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Development and Applications of GIS-Based Bridge Lifecycle Management System

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With the increasing volume of traffic and the rapid deterioration of bridges, the effective bridge management approach is becoming important for the bridge agency to keep the bridges up with the growing transportation demands. In this paper, the data structure and data flow of a GIS-based bridge lifecycle management system are discussed. By integrating the spatial and feature data of bridges, the digitized data of roads and rivers, soil data, and so on, a new type of bridge management system is developed within the GIS environment for the bridge lifecycle. This system is applied for several practical issues in the primary stage of bridge planning, and the service and monitoring stage.

Key Words: bridge lifecycle management system, GIS, data modeling

1. Introduction

For the past years, several approaches have been suggested to develop bridge management systems (BMSs). However, these systems still have difficulties in handling the lifecycle management of a network-level bridge system because of the two following problems.

The first problem in dealing with bridge management as a network level is the difficulty of identifying the geographic relationships involved in bridge management activities. Knowing the geographic relationships between bridges and other related infrastructures is essential for integrating the BMS with other management systems such as pavement management system. For example, in the service and monitoring stage of a bridge, the spatial relationships among bridges, and among bridges and other infrastructures such as roads and rivers challenge the bridge agency. The rapid development of Geographic Information Systems (GISs) has provided a great opportunity for developing a new type of BMS, GIS-based bridge lifecycle management system (GBLMS), including bridge planning, design, construction, service and monitoring, maintenance, and demolition. GBLMS can help in combining bridge management information with spatial data to improve the bridge management efficiency.

Research efforts have focused on GIS applications in bridge engineering such as using GIS in bridge planning[1)], developing a prototype GIS-based bridge management database system[2)], and evaluating the impact of an earthquake on the bridges in a region[3)]. As described by Tonias in 1995, over the next several decades, the BMS will mature and grow to the point where it will be difficult to imagine maintaining bridge structures without GIS[4)].

The second critical problem is the difficulty to quickly make an appropriate decision at each lifecycle stage of a bridge. For example, at the planning stage, the decision to build a new bridge draws upon many economical (e.g., budget), political (e.g., landuse, distribution of population), and cultural (e.g., landscape) issues[5)]. For the bridge designer, it is not easy to select the adequate types of superstructures and substructures of bridges. In the construction stage of a bridge, there is a need for a wealth of knowledge to deal with the bridge construction engineering and management such as the launching erection method. The decision making in the maintenance stage is also a difficult task because the number of possible combinations of maintenance plans increases exponentially with the number of bridges, the planning period, and the number of maintenance alternatives. Finally, the decision to demolish or rehabilitate a deteriorated bridge must be carefully planned at the the early planning stage in order to reduce the lifecycle cost and satisfy the environmental concerns.

In this paper, first, the data structure and data flow of GBLMS are discussed. Then, by integrating the spatial and feature data of bridges, the digitized data of roads and rivers, soil data, etc., a prototype GBLMS is developed. In this system, bridge engineers are allowed to more quickly identify and specify possible management strategies, and increase the efficiency of the overall management activities. Although several simplicities are adopted in this system because of the lack of data at present, the systemization of bridge management may be helpful to make clear issues of the future investigation.

2. Data Modeling for GBLMS

2.1 Data Structure for GBLMS

Bridge engineering is a complex practice that includes many interactive activities and generates significant amount of information. Although a particular bridge management task requires only a small subset of the agency's data, these data may come from diverse data sources. In order to efficiently collect, analyze, maintain, and utilize the data related to bridge lifecycle management, it is important to classify and identify the necessary data used in the bridge planning, design, construction, service and monitoring, maintenance, and demolition stages. Four types of data, project-level data, network-level data, related infrastructure data, and regulative data are classified according to the data sources: (1) specific bridge project, (2) network-level bridges, (3) other infrastructure systems related to bridges, and (4) bridge agency and government, respectively. Among these four types of data, project-level data are created and accumulated over the lifecycle of a bridge. Network-level data are necessary in order to deal with the bridge management at a network level. The related infrastructure data and regulative data are used for the lifecycle of a bridge. As shown in Fig. 1, these data are necessary to accomplish the tasks of each lifecycle stage of a bridge considering the network-level bridge system. The effective data of each type change from one stage to another. In the following paragraphs, each type of data is discussed.

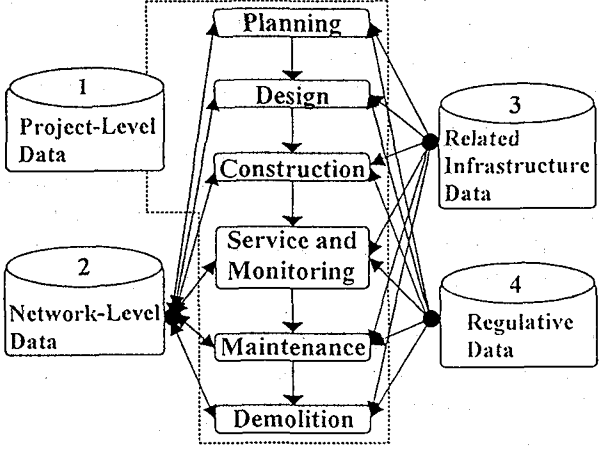


Figure 1 Lifecycle Data Structure and Flow

(1) Project-Level Data

Project-level data represent all data derived from the lifecycle of a specific bridge project. The contents of these data start from the planning stage, and are accumulated over time and used in the subsequent stages. At the planning stage, the main data are the bridge name, location, road name on which the bridge is located, river name in case of a river-crossing bridge, and so on. At the design stage, the new data are the types of superstructures and substructures, structural materials, forms and dimensions, designed load-carrying capacity, service limitations, requirements on environmentally conscious design, construction budget, design schedule, and so on. The lifecycle cost analysis is difficult at present because of the lack of reliable and consistent data. However, it is necessary to accumulate data for estimating the rough lifecycle cost value and calculating it more accurately in future. The main data from the construction consist of the construction schedule, cost, quality, safety requirements, methods, technologies, materials, machines, man power, energy consumption, construction supervisory report, and so on.

