Geographic Information System Application for the Geotechnical Instrumentation Program on the Central Artery/Tunnel Project

Integrating spatial analysis with geographic correlation and cartographic display is necessary in order to meet the information processing needs of a project of this size.

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The Central Artery/Tunnel (CA/T) Project entails underground construction through areas of fill, beneath bodies of water and around existing utilities infrastructure in a historic urban environment, potentially creating numerous opportunities for adverse effects on nearly two hundred buildings. These buildings range from modern 40-story office towers on mat foundations to nineteenth century residential and commercial structures founded on wooden piles. Monitoring geotechnical conditions through instrumentation is critical to protect these buildings from damage during the construction phase.

The CA/T Project's geotechnical instrumentation program consists of seven major components:

1. Designing and specifying instruments for construction contracts;
2. Installing and initializing instruments, and taking baseline readings;
3. Collecting instrumentation data during construction;
4. Making site observations of construction activities;
5. Managing instrumentation data using a

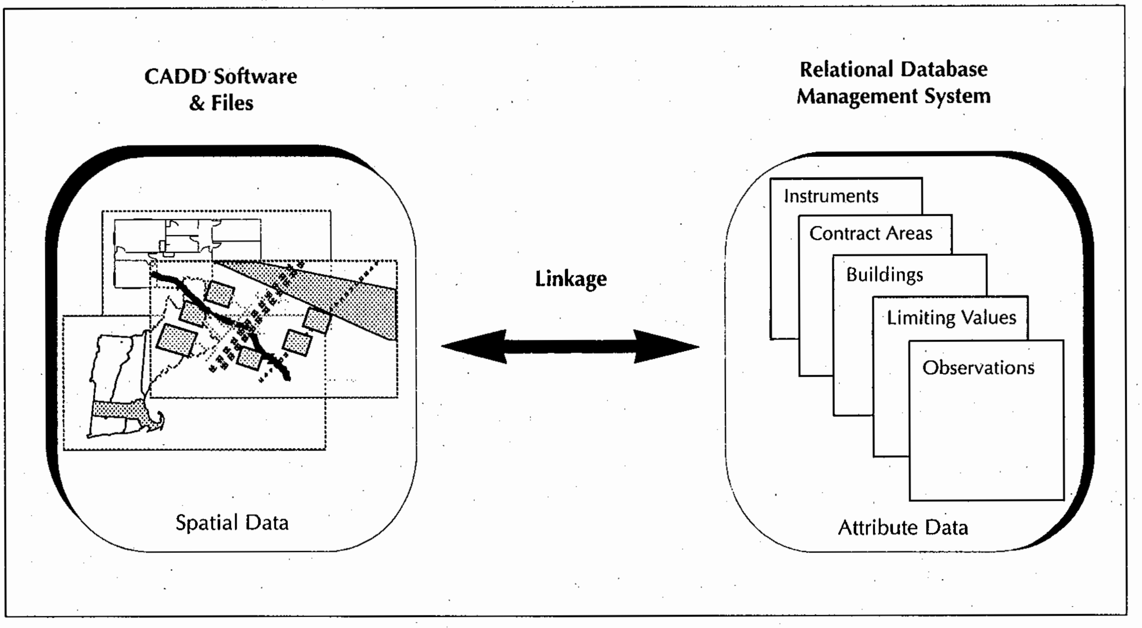

FIGURE 1. Components of a GIS.

comprehensive data storage/retrieval system;
6. Reviewing data and construction observations; and,
7. Taking appropriate mitigating action based on data analysis.

The use of information technology for design, construction and project management was recognized by the CA/T Project staff as being key to its successful completion. Management of geotechnical data from instruments at hundreds of locations was an especially important and complex task due to sensitive issues such as tunneling through varied media and construction near building foundations.

The tool created to manage and interpret the voluminous data from the project's geotechnical instrumentation program was a geographic information system (GIS) application. This application integrates field observations from instruments with its graphic data and geographic references using computer-aided drafting and design (CADD). This user-friendly system helps geotechnical engineers obtain, analyze and report on their findings in a timely manner and also provides visual aides to help them and other engineers conceptualize, understand and effectively employ the information provided.

GIS Concepts

GIS technology integrates spatial data (stored in CADD systems) with tabular data (stored in relational database systems). The integration of these two data streams makes possible the spatial analysis of events and enhances reporting these events in tabular and graphic formats.

A relational database management system consists of an organized collection of information that uses a set of computer programs to manage, retrieve, report and analyze data. These data are typically known as *attribute data* and are stored in tables. One characteristic of a relational database management system is that it tracks relationships between records in different tables. The attribute data are indexed to gain fast access, to ensure that each record in the table does not duplicate other data and to correlate information from different tables. The major advantage of a relational database is that it can impose integrity checks to ensure the accuracy and consistency of the data.

To communicate with the relational database, the Structured Query Language (SQL) is used. This international standard language was developed in the early 1970s to communicate with a variety of different types of databases from simple spreadsheets to relational databases. SQL is easy to learn because it is based upon English-like statements.

SQL is used to query, insert, update, delete and modify data. It allows users to create the database tables, store and change information in these tables as well as to maintain the database itself. It also interfaces with additional programming languages, thereby allowing the processing of many sets of records at a time.

While relational database management system technology is powerful and sufficient to store and analyze attribute data as well as generate reports, it does not incorporate spatially defined graphics such as map data. However, the attribute data contained in the relational database can be linked to files containing graphics, such as CADD files that contain the location of the various geotechnical instruments. The major components to create the GIS for the project's instrumentation program are (see Figure 1):

- A relational database management system;
- CADD software and files; and,
- Software to link the relational database management system and the CADD system.

The GIS application for the geotechnical instrumentation program consists of customized graphic user interface (GUI) software that permits the user to interact with the relational and graphics databases. This software provides geotechnical engineers with easy and efficient access to complex graphics databases so they can build customized maps without requiring extensive training in the use of CADD software. The GUI facilitates the link between the relational database and the CADD software and data. It provides a user-friendly GIS environment that allows users to map tabular data from the relational database, interactively query graphics for associated tabular data and restrict tabular data to a geographic area (defined in the CADD system). GIS technology also supports complex spatial operations such as network analysis, polygon processing and routing.

With GIS technology, geotechnical engineers are able to generate maps that color-code instruments based on information in the relational database such as the characteristics of instruments or the results of field observations.

GIS Development For the CA/T Project

During the design phase, CA/T Project staff used its integrated CADD system to support design development and produce contract drawings. Many of the CADD files acquired and developed during this phase were structured so that they could be used in a GIS without modification. These CADD files form the graphics foundation of the project's current GIS efforts.

