Plasticity Index is <10 and
   Karst is No
THEN Class is Ib

IF Flooding is Rarely or Never and
   Slope is <5% and
   Plasticity Index is 10 to 20 and
   Karst is No
THEN Class is Id

        .
        .
        .

IF Plasticity Index is > 40
THEN Class is Xc
```

FIG. 4. An example of the if-then rules used in the final system design of the KBGIS.

map but also will produce a map accepted and utilized by the geological engineering community. However, it is difficult to devise a single scheme that will suffice for all conditions.

The most favorable approach is to determine a consistent format using the basic Earth resource information that can accommodate several different regions. Consistency is a problem because numerous geological engineering maps cannot be related because the classification schemes vary with respect to the types of factors considered and to the ranges used to define the factors.

To form a basis for classification, several schemes were reviewed and critiqued. Most include bedrock geology and topography information as important factors. However, the factors deviate at that point, with some considering alluvial soils and others considering faults and fractures. In all cases, the products were the result of a combination of factors, and the scheme used by Lutzen and Rockaway (1971) forms a basic structure for a general classification in the Midwest.

The second question to be addressed is the type of geological engineering map to be created. Should the final product be just the factors needed to create a unique entity, or should it make judgments on how the units will function under various conditions? The answer depends on who will use the information. The product is intended for geological engineers to obtain reconnaissance-level information on the geological engineering conditions in an area. The logic used by Lutzen and Rockaway provides an excellent method to meet the needs of the geological engineering community. The classification scheme determines unique entities with respect to their geological engineering contribution, and the entities are evaluated, in a table format, on how they will perform under different site-utilization situations.

Once the basic information was determined and a classification scheme devised, the production rules were entered into an expert system shell. The decision tree results produced in 1st Class were converted to if-then structured rules (Figure 4). The rules from the decision tree were expanded to incorporate the terminology anticipated in the digitized information.

KBGIS DESIGN AND IMPLEMENTATION

In the initial development a rule base was implemented in LISP for producing geological engineering maps (Usery *et al.*, 1988). All GIS processing was performed using the Earth Resources Data Analysis System (ERDAS), a raster-based GIS and image processing system (ERDAS, 1987). The commands to drive ERDAS were generated by the LISP application program from the rule base and the specific pixel values in the Earth resource data files. Using the experience garnered from this initial implementation, a second approach was developed in which a rule base for the geological engineering application and a rule base for GIS processing were implemented in a KBGIS.The KBGIS is frame-based with an inference engine and direct interface to the LISP language as provided by the Goldworks expert system development shell (Figure 5) (Gold Hill, 1987).

In the KBGIS, a frame is used to represent a group of entities with attendant facts. The set of facts or attributes are called the slots of a frame. The actual occurrence of a frame is called an instance. For example, a frame called **Pixel** contains slots for each type of GIS file used in the geological engineering application (Figure 6). An instance of **Pixel** is an actual occurrence with slot values filled.

A rule is knowledge that is used to deduct new facts from existing facts. A fact is referred to as passive knowledge, whereas a rule is referred to as active knowledge. Both fact bases and rule bases are important parts of a knowledge-based system. The mechanism that uses rules and facts to derive new facts is called an inference engine.

In the final system design, ERDAS is used to prepare the Earth resource data files needed to create the geological engineering map. Within ERDAS GIS files, each pixel contains a numeric value between 0 and 255. The expert system uses conceptual values rather than numeric pixel representations.

Conceptual values are actual symbolic language values such as low, medium, and high for slope. The KBGIS uses conceptual values to relate actual GIS overlay pixel numbers to the knowledge base generated from the rule and fact bases. The GIS files, along with a set of rules and a mapping of pixel values to conceptual values, are used by the KBGIS to produce the map. ERDAS is used to display the final map and perform other GIS processing.