At the service and monitoring stage, the main data include the testing results before opening the bridge to traffic, changes of load-carrying capacity, environmental conditions, traffic volumes, inspection and diagnosis data, image data, and so on. These data are accumulated over time, and used as history data for the maintenance planning. The data from the maintenance stage are the damaged components, maintenance methods, cost, effectiveness, and so on. The demolition closes the lifecycle loop back to the beginning of a new bridge lifecycle. Demolition data include the demolition methods and machines, volumes of materials, recycling plans, and so on. Furthermore, the costs and benefits of both users and agency associated with alternative bridge improvements are needed. These data are useful for lifecycle cost analysis when a new bridge or a major maintenance activity is proposed[6].

(2) Network-Level Data

The network-level data are the data related to the network-level bridge system such as the origin-destination traffic volumes. Some other data are obtained from the statistical processing of long-term observations of a great number of bridges. For example, the yearly deterioration rate of a concrete deck should be based on the observed inspection data in a network-level bridge system for a long period[7]. Although these inspection data are difficult to be obtained, a simple deterioration model is still useful at present for investigating the factors involved in the deterioration process, in addition to predicting the possible deterioration condition in the future. The deterioration model is expected to become more sophisticated and more practical in the future by considering these factors and accumulating more inspection data. The network-level data can be used across different bridges in the network. For example, the landscapes of available bridges can be used for the type selection of a new bridge[8]. An improved bridge management system should be able to provide information on past mistakes and use these findings for the design and construction of new bridges[9].

(3) Related Infrastructure Data

The data of related disciplines, including soil, road, and river data, are also necessary for bridge lifecycle management. For example, soil data are necessary to know the *N-Values* of soil, load-carrying capacity, underground water level, and so on. Road data are necessary to know the relationship between bridges and roads, including the road locations, network connectivity, road types, and traffic volumes and distribution. Further data are necessary about the landuse, demographic data, and so on. The lifecycle of a bridge also effects the data of other infrastructure. For example, the employment of a new bridge may redistribute the traffic volumes among the roads surrounding this bridge. However, the modification of these traffic data are due to the road management agency and beyond the functions of a BMS.

(4) Regulative Data

Regulative data include the bridge agency's policies and goals, external constraints such as national laws and regulations, and other social, political, and economic considerations. The environmental regulations are also important for the bridge lifecycle management. These data are mainly in the form of text format. The lifecycle of a bridge also generates the basic data used by the concerned authority for creating and modifying design specifications. For example, the minimum concrete deck thickness of a new bridge is strictly limited to 18 cm in the design specifications[10]. This is because it is found from the services and monitoring of bridges that this thickness has a close relationship with the bridge performance.

2.2 Data Flow of GBLMS

Each stage in the bridge lifecycle utilizes and generates data. From the data flow point of view, the flow of the four types of data mentioned above is different as shown in Fig. 1. Some project-level data happen and disappear within one or a few stages such as the design and construction schedules, the data about construction machines and man power, and traffic volume at one year. However, most of the project-level data effect the stages of the lifecycle following their appearance such as the bridge location, construction materials, possible construction deficiencies, rehabilitation methods, and so on.

Taking the reinforced concrete bridge deck as an example, the dimension data are accumulated and used throughout the whole bridge lifecycle. Fig. 2 shows several examples of the data usages, which change from the planning stage to the demolition stage. At the planning stage, the length and width of a bridge deck are tentatively estimated, which are related to the predicted traffic demands. At the subsequent stages, the deck dimension data are determined, and then used to calculate the load-carrying capacity and the material amounts by the bridge designers and construction managers, respectively. At the service and monitoring stage, the deck width is related to the traffic capacity. The deck area is also an important factor used to determine the maintenance cost. Finally, the deck volume is related to the demolition volumes of materials.

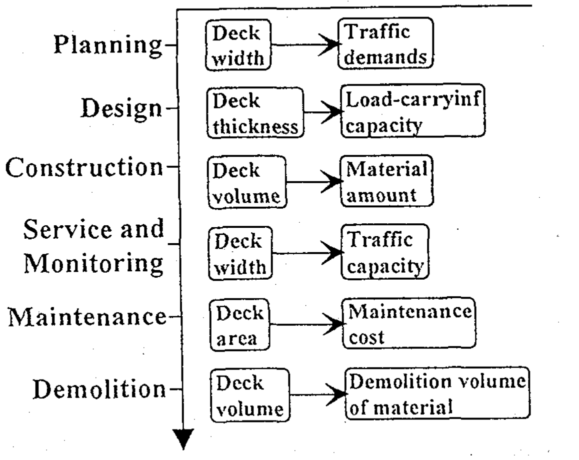


Figure 2 Examples of Lifecycle Usage of Deck Dimension Data

The network-level data used at one stage of a bridge may be originated from a subsequent stage of another bridge at the same network. For example, the bridge type selection at the design stage may use the data from the service and monitoring stage of other bridges. The network-level data are enriched by the project-level data of all bridges in the network. The related infrastructure data and regulative data are useful for every bridge at any stage. However, the specific data items may be much different. The scope of these data is wider than the conventional BMS. Many countries have established projects to collect more information about bridges, and many local agencies are developing more elaborated bridge management systems to manage their bridge inventories[5,11]. One way to effectively utilize these data is to improve the data communication among all stages of a bridge lifecycle, among bridges in a network system, and among several bridge agencies. With the development of bridge management and computer network such as the Internet, more data are being collected, shared, and utilized effectively.