As construction progressed, CA/T Project staff recognized a need to manage and utilize geographic information. To meet that need, the CA/T Project initiated a program to develop and implement a project-wide GIS. This program was needed to permit engineers across all disciplines to exchange and share information, access comprehensive graphic databases and express tabular data graphically.

The first step in developing the project-wide GIS was to establish a GIS framework. This framework provided a project-wide platform for maintaining and sharing geographic information, developing GIS applications and supporting spatial analysis. The GIS framework consists of the following core databases:

- An accurate survey control network allowing data to be added in terms of its location;
- Base mapping that contains detailed graphics of roads, railroads, buildings, surface utilities, barriers, topography and hydrographic features;
- Subsurface utilities inventories consisting of graphics and attribute databases; and,
- Parcel mapping linked to a master address database.

The CA/T Project has adopted a standardized approach to GIS application development. The intent of this approach is to provide the CA/T Project with the ability to re-use software, provide well-integrated and maintainable applications, and ensure that development occurs in a standardized and uniform way. The approach toward the design of the GIS applications emphasized issues regarding:

Software Modularity. The creation of software modules common to all GIS applications is a major goal in the development process. It enables the programmers to re-use software code in the development of several products. It also significantly shortens the learning curve and the time required to develop additional applications.

Standardized Software Development & Support. Any applications developed must be easy to maintain, debug or modify. Software application tools are used to minimize programming efforts. All GIS applications are developed according to in-house standards and procedures.

Data Maintenance. Each organizational unit is responsible for maintaining its own application's specific data sets, while the GIS team is responsible for maintaining the data sets that form the core of the GIS.

Data Access. Data access is critical to enable the sharing of data among organizational units. Each application is designed to hide the complexity of the data structures and provide easy access to the spatial and attribute databases.

GUI. A consistent 'look-and-feel' of the software modules is emphasized. The GUI supports interactive ad-hoc queries and generates customized output from the results.

Database Design & Linkage Mechanism. Each database must be well integrated with existing databases to preserve the data integrity and referential integrity necessary to enable the data to be shared. Since most applications use a physical address as a spatial reference, the master address database is the most critical component in linking tabular and graphic databases. The data structure of the CADD files must support overlay functionality and attribute linkage without conversion.

Staff working on developing the geotechnical instrumentation program recognized at an early stage that GIS technology would add a critical dimension in analyzing data. The development approach to this GIS application consisted of creating an initial prototype, defining user requirements, designing a database, creating customized user interfaces, documenting the process and training the staff. For the CA/T Project's geotechnical instrumentation program, the GIS application provides a tool to:

- Enhance geotechnical information management and analysis;
- Track the spatial locations of instruments;
- Geographically relate geotechnical instrument observations and construction activities;
- Store, cross reference and manage large volumes of data; and,
- Expedite the reporting of geotechnical information in both tabular and graphic formats.

The CADD software resides on a mixed mini-computer cluster with over 65 workstations and the relational database resides on a mini-computer server. The mini-computer cluster, database server and personal computers are connected via a common Ethernet network. The GIS data resides on servers located at the project Management Consultant's headquarters at South Station in Downtown Boston and is accessible via a wide area network (WAN) to computers at other facilities downtown, East Boston and South Boston. Almost a thousand personal computers are linked into this network. GIS applications can be accessed from either a server workstation or personal computer running X-Terminal emulation. The database can be accessed through screens that run on both a server workstation and on a MS-DOS-based personal computer.

Database Design Process

The geotechnical and instrumentation data to be managed by the GIS are generated by the CA/T Project staff, contractors, and the project survey sub-consultant. Originally, these data were recorded in various databases and spreadsheets and made use of an independent CADD package to produce instrument location plans. This approach has necessitated time-consuming data transfers from one system to another. The geotechnical staff recognized these inefficiencies at an early stage and looked at GIS technology as the means to create one comprehensive database with graphics capabilities.

The database design phase was an interactive process. Project geotechnical staff and the GIS team worked together to address the existing database limitations. The design process required a user needs analysis to meet the relational database and the graphics requirements. This needs analysis also served as a forum for the geotechnical staff to familiarize itself with GIS concepts at the same time as the GIS team developed an understanding of the characteristics of the various instruments, the data collection process, different types of data collected, reporting requirements and the formulas to calculate and analyze the results.

The needs analysis identified a number of the user requirements including:

- Controlled database access, limiting access to general users to verified/released information only, while authorized users would be given the privilege to insert, update and delete data;
- The ability to correlate data from different instruments geographically;
- Multi-user environment, allowing authorized users to simultaneously enter data and generate reports from different locations;
- Ease of use and user-friendliness;
- Maintenance of data integrity through database validation rules such as imposing range values, lookup tables and elimination of duplicate records;
- Data protection to minimize accidental deletions, and a mechanism to restore data;
- Flexibility for making ad-hoc database queries based on varied criteria;
- Flexibility in making reports, both in graphic and tabular format, based on geographic area and instrument type; and,
- Fast downloading and validation of field data and subsequent report generation, since contracts have a 24-hour turnaround requirement for these activities.

Another important design factor was that the database must be flexible enough to accommodate new types of geotechnical instruments. Initially, about 15 different instrument types were in use; however, data from almost 30 different instrument types have been incorporated in the database to date. To meet the data recording requirements of different instruments and keep the flexibility to add new instrument types, the GIS team developed a database design concept that classifies the instruments into one of four categories:

Single-Observation Instruments. For instruments that generate only one observation at a given time. This category includes instruments such as Borros points, observation wells, open standpipe piezometers and utility monitoring points.

Two-Observation Instruments. For instruments that generate two different types of observations at a given time. This category includes instruments such as vibrating wire load cells, vibrating wire piezometers, vibrating wire strain gages, tiltmeters, inclinometers and several types of deformation monitoring points.

Three- or Multi-Observation Instruments. For instruments that generate three or more observations of the same type at a given time. This category includes instruments such as multi-point heave gages and probe extensometers.

Complex Observation Instruments. For instruments that generate various types of observations over a period of time requiring complex database analysis. This category includes several types of deformation monitoring points.

Based on the user requirements, the application's design was approached from five perspectives:

- Human interface for data entry;
- Data management;
- Spatial analysis;
- Reporting; and,
- Program management.