Currently, the only GIS operations implemented in the KBGIS are those needed to produce a geological engineering map which are the ERDAS recode and matrix functions. A recode operation in a traditional GIS essentially reassigns classification values to new zones. For example, slope may be represented in 5 percent increments from 0 to 100 percent in a GIS overlay by numbers from 1 to 20. A recoding of the slopes to a total of three classes, 1 for numbers 0 to 5, 2 for numbers 6 to 12, and 3 for numbers 13 to 20, can be performed if the analysis requires values of only low, medium, and high.

In contrast to traditional GIS, the KBGIS recode operation must

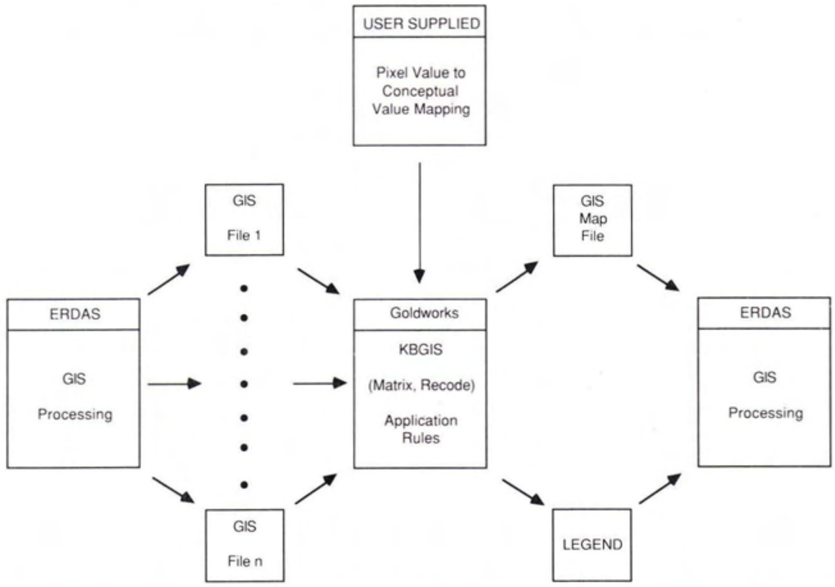
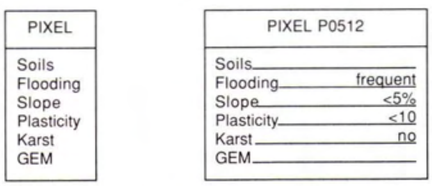


FIG. 5. The system configuration used to generate geological engineering maps from basic earth resource information.



a) A Frame b) An Instance

FIG. 6. An example of a frame and an instance of that frame used in the KBGIS. GEM represents the geological engineering map slot.

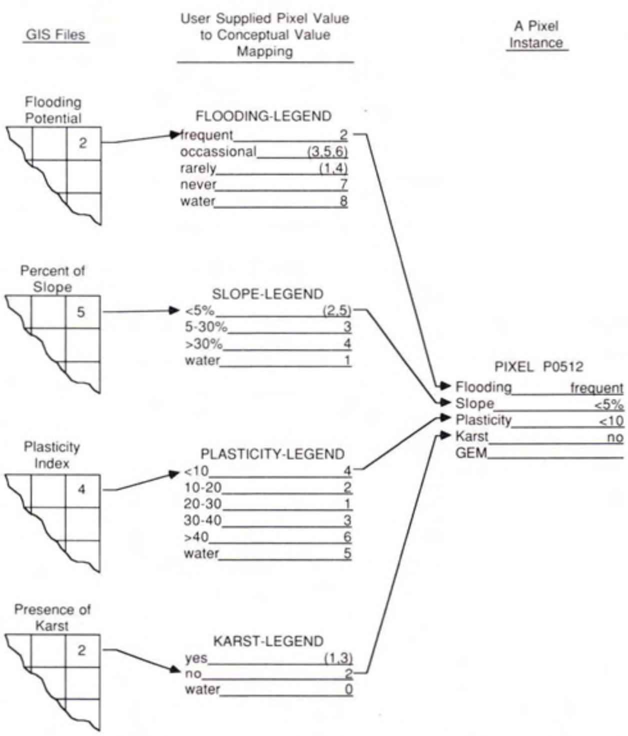


FIG. 7. Frame-based implementation of a GIS recode operation.