In this research, the above mentioned four types of data are to be gradually collected, analized, installed, maintained, and utilized with time within the GBLMS environment for the bridge lifecycle management. It is noted that all data items must be transformed to a uniformed data format from their original formats to fit for the purpose of lifecycle management. An object-oriented database approach was adopted to represent the bridge structure for developing a prototype bridge database system[2]. Each component of a bridge contains its related data in each lifecycle stage by adding them periodically to copies of the bridge objects. The network-level data are based on the collection of project-level data. The related infrastructure data are created using GIS. The regulative data are installed as a database in the system. However, the development of such a system is time consuming, needs a long-term procedure to accumulate data, and needs the contributions of engineers from different disciplines.

Because this system treats a combination of geographic data, image data, document data, numerical data, and graphics extensively, the hardware of the system should have a fast processing speed, a large memory space, and a user-friendly window-based user interface. For example, about 0.2 Gbytes are necessary for the available bridge image data of 5000. In addition, having networking capabilities is desirable for this system in order to facilitate the access to the data between the main system and subsystems that may be applied for several purposes at different computer platforms. For these reasons, the system is developed on a Sun workstation. The object-oriented programming language C++ and Versant Library[12] are used to develop the system database. Versant has a C++ library for developing and managing object-oriented databases. At the time being, only a part of data have been installed into GBLMS as shown in Fig. 3. These data include the digitized geographic data, bridge images, design data of bridges, bridge inspection data, and soil data. GIS technology has been adopted to integrate and share the project-level data and the related infrastructure data for the bridge lifecycle as will be explained in the next section.

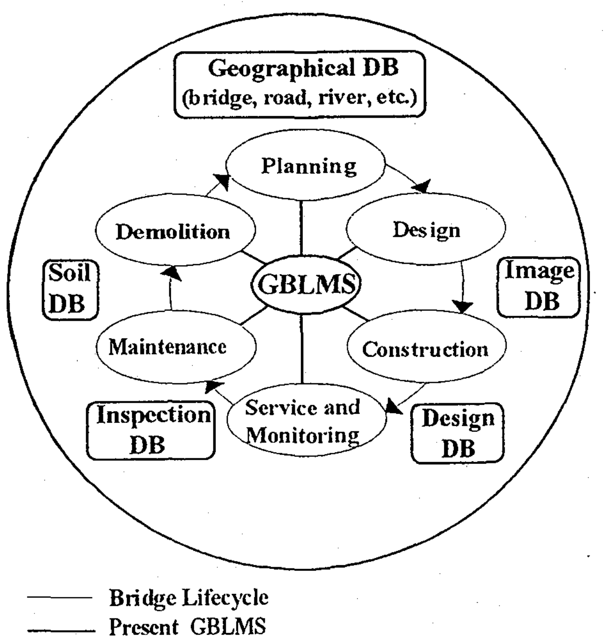


Figure 3 Conceptional Graph of GBLMS

3. GIS Database for BMS

3.1 GIS Data Representation and Function

GIS uses two types of data: geocoded spatial data and attribute data. The spatial data are represented by the vector or raster method. Vector data represent objects as graphical features by point, line, or polygon coverages. In ARC/INFO, a coverage is a digital form representing one type of map feature, such as bridges, rivers, and roads[13]. In a coverage, map features are stored as points, arcs or polygons. Map feature attributes, such as the lanes' number of a bridge, are described and stored in associated feature attribute tables. A layer is a set of coverages described and stored in a map library, which is an organized, uniformly defined collection of spatial data[13]. Point coverages represent the objects that can be considered as a set of points such as wells. Line coverages are used to represent roads, river centerlines, and district borders. Polygon coverages may depict other feature where areas are the dominant property such as soil types, river borders, and landuse zones. Raster data use two dimension matrices as an indicator of the spatial location of the points, and use the contents of the matrix as the attributes of these points. In this research, the vector method was adopted to digitize spatial data as will be explained later.