The GIS application for the instrumentation program started with a prototype to demonstrate that the program's needs could be ad-

TABLE 1.
Entities Defined for the Entity-Relationship Diagram

Entity Group	Description
Instruments	Characteristics of instruments such as type, location, strata, contractor, baseline reading, threshold and limiting values need to be recorded only once when an instrument is installed and brought on-line. These kinds of data belong to a group of entities known as the initialization entities.
Observations	Containing data generated by the various instruments, consisting of four entities: Single-observation instruments Two-observation instruments Three- or multi-observation instruments Complex observation instruments
Buildings	Containing building characteristics such as foundation type, access requirements, ownership and address.
Calculation Factors	Containing the formulas for each instrument type and units of measurement used for the report generation.
Observation Types	Containing a listing of observation types and their units of measurement generated on an instrument basis.
Addresses	Address-related data and links to parcel graphics.
Contractors	Contractor information such contact names, contract number and contract area.
Graphics	Mapped location of each instrument.

dressed using GIS technology. The prototype not only confirmed this, but also allowed the GIS team to identify potential problems prior to final design and implementation.

Database Entities

The user needs analysis formed the basis for defining the database entities and attributes, and their relationships with each other. Entities are self-contained groups of information critical to the user. Attributes keep information about an entity. For the GIS team, it was critical that all entity relationships were defined to meet the current and future instrumentation requirements. If relationships were not recognized, the correlation and analysis of data could not be accomplished. The description and relationship between entities were presented in a diagram called an *entity-relationship diagram.*

The entity-relationship diagram includes the identification of links from the relational database to the graphics files as well as other databases available on the CA/T Project. Based on the entity-relationship diagram, the database was designed to store data generic to all instruments in the same table, while data specific to individual instrument types is stored in specific tables. Entities defined for the geotechnical instrumentation program are listed in Table 1.

Data Entry Screens

Part of the design effort included developing screens the geotechnical staff could use for entering, viewing and editing data. Even though the database structure was complex, the screens were designed to hide the database structure from the users. During the data entry process, software associated with each screen was designed to evaluate and restrict the entered data. A thorough understanding of the data types and the data validation process was critical in building screens that ensure data integrity. Furthermore, user interaction and workflow considerations were incorporated into the forms to minimize mistakes and optimize data entry efficiency.

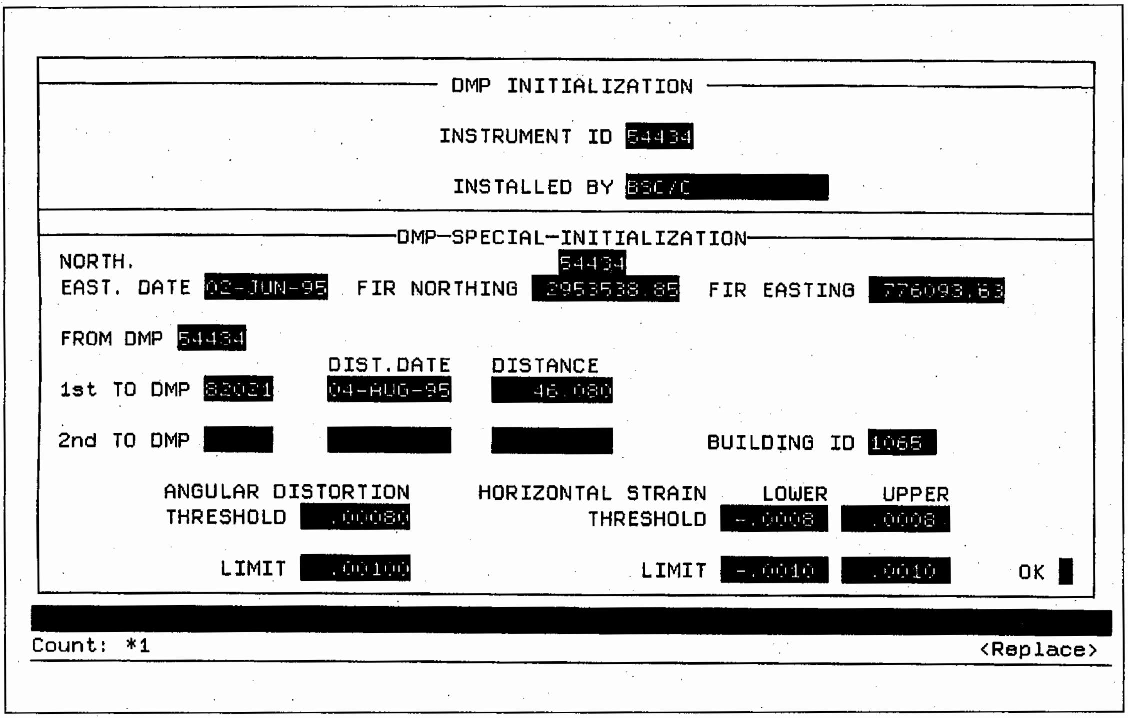

FIGURE 2. A sample data entry screen.

The geotechnical staff and GIS team decided to store all raw field data in the database and use the database as a tool to calculate and analyze data. The screens were designed to prompt the user for raw field data, as opposed to calculated or "reduced" readings. This approach provided several advantages. It eliminated tedious data manipulations and calculations — such as applying calibration factors, unit conversions and trigonometric functions — to reduce data. It also made it possible to validate and report on the vast amount of data collected in a 24-hour delivery time period (as required by certain contracts). Furthermore, the risk of human error was minimized since the user would be familiar with raw data formats and magnitudes, making erroneous readings easy to spot and double check. Overall, the chance for human error in calculations was minimized and the workload of the user was decreased, thereby making the data entry process much quicker.

The many instruments and different observation types required the creation of over 40 screens, with each screen enforcing different data integrity rules based on the instrument type and associated observations. However, it would be onerous for the geotechnical staff to recall over 40 screen names. For that reason the GIS team developed two master screens: instrument initialization and field observations. For each master screen, the geotechnical engineer enters the instrument identifier. The master screen was designed to navigate the user to the appropriate data entry screen based on which instrument identifier was chosen. For instance, some instruments require one limiting value while others require two. The screens were designed to take control and skip fields that are not required for a particular instrument type.

The master screens fulfill several functions:

Database Entry. This mode is used for instrument initialization, entering observations, executing reports and updating functions. The screen was designed to verify that the instrument exists in the initialization tables before the user would be allowed to enter observations. Figure 2 shows a sample data entry screen.

Database Queries. The user can specify restrictions such as instrument type, contract area or date. By entering restrictions into the query mode of the screen, the database retrieves only those instruments that satisfy the query. This aspect of the screens made viewing a large data set manageable.

Running Reports. The master screen was designed to include a subset that allows users to run reports or create simple plots of the instrument's observations. The GIS interface in the CADD system permits creating more detailed plots.