handle pixel value to conceptual value and conceptual value to pixel value recodes, as well as the typical pixel value to pixel value recodes. In the slope example above, pixel values 0 to 5 are recoded to conceptual value low, 6 to 12 to medium, and 13 to 20 to high. Also, in a traditional GIS, a new file must be created containing the recoded pixel values, whether it is a final product or an intermediate result. In the KBGIS, a recode only produces files that are final results.

The recode operation in the KBGIS is implemented using frames (Figure 7). A frame is defined for each type of GIS data file such as flooding. The set of conceptual values for the GIS data file are the slots of the frame. An instance of each frame is created in which the slot values are the pixel values to be recoded to the conceptual values represented by the slot names. A slot may have multiple values to allow multiple pixel values to be recoded to a single conceptual value. For GIS files used as input, the user must specify the slot values. For any created GIS file, the slot values are supplied by the system.

To recode a pixel value from a GIS file to a conceptual value, the name from the GIS file instance of the slot containing the pixel value is used. To recode a conceptual value to a pixel value, a pixel value is selected from the slot of the same name as the conceptual value. To perform a pixel value to pixel value recode involves first recoding a pixel value to a conceptual value and then recoding the conceptual value back to a pixel value.

The matrix function in a traditional GIS analyzes two overlays and produces a new overlay containing class values that are coded to indicate how the class values from the original files coincide or overlap. For example, a 4 by 3 matrix to determine intersection of soil type and vegetative cover would be formed as follows. Class values of 1, 2, and 3 for soil type are assigned to the columns of the matrix. Class values of 1, 2, 3, and 4 for vegetative cover are assigned to the rows of the matrix. Matrix positions are sequentially numbered and become the class values in the output file. Thus, a value of eight in the output file indicates a soil type of two and a vegetative cover of three. This operation allows creation of logical combinations of classes such as union, intersection, complement, or any combination. To matrix more than two files requires a complex series of matrix and recode operations to achieve a result.

In the KBGIS, a matrix operation is required that can operate on any number of files simultaneously. The implementation in the expert system requires creating a frame to represent a pixel (Figure 8). Slot names in the frame represent Earth resource data files from which pixel values will be retrieved and data files to which resultant pixel values will be written. The slot values of pixel instances will be conceptual values. These recoded values correspond to the pixel values as retrieved from the file associated with each slot name.

Rules specific to the geological engineering application are established as if-then constructs. The rules inspect conceptual values in the slots of a pixel instance and set the geological engineering map slot of the pixel instance to the appropriate conceptual value. In this manner, any number of files represented as slots in pixel instances can be matrixed simultaneously to produce a single new overlay. The matrix operation is flexible because not all slots, hence files, need to be inspected by every rule to set the geological engineering map slot value.

Both the matrix and the recode operations, which comprise the GIS processing rule base in the KBGIS, are made more powerful by using the frame data structure and if-then rule constructs. From a user viewpoint, simultaneous processing of multiple overlays and automatic generation of intermediate products greatly simplify the GIS approach to problem solving.

The current implementation of the geological engineering application allows a geological engineering map to be produced from a single overlay with multiple factors or from multiple overlays. For example, separate overlays for flooding, slope, plasticity, and karst can provide input, or a single soils overlay with four factors may be used.

To create a geological engineering map from multiple overlays, the user must specify the information relating pixel values to conceptual values for each of the overlays. Using this information, the KBGIS then recodes the pixel values from the overlays to conceptual values and places them in a pixel instance (Figure 7). The application-specific rules are used to perform the matrix operation to set the geological engineering map slot to a conceptual value for each pixel (Figure 8). The conceptual value of each geological engineering map slot of a pixel instance is recoded to create an ERDAS-format GIS file. A legend is placed in a trailer file so the user knows how to interpret the pixel values generated by the KBGIS.