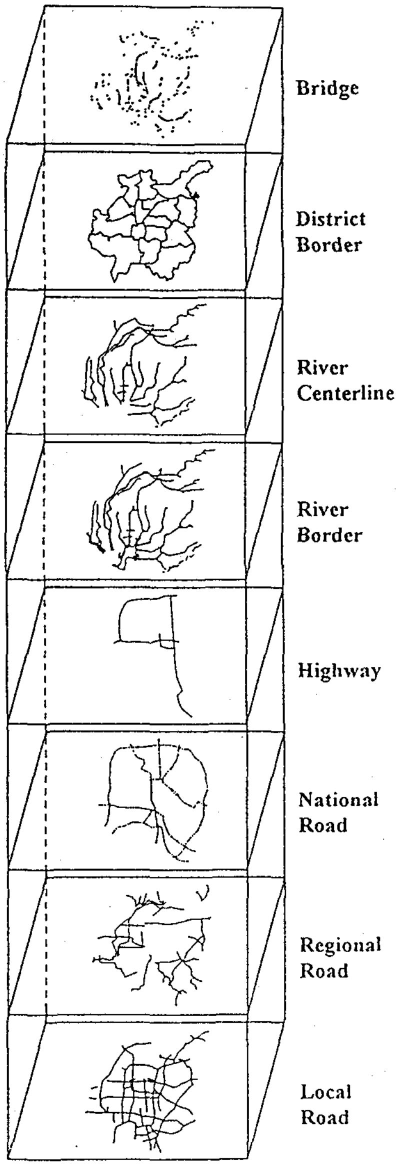


Figure 4 Digitized Geographic Data

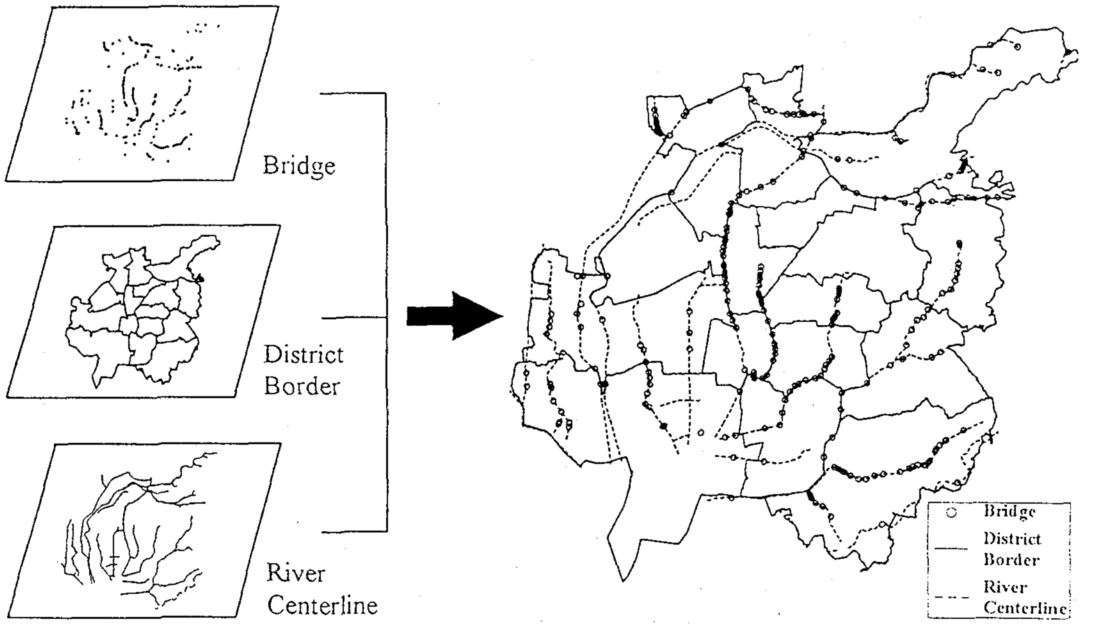


Figure 5 An Example of Overlapped Geographic Data

GIS has the following five functions: (1) Storing and retrieving data: This forces the bridge agency to establish a database that is required for the efficient integration of various data residing in different units of the agency. (2) Analyzing data: This is derived from the ability to link data files to statistical packages, mathematical programs, and plotting software. Consequently, the user can almost instantly extract summary information, statistical results, or graphs about a bridge or a bridge system. (3) Displaying data: This function is helpful for the visual management of bridges such as displaying the distribution of deficient bridges. Until recently, these analyses and display of bridge data were carried out in a tabular format without consideration of the spatial constraints. (4) GIS can relate separate infrastructure management databases such as bridge management database and road management database into a comprehensive information management system. GIS makes it possible to integrate these systems according to their spatial relationships. (5) GIS is able to rapidly respond to questions given by the users about how the data are spatially related. For example, what are the deficient bridges within a particular area and how many people are living in a one kilometer buffer around the boundaries of a construction project? These distinguished functions of GIS for handling geographic data fulfill the needs of a BMS.

3.2 Development of GBLMS

For the purpose of bridge management, the geographic databases of bridges, roads, and rivers are developed by digitizing from the authorized maps with 1:25000 scale using the ARC Digitizing System (ADS)[13]. A visual representation of these digitized geographic data is shown in Fig. 4. In order to determine the directions and locations of bridges, 287 bridges managed by Nagoya city are digitized as a line coverage. These directions are important for relating bridges and roads, or bridges and rivers. The district borders, river centerlines, highways, national roads, regional roads, and main local roads are also digitized as line coverages. The river borders are presented as a polygon coverage to reflect the urban land use and determine the shapes of rivers. Four types of roads are adopted because they belong to different management agencies. Because 240 of the 287 bridges are river-crossing bridges, the centerlines and borders of 27 rivers in Nagoya city are digitized. The river attributes are registered in the line coverage. The reason of using two types of coverages for representing the rivers is that both types are necessary, and it is difficult to get the centerline coverage from the border coverage. Both types of coverages should be modified once there is a need to change the data of a river. Fortunately, this change is very rare.

The digitized coverages, or a part of them, can be overlapped in one map to study their relationships. Fig. 5 shows the overlapping of river-crossing bridges, district borders, and river centerlines. Besides the digitized spatial data, the soil data of 4190 previous borings in the area of Nagoya city are stored and maintained as point coverage[14]. The general and seismic inspection data of Nagoya city bridges in 1992 are linked with the bridge coverage. These data contain the bridge inventory data, superstructure and substructure inspection data, deterioration level data, and maintenance history data[11]. More than 5000 pictures of the Nagoya city bridges are input into the system. A bridge image management system has been developed and can be utilized through the World-Wide Web (WWW) of the Internet. These several types of data were discussed elsewhere[2].

GIS has the basic functions to deal with the geographic data, and do spatial analyses. However, these functions can not be applied directly for solving bridge management problems. Several application programs in GBLMS are developed using menu-driven user interfaces for the retrieval of specific information related to bridges, soils, and so on. These applications will be discussed in Section 4.

4. Applications of GBLMS

4.1 Lifecycle Usage of GBLMS

Bridges constitute a unique class of structures that are influenced by a continuously changing load environment. Therefore, bridges are subject to a more rapidly deterioration process than most other civil structures. With the increasing volume of traffic and the rapid deterioration of bridge elements, most bridges are rapidly approaching a state that requires some types of maintenances or reconstruction. Bridge management is responsible for keeping the bridges up with the growing transportation demands by designing and constructing new bridges and by maintaining the condition of existing bridges. However, as explained in Section 1, the conventional bridge management practice generally focuses on dealing with a particular task of a bridge at one lifecycle stage without efficiently integrating lifecycle stages, bridge network, and related infrastructures. GBLMS can help bridge engineers to deal with each bridge lifecycle and network-level bridge system management more effectively as explained in the following subsections.