Database Quality Control

To ensure data integrity, the GIS system relies on triggers during data entry. A trigger is a piece of software that validates the data as it is entered into its field and alerts the user to possible data entry mistakes. The triggers on numeric fields typically perform some calculation after looking up the calibration factors associated with the record being entered. This calculated value is then stored in an appropriate field in the database. Triggers are also used to ensure that a raw reading falls within a prescribed range. For example, the GIS system will not allow the user to enter spatial coordinate values that fall outside of the region of the CA/T Project.

Triggers on non-numeric fields are used for a great variety of tasks. One commonly invoked trigger was designed to ensure that instruments and/or contractors are never associated with the wrong contract area as defined by the user elsewhere in the database. Triggers also check all dates to assure, for example, that an installation date precedes all reading dates, but fall between the contract start date and the present date. Spelling of acronyms as well as proper nouns is also checked. Other triggers navigate the user through the screen, giving the user access only to the fields and subsequent screens that are appropriate to the data initially entered. Triggers are also used to generate a list of allowable values for a field in case the user would rather work from a list.

Triggers are not only used for data entry and automatic input-sensitive navigation through the forms, but also to assist in the querying of records, or in filling out screens to generate reports. For example, users can specify instrument types, date ranges and contracts. Based on these criteria, the software will then generate a screen with a listing of instruments, reading dates and contracts from which the user select the appropriate date and contract to create the report.

Standard Report Generation

Reporting is one of the most frequently used functions of the GIS system. The geotechnical staff specified in detail the required calculations and exact formats for the reports. Data are typically entered, checked and reported in response to a 24-hour turnaround time required by contractual specifications between the CA/T Project and its contractors. The reporting process was streamlined to reduce the time-consuming data calculation and report formatting processes. Using the master screens, users access interactive reporting capabilities for over 60 types of reports serving almost 30 types of instruments. All reports automatically generate a legend, notes and highlight the instruments that exceed the threshold or limiting values.

The master screen prompts the user for various input parameters that the system will use to generate a report with the desired selection criteria. Based on the user's selection, the system displays the appropriate report form. The database executes the report, performs the necessary calculations on the raw data retrieved from the database, and displays the report in a matter of seconds. The report preview appears on the screen and the user can scroll through it in the same manner as navigating through a text file. After reviewing the report content on the computer screen, the user exits with a single keystroke and is prompted for the option of printing, saving to a file or discarding the report. A sample report format for deformation monitoring points is shown in Figure 3.

Instrumentation-Specific CADD Files

A unique symbol was designed for each instrument type and added to the CADD symbol library. This library can be accessed to add new instruments to the CADD mapping files. Each instrument symbol is encoded with the instrument type and a unique identifier that corresponds to the identifier stored in the relational

Central Artery/Tunnel Project
Bechtel/Parsons Brinckerhoff
Date: 15-NOV-95 02:11:25

Generated By: DMPDIST.SQL

BUILDING DEFORMATION MONITORING
DISTANCE REPORT

Contract Area: C11A1
Contract Name: I-93 NORTHBOUND TUNNEL - ATLANTIC AVENUE
Company: PERINI/KIEWIT/CASHMAN (JV)
Calc'd By:
Checked By:

B/PB ID	B/PB ID	DATE (5)	Distance (ft.) (5)		CHANGE FROM FIR (ft.) (5)	DATE (6)	Distance (ft.) (6)		CHANGE FROM FIR (ft.) (6)	DATE (7)	Distance (ft.) (7)		CHANGE FROM FIR (ft.) (7)	REMARKS
11A1-DMP2-51856	11A1-DMP2-82038	09/20/95	36.591	U	0.002	10/02/95	36.603	U	0.014	11/03/95	36.590	U	0.001	MEAS. AROUND CURVE OF BLDG.
11A1-DMP2-54402	11A1-DMP2-54403	--------	---------		---------	09/20/95	74.914	U	-0.005	11/03/95	74.923	U	0.004	
11A1-DMP2-54403	11A1-DMP2-54404	09/20/95	25.704	U	-0.002	09/27/95	25.709		0.003	11/03/95	25.703	U	-0.003	
11A1-DMP2-54405	11A1-DMP2-54406	09/20/95	25.717	U	-0.002	09/27/95	25.758		0.039	11/03/95	25.717	U	-0.002	
11A1-DMP2-54407	11A1-DMP2-54408	09/20/95	25.727	U	-0.002	09/27/95	25.737		0.008	11/03/95	25.726	U	-0.003	
11A1-DMP2-54409	11A1-DMP2-82010	09/20/95	38.575	U	-0.009	09/27/95	38.579		-0.005	11/03/95	38.500	U	-0.004	
11A1-DMP2-54410	11A1-DMP2-54458	09/20/95	41.347	U	-0.008	09/27/95	41.349		-0.006	11/03/95	41.352	U	-0.003	
11A1-DMP2-54411	11A1-DMP2-54412	--------	---------		---------	--------	---------		---------	11/03/95	46.262	U	---------	
11A1-DMP2-54413	11A1-DMP2-54414	09/20/95	44.333	U	-0.010	09/27/95	44.344		0.001	11/03/95	44.338	U	-0.005	
11A1-DMP2-54414	11A1-DMP2-54415	09/20/95	45.086	U	-0.006	09/27/95	45.096		0.004	11/03/95	45.087	U	-0.005	
11A1-DMP2-54416	11A1-DMP2-54417	09/20/95	29.952	U	-0.002	09/27/95	29.943		-0.011	11/03/95	29.952	U	-0.002	
11A1-DMP2-54417	11A1-DMP2-54418	09/20/95	44.934	U	-0.008	09/27/95	44.921		-0.021	11/03/95	44.938	U	-0.004	
11A1-DMP2-54418	11A1-DMP2-54419	09/20/95	44.964	U	-0.005	09/27/95	44.952		-0.017	11/03/95	44.966	U	-0.003	
11A1-DMP2-54420	11A1-DMP2-82011	09/20/95	58.411	U	0.007	09/27/95	58.424		0.020	11/03/95	58.415	U	0.011	
11A1-DMP2-54421	11A1-DMP2-82011	09/20/95	25.300	U	0.001	09/27/95	25.304		0.005	11/03/95	25.303	U	0.004	
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11A1-DMP2-54423	11A1-DMP2-82038	09/20/95	40.918	U	-0.005	10/02/95	40.921	U	-0.002	11/03/95	40.922	U	-0.001	
11A1-DMP2-54424	11A1-DMP2-54471	--------	---------		---------	--------	---------		---------	11/03/95	29.038	U	---------	
11A1-DMP2-54425	11A1-DMP2-54472	--------	---------		---------	--------	---------		---------	11/03/95	19.069	U	---------	
11A1-DMP2-54453	11A1-DMP2-54454	09/20/95	37.835	U	-0.008	09/27/95	37.837		-0.006	11/03/95	37.837	U	-0.006	MEAS. AROUND OBSTRUCTION
11A1-DMP2-54458	11A1-DMP2-82035	09/20/95	41.467	U	-0.008	09/27/95	41.475		0.000	11/03/95	41.468	U	-0.007	
11A1-DMP2-54459	11A1-DMP2-59005	09/20/95	37.805	U	0.032	09/27/95	37.811		0.038	11/03/95	37.810	U	0.037	
11A1-DMP2-54471	11A1-DMP2-81801	--------	---------		---------	--------	---------		---------	11/03/95	32.502	U	---------	
11A1-DMP2-59001	11A1-DMP2-81800	--------	---------		---------	--------	---------		---------	11/03/95	56.765	U	---------	
11A1-DMP2-81800	11A1-DMP2-82039	--------	---------		---------	--------	---------		---------	11/03/95	36.028	U	0.017	