To create a map from soils data which is a composite of four overlays, the user must describe each soil class (pixel value) in terms of the properties flooding, slope, plasticity, and presence of karst. The matrix operation is then performed on these pixel value descriptions to set the geological engineering map slot. In essence, the application has derived a recode of the soils pixel values to map conceptual values. The map conceptual values are then recoded to map pixel values. The resulting product is a recode of soils pixel values to map pixel values. To produce the final map, the entire soils GIS file is simply recoded and a trailer file is produced.

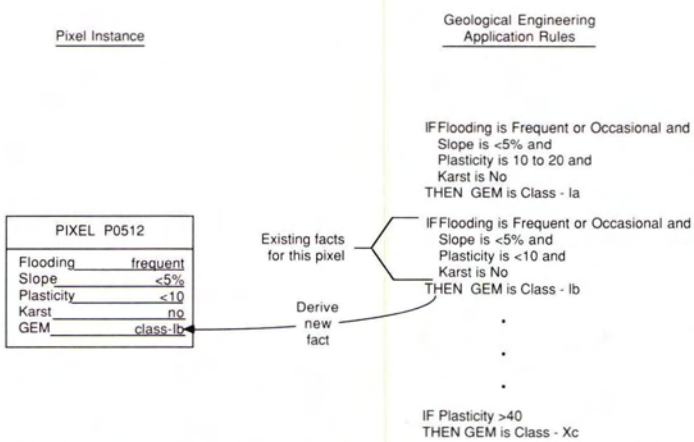


FIG. 8. Frame-based implementation of a matrix operation to set the geological engineering map slot to the correct value according to the knowledge base.

RESULTS

To test the initial implementation in LISP, a combination of actual and simulated data over an Aspen, Colorado, test site was used to numerically validate the functioning of matrix and recode operations in a LISP environment. Simulated swelling and soils data were combined with actual overlays of topography, bedrock, and permeability. Although ERDAS was used to perform all GIS processing, the sequence of commands was generated by the LISP application and placed in an audit file. ERDAS then executed the commands from the audit file to create the map. The Aspen test site and the rule base provided the first test of the basic concept and yielded a correct result which was validated by a manual tabulation procedure.

The final system design implements GIS processing within the expert system. For this implementation, a new rule base was developed consisting of two parts, a GIS processing rule base and a geological engineering applications rule base.

This implementation was tested on the Creve Coeur, Missouri, U.S. Geological Survey 7.5-minute quadrangle where actual geological engineering maps exist (Rockaway and Lutzen, 1970). Based on the geological engineering applications rule base, the minimum number of Earth resource files consists of one data set obtained from the Soil Conservation Service soil survey which provides information on four geological engineering factors: soils plasticity index, flooding potential, presence of karst, and topographic information (Anon, 1982). A geological engineering map of the Creve Coeur area was generated from the basic input data and the knowledge bases by the KBGIS. The resulting map was reformatted to an ERDAS GIS file and displayed on a graphics system.

Comparison to the actual geological engineering map that has been digitized was performed by visual techniques using side-by-side displays (Figure 9). The correlation of the computer-generated product and the manually-produced map is believed to be good, especially considering the changes in land use over the 10-year elapsed time since the manually-produced map was compiled (Table 2). Discrepancies are largely a function of the method used for determining the characteristics of each unit.