4.2 Assistance for Bridge Location Selection

In the planning process of a new road network, the planner must consider possible locations of bridges[1). The selection of the best alignment is difficult because of the variety of factors involved in the decision making and the complex interaction among these factors. The current practice is deficient in considering the technical issues of the possible bridges, tunnels, and roads on each road alignment at the planning time. Moreover, the road alignment selection, including bridge site selection, is very important. For example, the selection of the bridge site influences the choice of the bridge type that, in turn, affects the construction cost. The process of road alignment selection needs more effective application of GIS technology to integrate the road alignment, landuse, demographic data, soil, main roads, and so on.

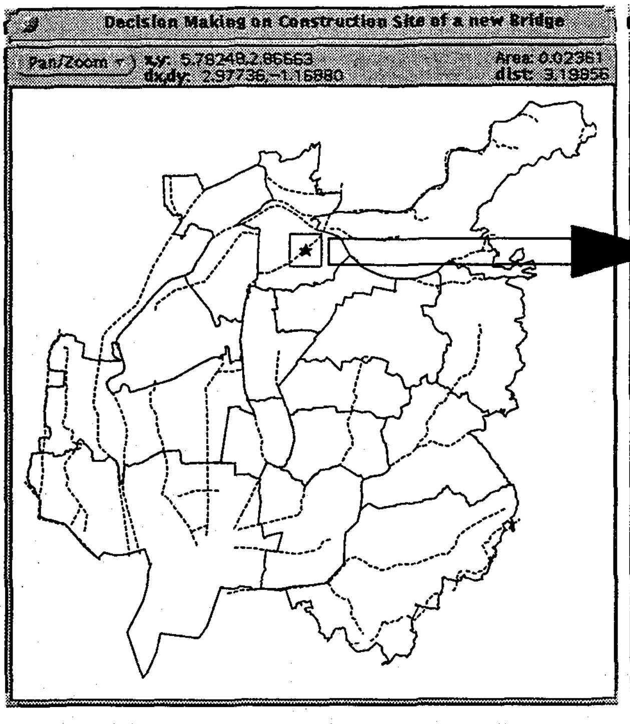
Soil data are one of the important factors influencing the selection of the bridge location. However, in the early planning stage of bridges, it is not possible to obtain new boring data at each potential construction site. One alternative approach is to investigate the available boring data around each candidate bridge location. GBLMS can help the engineers in implementing this approach effectively by the following process as explained by an example. First, a candidate location is marked by a star symbol as shown in Fig. 6(a). The area around the star is enlarged within a new ARCPLOT window as shown in Fig. 6(b). Furthermore, the reference numbers of boring data within this area are shown in Fig. 6(b). Given a radius of 250 meters, four boring points are found in this circle. Finally, the detailed data of these boring points are obtained, and their cross sections are shown in Fig. 6(c). The elevations at boring points are 5.50, 7.15, 6.39, and 6.22 m, respectively. The legends of the soil types in this figure are adopted from the reference[14)]. The *N-values* of standard penetration test are given at several depths. These values are generally used to select the foundation type and to calculate the capacity of foundations. This process can help the bridge engineers in comparing the candidate locations of a bridge quickly.

4.3 Advisory Support for Bridge Type Selection

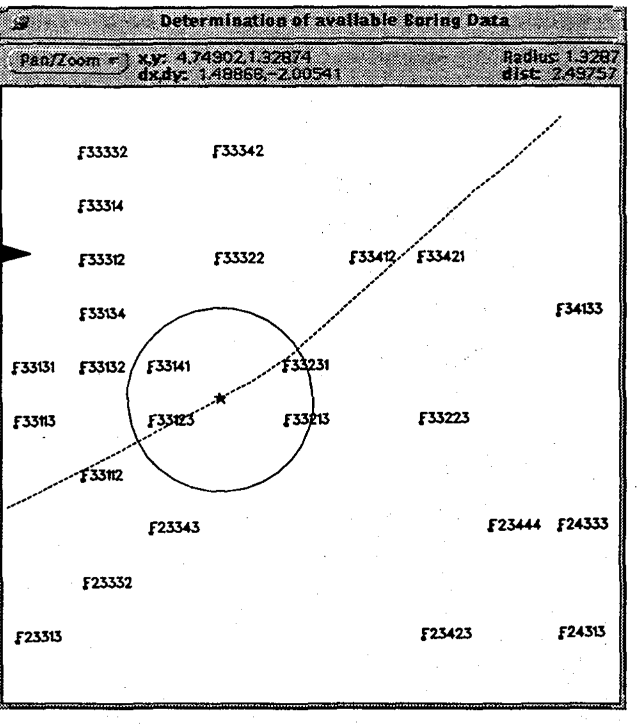
Selecting the type of a new bridge is important because of its influence on all the stages of bridge lifecycle. However, it is difficult to select a suitable type unless a designer has enough experience and a wealth of knowledge. This is because many factors influence the bridge type selection, and some factors such as the landscape are difficult to be quantified.

An advisory system was developed to select the types of superstructures and substructures of river-crossing bridges, and to quantitatively evaluate the landscape of different bridge types based on the knowledge of expert designers and the specification rules[8)]. Evaluating the landscape of bridges has been considered difficult since it involves subjective factors and aesthetic sense. Furthermore, the landscape of a new bridge is affected not only by the new bridge itself, but also by the landscape of available bridges near the new bridge. A common application in landscape evaluation is to consider the neighboring bridges crossing the same river or road. By integrating with the previous advisory system, the GBLMS can display the landscape of available bridges, help the selection of new bridge type considering the landscape of available bridges, and simulate the effect of the additional bridge on the current landscape.