NOTES:
1) All stresses are report in KSI (kips).
2) N/A indicates that the monitoring point was not included in the measurement set.
3) Response values specify fraction of allowable stress.
4) Elevations are on CA/T project datum.

	THRESHOLD VALUE	LIMITING VALUE
DMP2		

FIGURE 3. Sample report format for deformation monitoring points.

database. The GIS software utilizes this instrument identifier to control the display of instruments based on user-supplied criteria.

Before the GIS system was installed, the symbols were placed manually by keying in coordinates derived from field surveys. Since then, adding instrument symbols has been automated with a program that extracts coordinates from the relational database. This program is run on a weekly basis after new data have been entered. The locations of instruments are placed in the CADD files using the coordinate system derived from North American Datum 1983. This appproach allows the instrument locations to be overlayed with other project CADD files for the display and generation of customized maps showing buildings, roads, roadway alignment and contract areas.

The GIS User Interface

The GIS team created a GUI to simplify access to the CADD files in order to perform interactive analysis of tabular and graphic data. This interface is a critical component of the GIS since it provides the geotechnical staff with a user-friendly tool to interact with the databases. It consists of point-and-click menus and dialog windows that minimize keyboard entry. The GUI was customized to meet the functional specifications for the project's instrumentation program. It is key in performing analysis for the program and consists of six major menu modules:

- *Administration Module.* Used to exit, quit or reset the application.
- *Mapping Module.* Used to build customized mapping displays. Selection can be made from base mapping features, subsurface utilities, key maps with proposed, completed and active contract areas, roadway alignments, and parcel mapping.
- *Theme Module.* Used to select instruments to be displayed and to control their display colors based on user-specified criteria. Annotation of database values can be added to instruments.
- *Spatial Operations Module.* Used to navigate to different geographic areas, find locations of addresses, contracts or specific instruments. It also provides interactive

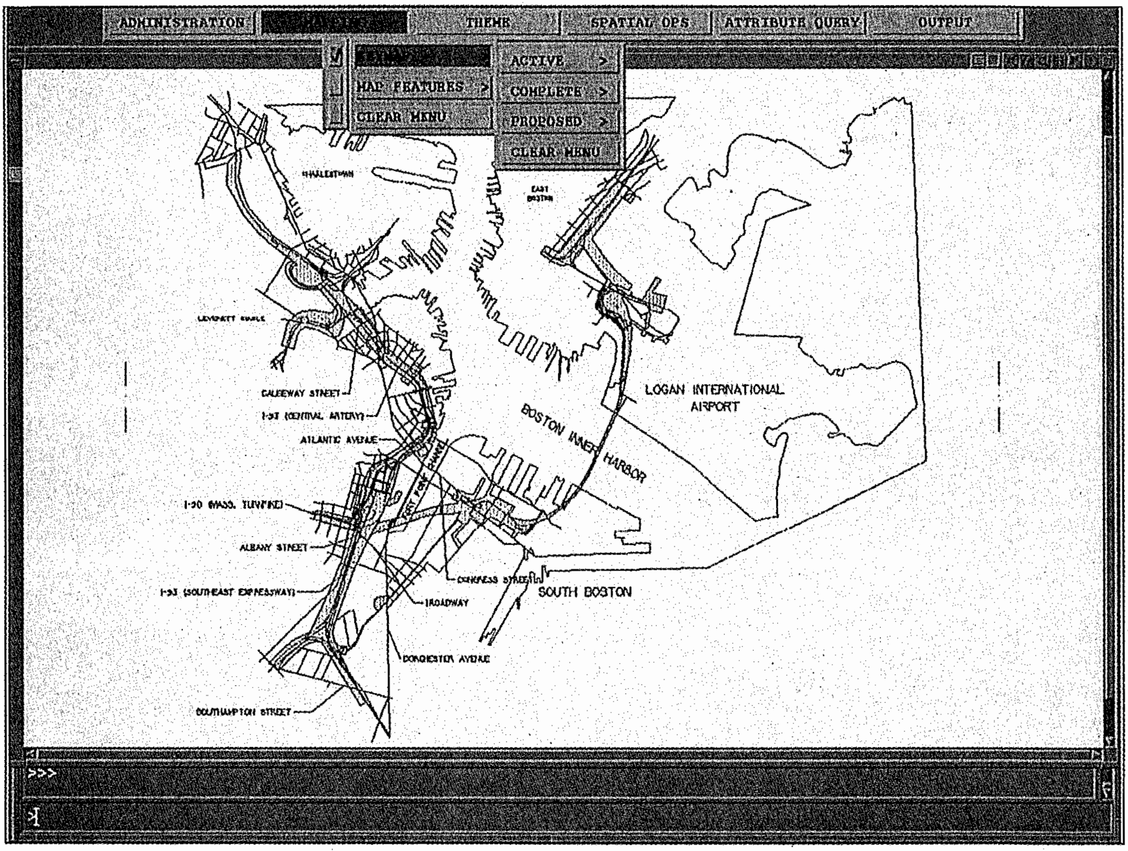

FIGURE 4. GIS application opening screen.

query capabilities by clicking on an instrument and retrieving data from the eight most recent observations to the screen.

- *Attribute Query Module.* Used to control the display of instruments based on user-specified criteria.
- *Output Module.* Used to generate hard copy output from the screen display.

The user can combine the selection criteria and display results of the different modules. When the user executes the application, the opening screen displays the main menu showing the six major modules. This opening screen is shown in Figure 4.

The administration and mapping modules automate to a great extent the CADD functions and eliminate the need for the geotechnical staff to possess in-depth knowledge to operate the CADD system. The theme, spatial operations, attribute query, and output modules represent the core functionality of the GIS application developed for the instrumentation program.