For example, considerable differentiation exists within the lowland area on the computer-generated map which affects the results of classes Ia, Ib, and Ic. The published map grouped the entire lowland area based completely on its topographic orientation without consideration for variation of engineering properties within the unit. Class Id represents the terrace deposits, or upland deposits, which on the computer-generated map combines areas on topographic divides with similar geological engineering properties. The published map considered only those upland areas adjacent to Class Ic. Classes IIa and IIf differ only in terms of their relative plasticity index. The plasticity index of the soils in the published map were averaged from any available source or location, resulting in an unrepresentative value for the unit. The computer-generated map uses values to a depth of 1 foot for its determination, resulting in a more consistent value for the unit. The published map considered only those areas with visible karst features to be included in class IIc. The computer generated map includes areas adjacent to the visible karst features to be included in class IIc. The difference in the reporting of Class IId is a result of the changing

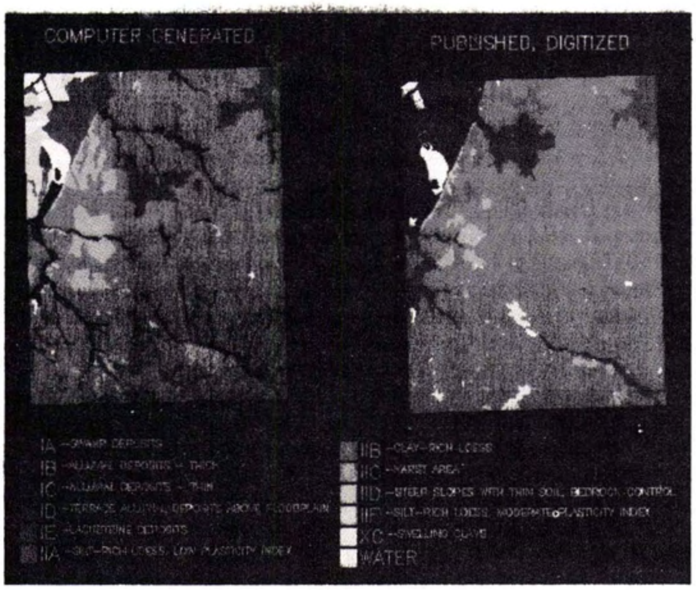


FIG. 9. Comparison of KBGIS generated geological engineering map for Creve Coeur, Missouri, to the manually produced map.

TABLE 2. COMPARISON OF COMPUTER GENERATED AND PUBLISHED GEOLOGICAL ENGINEERING MAPS OF CREVE COEUR, MISSOURI

Class	Percent of Total Area Computer Generated	Published Map
Ia, Ib, Ic	7.32	11.32
Id	10.37	2.67
Ie	3.62	2.02
IIa/IIf	2.30	1.95
IIb	67.00	76.89
IIc	5.63	2.11
IId	1.25	0.39
Xc	1.05	0.84
Water	1.47	1.79

land use and development over the 10-year period as well as a more rigid adherence to the classification rules.

CONCLUSIONS

A number of conclusions may be drawn from this work. However, because of the limited testing to date, they must be considered preliminary. It is clear that geological engineering maps can be generated through KBGIS techniques. It appears that a minimum number of Earth resource data sets and a rule base are adequate to generate a map closely resembling a manually produced product. In the case of the Creve Coeur quadrangle, the minimum number is four. Through the course of this work it has become evident that a KBGIS must consist of two knowledge bases, one for GIS processing knowledge and one for application-specific knowledge. The development of additional applications requires implementing a new applications rule base from which the KBGIS can generate a new knowledge base and a new type of product. Future work will consist of using these knowledge bases on additional test sites and expanding the GIS processing knowledge base to implement new GIS operations and applications.

REFERENCES

Anon, A., 1982. *Soil Survey of St. Louis County and St. Louis City, Missouri*, United States Department of Agriculture, Soil Conservation Service, 137 p.

Bossler, J. D., D. L. Pendleton, G. F. Swetnam, R. L. Vitalo, C. R. Schwarz, S. Alper, and H. P. Danley, 1988. Knowledge-Based Cartography: The NOS Experience, *The American Cartographer*, Vol. 15, No. 2, pp. 149–161.

Campbell, W. J., and L. H. Roelofs, 1984. Artificial Intelligence Applications for the Remote Sensing and Earth Science Community, *Proceedings, Ninth Pecora Symposium on Spatial Information Technologies for Remote Sensing Today and Tomorrow*, Sioux Falls, South Dakota.

ERDAS, Inc., 1987. *ERDAS-PC and PC Kit: Image Processing System User's Guide*, ERDAS, Inc., 430 Tenth St., N.W., Atlanta, Georgia.