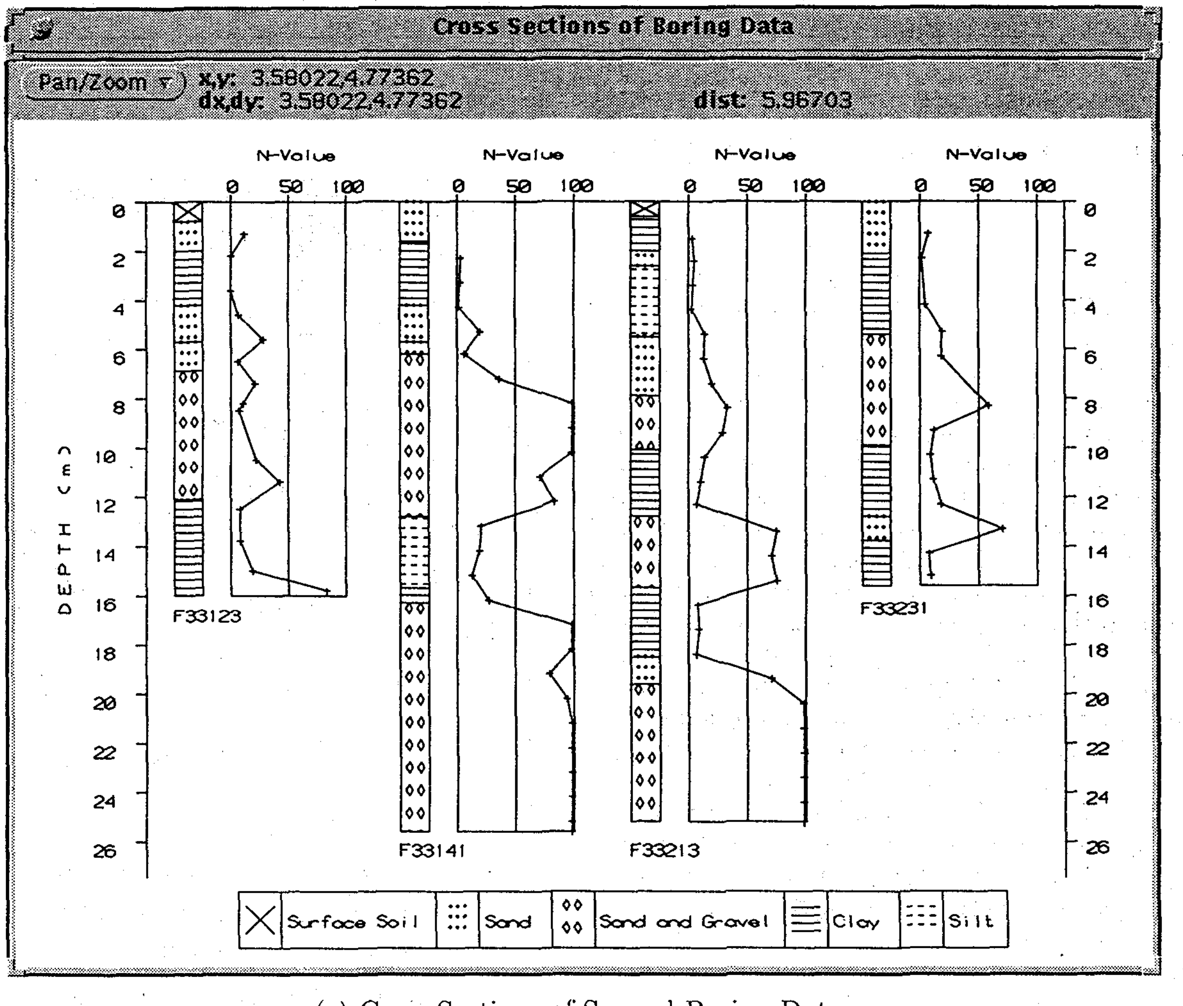
For example, Fig. 7 shows the landscape of several bridges crossing Syonai river. This figure is helpful for bridge engineers in evaluating the landscape of a new bridge type according to the landscape, service and monitoring data, of other bridges at a network because of the common surrounding landscape for the bridges crossing the same river. Furthermore, the bridge type is decided by considering the possible change of landscape due to the construction of the new bridge. By integrating the GIS, image management system and the above mentioned advisory system, the bridge designer can evaluate quickly the landscape of selected types by seeing and quantitatively evaluating the landscape of a set of bridges.