Theme Module

The theme module is used to control the cartographic display of selected instrument types. The module first displays a selection menu of all instrument types installed at the CA/T Project. Once instruments have been selected for display, the geotechnical engineer can employ the theme module as a tool to color-code instruments based on user-defined criteria or categories. The benefit of this capability is that basing instruments on color patterns representing certain events makes them easier to analyze than by studying tabular reports. The theme module also provides the capability to add text that is based on observations stored in the relational database directly to the CADD file.

Seven theme choices were identified during the needs analysis. Each theme assesses and

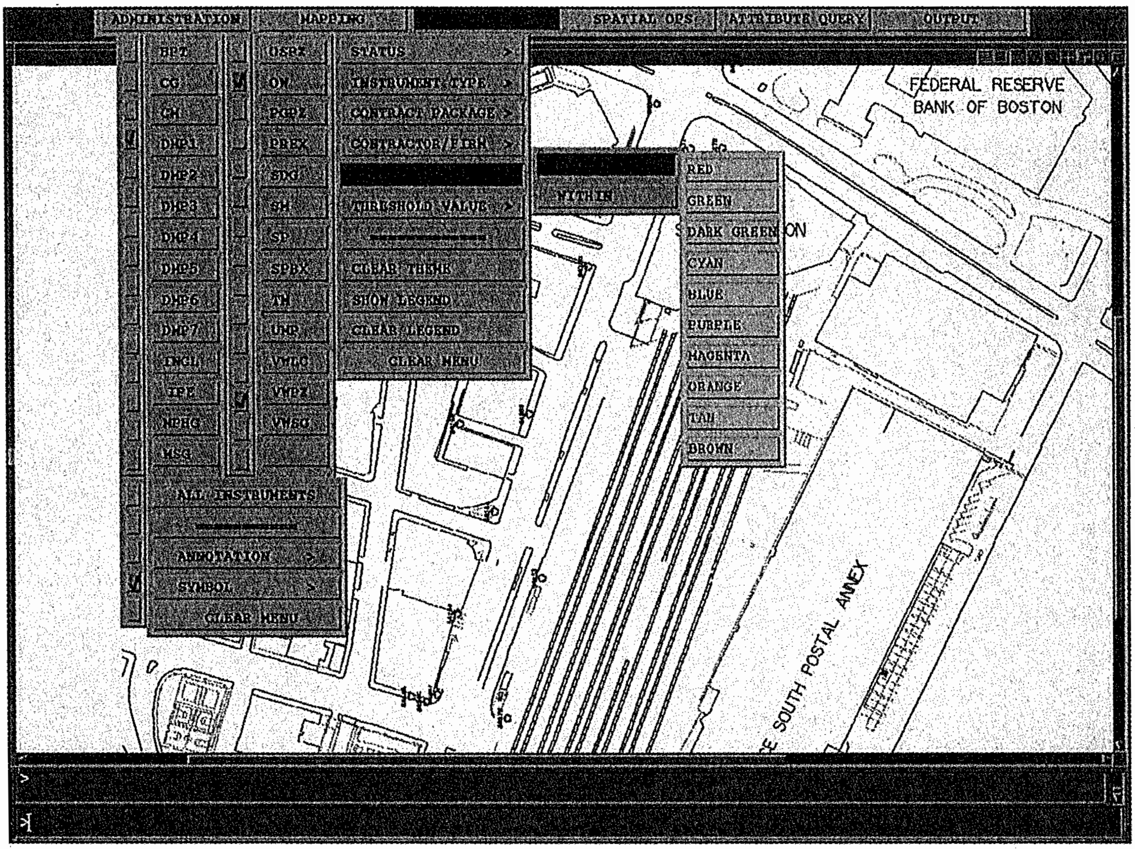

FIGURE 5. A sample user interface menu.

provides color coding for a specific group of attribute data. These theme choices consist of the following data:

- Instrument status (active, inactive or destroyed);
- Associated geological strata;
- Instrument type;
- Contract package;
- Contractor/firm that was responsible for installation;
- Instruments that fall within or exceed the limiting values; and,
- Instruments that fall within or exceed the threshold values.

The threshold and limiting value color-coding themes have been extremely useful in determining which instruments exceed these values since the software calculates these values from the most recent observations stored in the relational database. A sample user interface menu is shown in Figure 5. Displaying these data in a graphic format versus a table allows the geotechnical staff to analyze specific areas and look for patterns by instrument type as well as by patterns of association between different instrument types. Another benefit of using color is that, although each instrument has its own graphic symbol, it may be difficult without color to differentiate between instrument types on a small-scale plot.

Spatial Operations Module

The spatial operations module defines the geographic extent to which the analysis is applied. For instance, the definition could be within a contract area or a buffer distance of 1,000 feet from a building. This module consists of three key components:

- Spatial selection set definition;
- Locate function; and,
- Query function.