Gold Hill, 1987. *Goldworks Expert System User's Guide*, Gold Hill Computers, Inc., 26 Landsdowne Street, Cambridge, Massachusetts, 282 p.

Lutzen, E. E., 1968. *Engineering Geology of the Maxville Quadrangle, Jefferson and St. Louis Counties, Missouri*, Engineering Geology Series *No. 1*, Missouri Geological Survey and Water Resources, Rolla, Missouri, 4 p.

Lutzen, E. E., and J. D. Rockaway, Jr., 1971. *Engineering Geology of St. Louis County, Missouri*, Engineering Geology Series No. 4, Missouri Geological Survey and Water Resources, Rolla, Missouri, 23 p.

McKeown, D. M. Jr., 1987. The Role of Artificial Intelligence in the Integration of Remotely Sensed Data with Geographic Information Systems, *IEEE Transactions on Geoscience and Remote Sensing*, Vol. GE-25, No. 3, pp. 330-348.

Peuquet, D. J., 1984. A Conceptual Framework and Comparison of Spatial Data Models, *Cartographica*, Vol. 21, No. 4, pp. 66–113.

Programs-In-Motion, 1987. *1st Class User's Guide*, Programs-In-Motion, Inc., 10 Sycamore Road, Wayland, Massachusetts.

Ripple, W. J., and V. S. Ulshoefer, 1987. Expert Systems and Spatial Data Models for Efficient Geographic Data Handling, *Photogrammetric Engineering and Remote Sensing*, Vol. 53, No. 10, pp. 1431–1433.

Robinson, V. B., and A. U. Frank, 1987. Expert Systems for Geographic Information Systems, *Photogrammetric Engineering and Remote Sensing*, Vol. 53, No. 10, pp. 1435–1441.

Rockaway, J. D., Jr., and E. E. Lutzen, 1970. *Engineering Geology of the Creve Coeur Quadrangle, St. Louis County, Missouri*, Engineering Geology Series No. 2, Missouri Geological Survey and Water Resources, Rolla, Missouri, 19 p.

Smith, T. R., 1984. Artificial Intelligence and its Applicability to Geographical Problem Solving, *The Professional Geographer*, Vol. 36, No. 2, pp. 147–158.

Smith, T. R., and M. Pazner, 1984. Knowledge-Based Control of Search and Learning in a Large-Scale GIS, *Proceedings, International Symposium on Spatial Data Handling*, Zurich, Switzerland, pp. 498–519.

Smith T., D. Peuquet, S. Menon, and P. Agarwal, 1987. KBGIS II: A Knowledge-Based Geographical Information System, *International Journal of Geographical Systems*, Vol. 1, No. 2, pp. 149–172.

Tomlinson, R. F., 1987. Current and Potential Uses of Geographical Information Systems. The North American Experience, *International Journal of Geographical Information Systems*, Vol. 1, No. 3, pp. 203–218.

U.S. Geological Survey, 1967. *Engineering Geology of the Northeast Corridor Washington, D.C., to Boston, Massachusetts: Bedrock Geology*, U.S. Geological Survey Miscellaneous Investigations Map, I-514-A.

Usery, E. L., R. R. P. Deister, and D. J. Barr, 1988. A Geological Engineering Application of a Knowledge-Based Geographic Information System, *Proceedings, American Congress on Surveying and Mapping/American Society for Photogrammetry and Remote Sensing, Vol. 2, Cartography*, St. Louis, Missouri, pp. 176–185.

Varnes, D. J., 1974. *The Logic of Geologic Maps with Reference to Their Interpretation and Use for Engineering Purposes*, U.S. Geological Survey Professional Paper 837, 47 p.

Wentworth, C. M., S. Ellen, V. A. Frizzell, Jr., and J. Schlocker, 1985. *Map of Hillside Materials and Description of their Engineering Character, San Mateo County, California*, U.S. Geological Survey Miscellaneous Investigations Map, I–1157–D.