(a) A Candidate Construction Site



(b) Available Boring Data



(c) Cross Sections of Several Boring Data

Figure 6 GBLMS Assistance for Bridge Location Selection

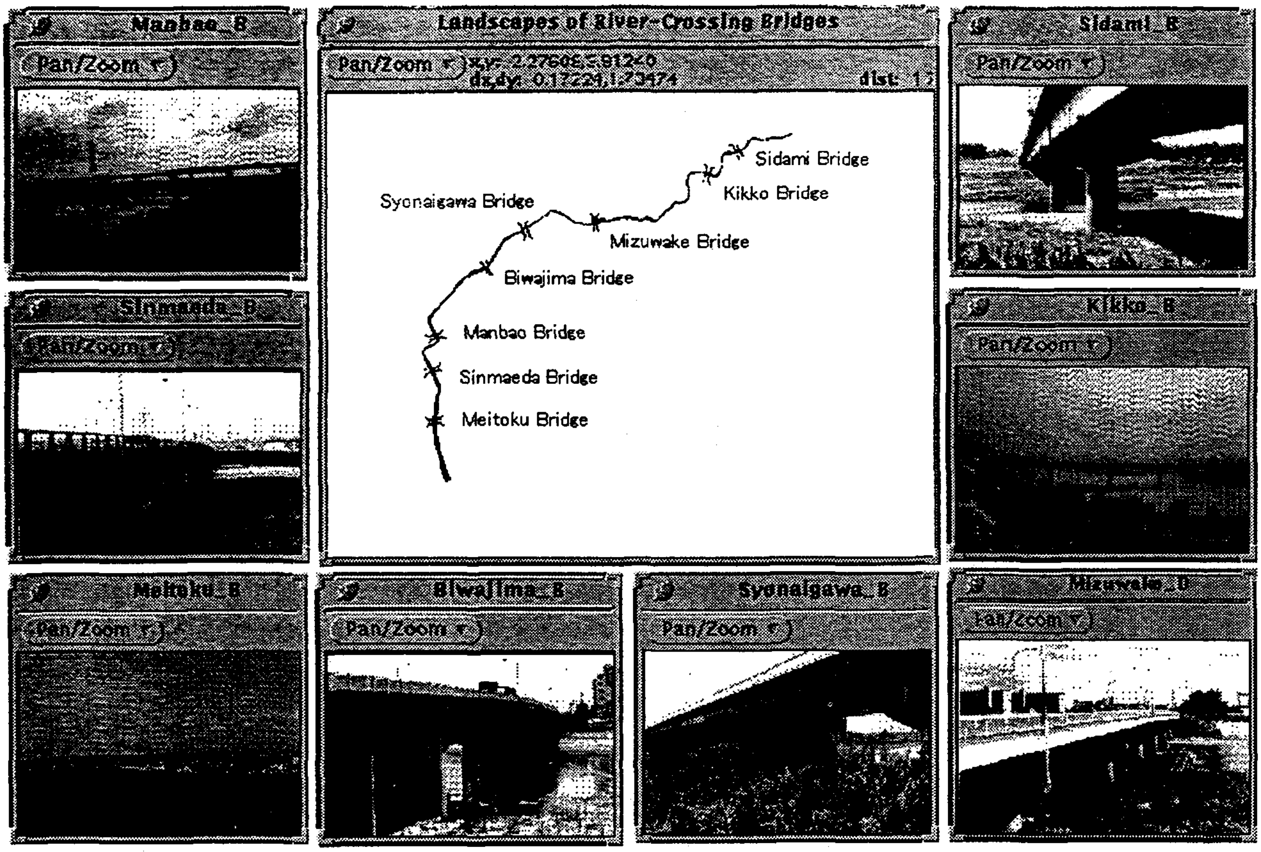


Figure 7 Landscapes of River-Crossing Bridges

4.4 GBLMS Application in Route Selection

In the service and monitoring stage of an integrated infrastructure system including bridges, roads, and tunnels, GBLMS is helpful for the bridge engineers to manage the network-level bridges together with other infrastructure systems. An example is the effect of bridges on the change of the shortest path regardless of the origin-destination patterns. Fig. 8 shows an example of road network including the national roads, a part of regional roads, and seven bridges numbered 1 to 7. In this figure, there are 42 intersections, and 66 road sections. It is assumed that traffic is possible in both directions for all road sections. It is also assumed that it is possible to change the direction at any intersection. The shortest path between an origin and a destination is found by network analysis[15]. For example, the shortest path between **a** and **b** is path $\mathbf{P}_1$ with eleven intersections and two bridges as shown with the thick line in Fig. 8. The total length is about 21 km. Once one bridge or one road section goes out of function, the shortest path between a pair of intersections changes. For example, in case that bridge 6 is not functioning such as under rehabilitation or replacement, the shortest path between a and b changes to path $\mathbf{P}_2$ with eight nodes, as shown with the dotted line. The total length is about 23 km. This example shows that GIS can help the traffic planning in case that one bridge is out of function.

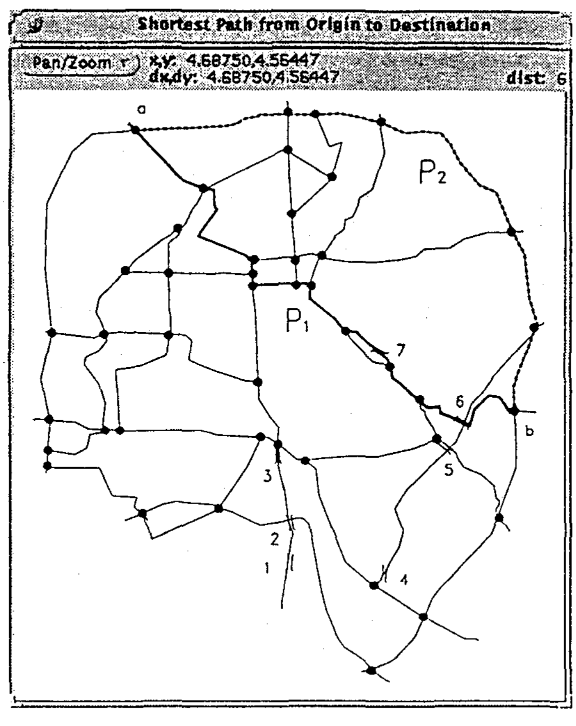


Figure 8 Determination of Shortest Path from Origin to Destination

By adding the traffic data such as the traffic volume and speed, the optimal route with the shortest time can be found considering the origin-destination