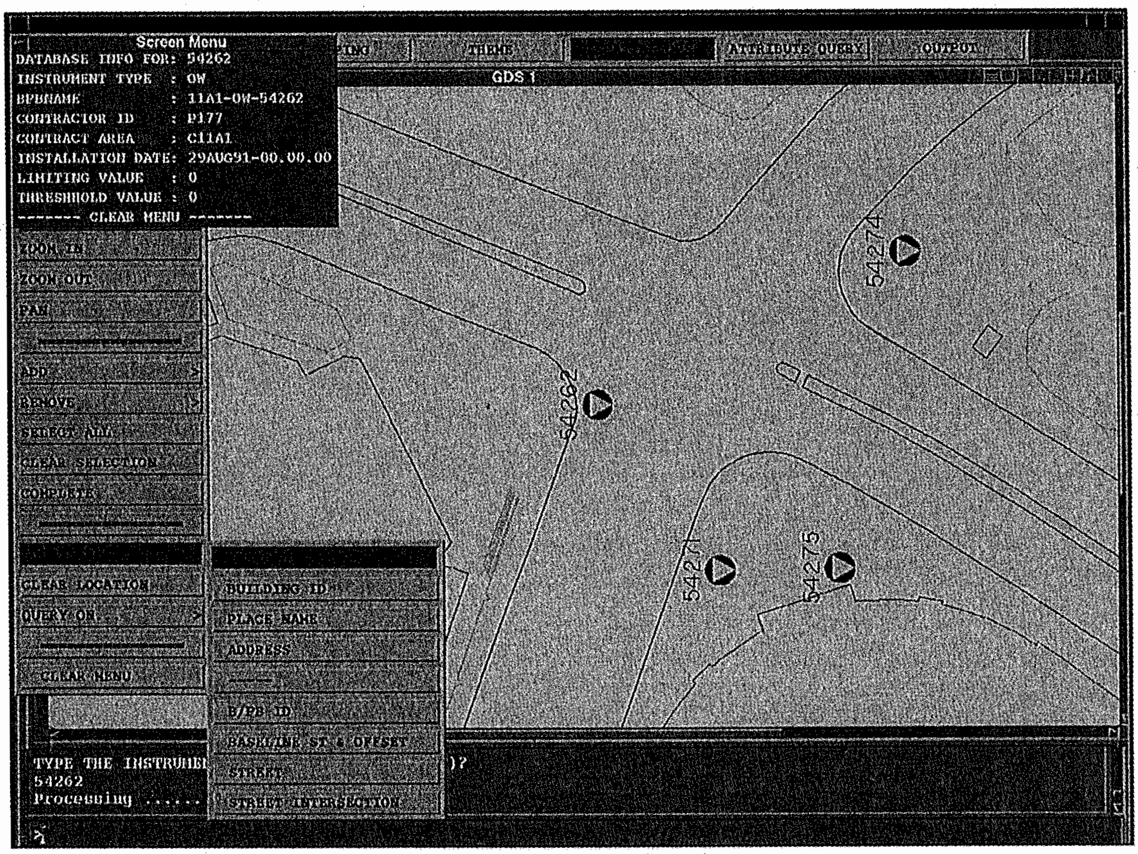

FIGURE 6. A demonstration of the locate function.

The spatial selection set definition follows the generally accepted categories of spatial analysis and prompts the user to either select an instrument or define a boundary by creating a rectangle, circle, polygon, line or buffer. Based on the selection, the software determines which instruments fall within a boundary and removes the instruments outside the boundary from the display.

The locate function allows the geotechnical staff to specify an exact geographic location such as a street address. The software will zoom in on this location and display the particular location in a bright color. The locate function is also used to find and display instruments as shown in Figure 6. Once the user specifies the unique instrument identifier, the locate function will find and display the instrument with the surrounding area and a small text window containing a synopsis of the instrument's attribute data stored in the relational database. Additional locate functions are available for addresses, parcels, building names and utility structures.

The query function lets the user retrieve detailed information from the last eight observations for specific instruments. By indicating an area of interest, the software displays a menu that lists all of the instruments contained within the specified area. The user can then select instrument identifiers from this menu in order to view the detailed instrument data in a text window.

Attribute Query Module

The attribute query module directly interacts with the relational database and displays only those instruments whose data satisfy the user-specified criteria. The following attribute queries have been defined:

- *Strata Type.* Results in display of instruments that have been set in a specific geological stratum;

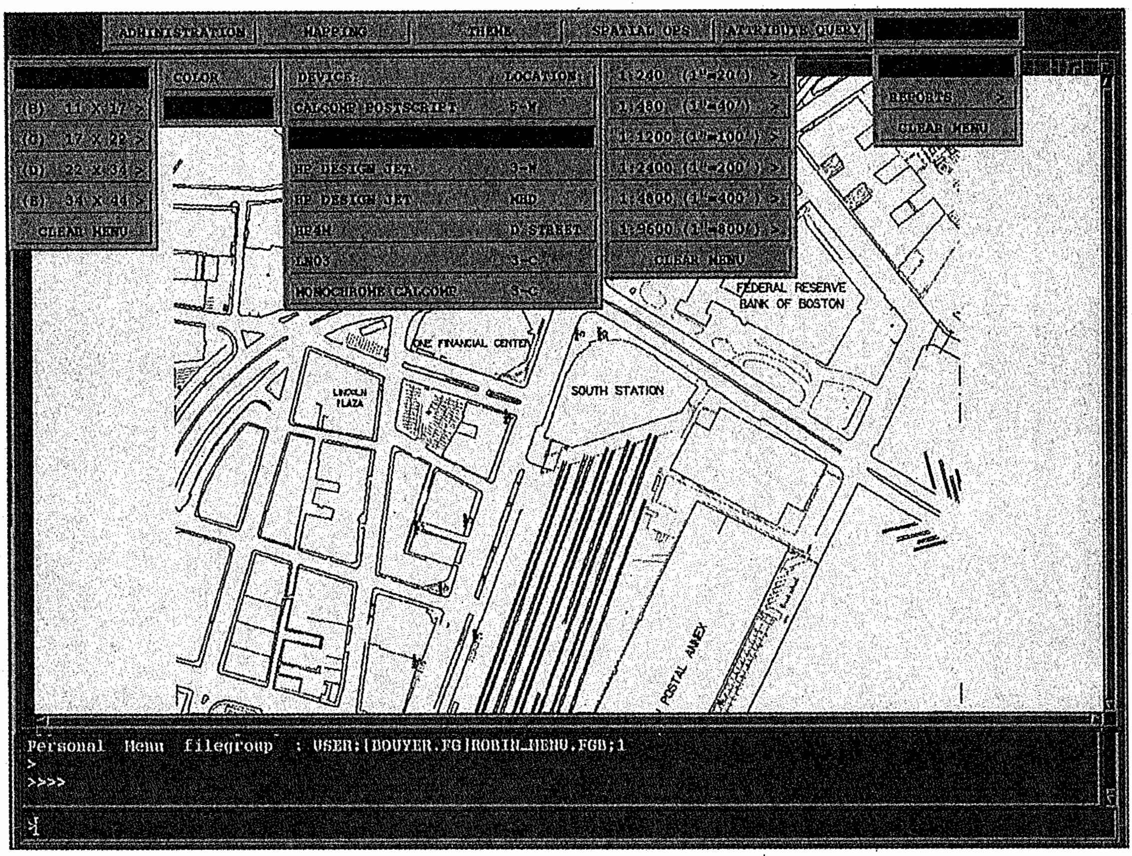

FIGURE 7. Plot setup menu.

- *Instrument Status.* Results in the display of instruments meeting only one specific status (active, inactive or destroyed);
- *Instruments in Multiple Contracts.* Results in the display of instruments that are observed by multiple contractors;
- *Time Period No Readings.* Based on user-defined date ranges, the system calculates and displays only those instruments that have not been read during a specified period. This query is extremely useful in monitoring the contractor's obligations and in checking that observation intervals are evenly spaced;
- *Near Threshold Value.* Based on a user-defined percentage, the system calculates and displays only those instruments that fall within the specified percentage of the threshold values. For instance, the system can be made to display all instruments that are 95 percent or closer to attaining their threshold values; and,
- *Near Limiting Value.* Based on a user-defined percentage, the system calculates and displays only those instruments that fall within the specified percentage of the limiting values. For instance, the system can be made to display all instruments that are 95 percent or closer to attaining their limiting values.