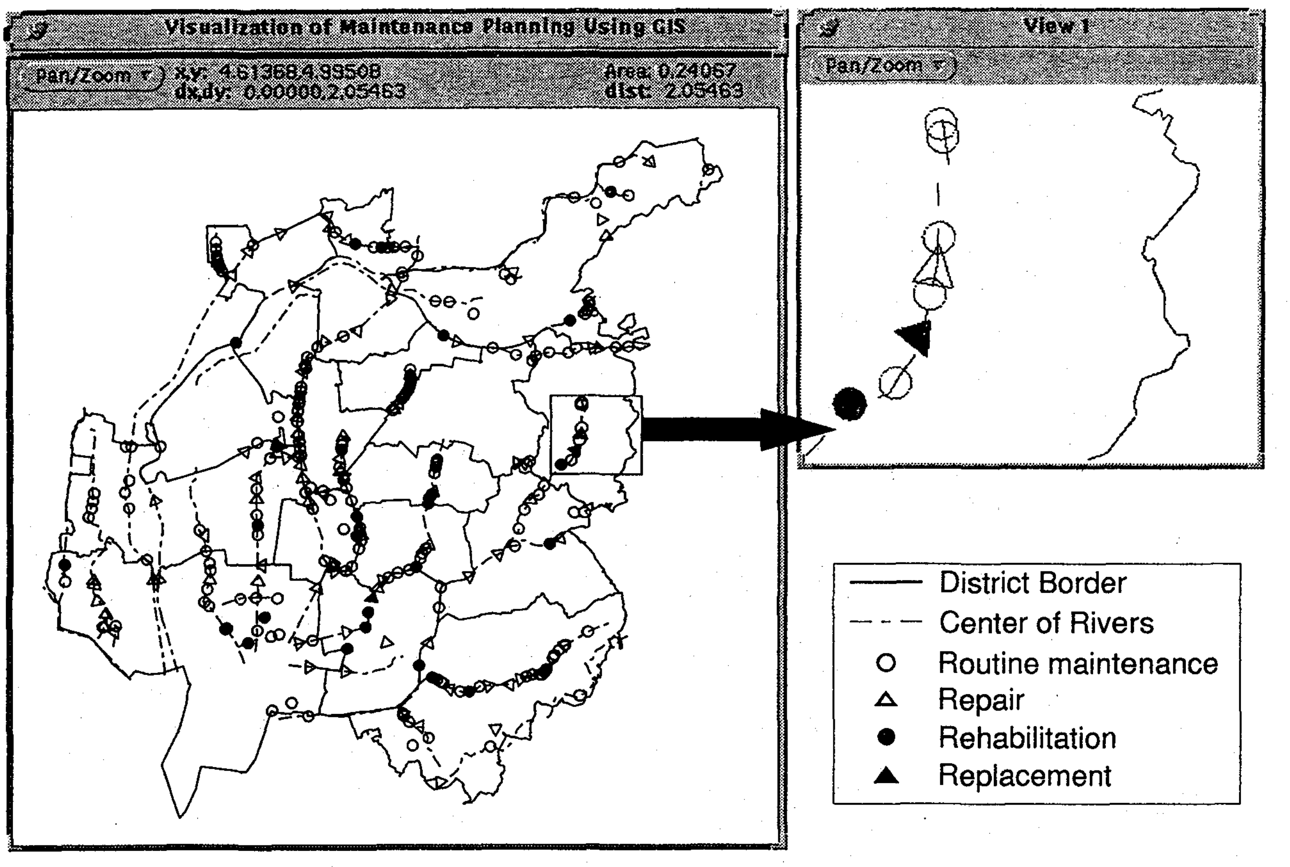


Figure 9 Visualization of Maintenance Planning

patterns. Furthermore, by installing the landuse data, traffic capacity and volume of each road section, and demographic distribution into the system, GBLMS can help bridge engineers to consider other related social, economical, and engineering issues when they deal with bridge management.

4.5 GBLMS Application in Visualizing Maintenance Plan

The bridge stock in many countries is in an extremely deteriorated condition[9]. Significant resources are needed for improving bridges, and preventing further deterioration. Neglecting these deteriorated or deteriorating bridges can lead to the loss of traffic safety, enforcement of load limitations, or the expenditure of substantial resources for premature replacement or emergency maintenance. The optimal solution for management decision can have a significant positive economical impact. However, this selection is extremely difficult because a variety of factors influence the decision making. These factors include the diverse data concerned: (1) project-level data of each bridge such as the design data (materials, dimensions, etc.), service and monitoring data (deterioration condition, load-carrying capacity, etc.), and maintenance data (method, schedule, etc.); (2) network-level data such as the yearly deterioration rate, and prediction of remaining life; (3) related infrastructure data such as traffic volume, and length of detour; and (4) regulative data such as maintenance budget, and structural and functional standards. Therefore, the selection of an ideal maintenance planning needs an interactive procedure under a BMS environment. GBLMS can assist bridge agencies to draw up several maintenance plans of a bridge system and visually check them.

Taking one bridge component of deck as an example, the maintenance plan is optimized for a given period of five years using a *Genetic Algorithm*[16]. GBLMS provides a good interface to represent the optimization results by showing the distribution of the bridges for each maintenance method at every year. Fig. 9 shows the maintenance method of each bridge deck of a maintenance plan at one year. By viewing the maintenance activities of the bridges over one river, traffic planners can visually check the effects of the candidate maintenance plans on the traffic flow, and choose the best maintenance plan. Detailed relationships at a local area can be investigated using the *Zoom* function of ARCPLOT. In the zoomed View 1 window in Fig. 9, eight river-crossing bridges are available in the selected area. The decks of two bridges are to be maintained by rehabilitation and replacement methods, which may severely effect the traffic flow. Based on this display, bridge engineers can also arrange the traffic flow passing these two bridges by investigating the nearby roads.

5. Conclusions

In this paper, a GIS-based bridge management system was presented after discussing the data modeling for bridge lifecycle management. This system was applied for several issues. The principal conclusions of this study are summarized as follows:
(1) Bridge lifecycle data structure and data flow were the basic framework of a bridge management system. By classifying the data into several types, the necessary data at each stage were identified for particular tasks of each lifecycle stage.
(2) The GIS-based bridge lifecycle management system was an efficient approach to integrating the data of each lifecycle stage of a bridge, the lifecycle data of other bridges on a network level, the data of related infrastructure, and regulative data.
(3) It was proved that the GIS-based bridge lifecycle management system could be helpful for bridge engineers to manage the network-level bridges at the service and maintenance stages.

From the bridge management point of view, it is important to integrate the management of all stages of a bridge lifecycle and all bridges in a network-level bridge system. With further development and experimental usage of the present prototype GBLMS, the simplicities in the present version will be lessened while increasing the data volume. More detailed problems of the bridge lifecycle management can also be considered, and more sophisticated models can be developed. In the short term, the role of GBLMS should be explored for further applications. For example, for the project-level management, GBLMS can be used by bridge engineers to incorporate the construction and maintenance issues at the early stages of planning and design, by better understanding the construction site. For the network-level management, GIS provides a wide perspective that is helpful to examine, compare and optimize the management actions of all bridges collectively.

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