Typically, user interaction with the module consists of selecting the attribute query from a menu, defining the operator (such as =, !=, >, ≥, < or ≤) and a valid value range. The GIS team designed the software to reject invalid data and out-of-range values, thus preventing the system from searching for non-existent results.

Output Module

Each of the previously noted modules is used to build a report in a cumulative fashion. The spatial operations and attribute query modules

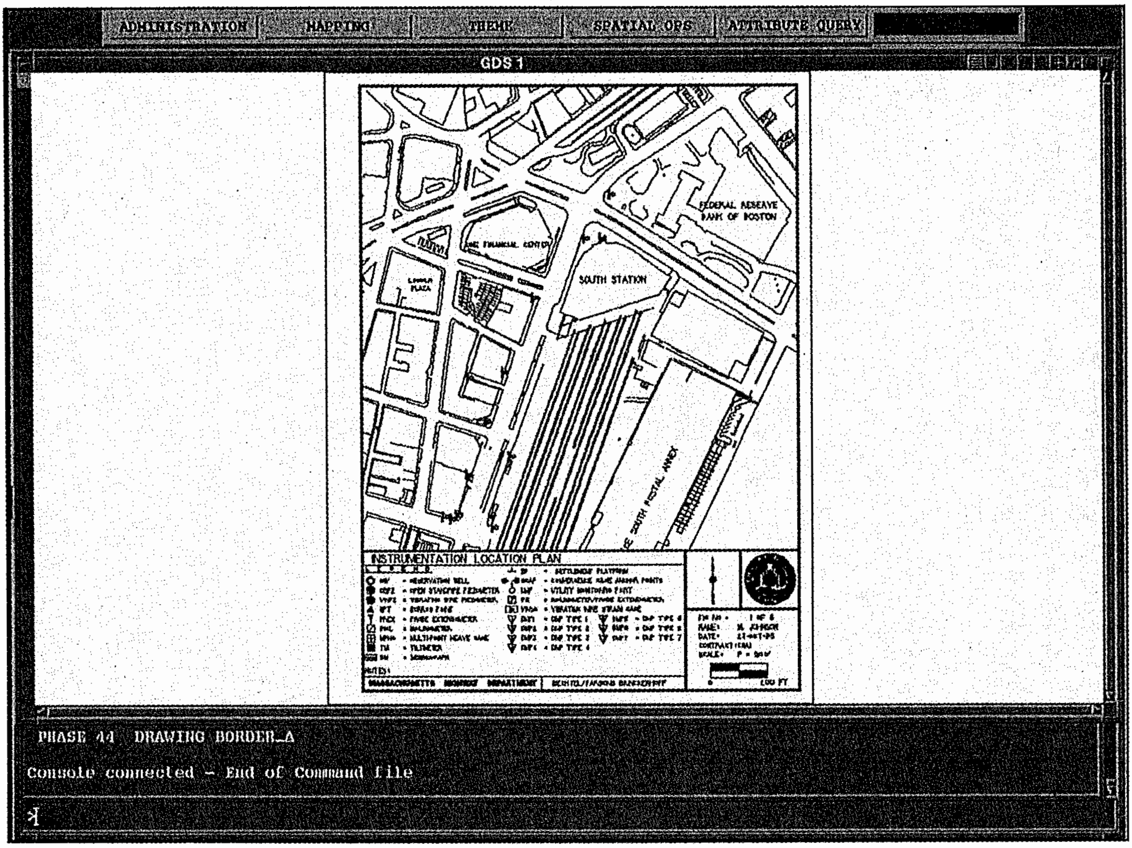

FIGURE 8. A sample plot preview screen.

allow the geotechnical staff to analyze the data on an area basis. The theme module adds color coding to enhance the interpretation of the data. The output module addresses the requirements of generating output, such as the plot required for inclusion in weekly reports.

The output module was specially designed to allow the user to create a customized plot by selecting a few menu choices. Requiring no prior knowledge of software commands, the user can choose between a plot with a frame containing customized title block, north arrow, and legend, or a plot without this information.

The plot option from the output menu provides the user with a plot setup menu as shown in Figure 7 (on page 75). This option requires the selection of plot size through a menu that lists five standardized plot sizes. Most plots are created using the 8.5- × 11-inch or 11- × 17-inch plot size. The plot setup menu also requires selecting either color or monochrome display, and plot location. A list of available plotting devices on the CA/T Project (at the various office sites) is stored in a database table. The user chooses the appropriate device depending on the user's location (the devices to which the user is connected). The plot setup is completed by selecting one of the six standard scales ranging from 1:240 (1 inch = 20 feet scale) to 1:9,600 (1 inch = 800 feet scale). The software then calculates and displays a frame with the dimensions that cover an area that fits the selected plot size (based on the selected scale). The geotechnical engineer can drag this frame to the area to be plotted. This frame can be rotated, moved, deleted or copied to create a sequence of plots.

Based on selections made from the theme, spatial operations and attribute query modules, the title block option generates a dynamic legend and a menu with title, user name, scale and date. The user can preview the plot on the screen or send the plot directly to the chosen device. A sample preview screen is shown in Figure 8.

Conclusion

The GIS application for the CA/T Project's geotechnical instrumentation program has provided the flexibility and functionality critical to its success. It represents the integration of the critical dimension of spatial analysis with geographic correlation and cartographic display capabilities — such an integrated package has never been used before in geotechnical instrumentation. The GIS application has become an effective management and decision-making tool with unique and powerful reporting capabilities to communicate results.

The GIS application facilitated the storage and maintenance of data in one central location and can be accessed via computer links from different offices. This configuration has eliminated data duplication and transfer from and to the various project office locations. The relational database used by the GIS has enhanced the overall quality and integrity of the data. Most importantly, the relational database is flexible and capable of storing large quantities of data. The system is designed ultimately to contain over a million records.

Frequent interaction between the GIS team and the geotechnical engineers was essential in making this GIS application successful. The user-friendly, multi-user environment and controlled access allow many users to use the system simultaneously without having to learn a complex or difficult database program.

One of the most striking benefits of the GIS application has been the speed of information management and retrieval. Complete reports — including data, observations and location plans — can now be produced by a single user, typically in less than fifteen minutes. This ease of use enables instrumentation data to be rapidly disseminated throughout the CA/T Project, facilitating timely decisions and actions based on current data.

Finally, the new application has enabled the project staff to generate specific reports in response to the varying needs of the project, using the same development platform. For example, certain abutters had requested instrumentation information specific to their buildings. The CA/T Project was able to develop a tabular report showing the most recent sets of data for a specific building at any given time. Now, the same report can be accessed and generated using the CADD system by simply locating the building of interest and creating a plot of the analysis.

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