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Geographic Information System-Based Visual Simulation Methodology and Its Application in Concrete Dam Construction Processes

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Abstract: System simulation has proved to be an effective tool for planning and improving the performance of a construction process in many successful case studies. However, with the aid of a three-dimensional (3D) visualization system, simulation technology will be engaged to its farthest-reaching potential. This paper presents a geographic information system (GIS)-based visual simulation method, in which system simulation techniques are integrated with visualization techniques. The GIS-based visual simulation system (GVSS) was developed by the authors. The GVSS is a simulation tool offering powerful planning, visualizing, and querying capabilities that facilitate the detection of logic errors in simulation models. The software also helps to understand the comprehensively complex modeled construction process, and is capable of organizing vast amounts of spatial and nonspatial data involved in simulation. A hydroelectric project, which will take place on the Yellow River in the northwest of China, is used as an example. An optimum equipment set scheme is determined by simulating a variety of scenarios taking place under different construction conditions. Likewise, other parameters, such as the construction sequence of dam blocks, the monthly intensity of the concrete process, and the construction appearance at the middle and end of each year, are obtained. Meanwhile, the complex processes of dam construction are demonstrated dynamically using 3D animation, which provides a powerful tool for quickly and comprehensively understanding the whole construction process. The GVSS has proven to be a helpful and useful tool for the design and management of concrete dams.

DOI: 10.1061/(ASCE)0733-9364(2004)130:5(742)

CE Database subject headings: Dam construction; Geographic information systems; Simulation; Imaging techniques; Three-dimensional models; Optimization; Dams, concrete.

Introduction

Concrete dam construction is normally the most critical construction process in a hydroelectric project due to its great influence on a project's cost, duration, quality, and safety performances. The dam construction process is extremely complicated and creates great challenges in terms of project management. Project managers must synthetically consider the unique surrounding environment, the distinct structure of the concrete dam, and the diverse and emerging construction technologies affecting the project construction process. Only after carefully investigating the spectrum of influencing factors, efficiently configuring every step of the dam construction process, and making a reasonable project schedule, is it possible to achieve the project objectives. However, it becomes difficult for engineers to arrange the construction sequence of dam blocks manually due to the large quantities of dam blocks, the large volume contained by the dam, and other various construction constraints. The construction rate, namely, the monthly increase in the concrete's height, is set based upon the experience. However, this experience is not adequate to verify the feasibility of a project or to optimize a project's schedule. With the rapid development of simulation technologies, the numerical simulation and visual demonstration of concrete dam construction processes become possible. This paper proposes a new simulation strategy, in the form of geographic information system (GIS)-based visual simulation methodology, intent upon improving the facilitation and implementation of a project schedule.

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Note. Discussion open until March 1, 2005. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on February 5, 2002; approved on August 5, 2003. This paper is part of the ***Journal of Construction Engineering and Management***, Vol. 130, No. 5, October 1, 2004. ©ASCE, ISSN 0733-9364/2004/5-742–750/$18.00.

Review

Discrete system simulation has been used to plan and analyze construction processes for over 3 decades. Many general-purpose simulation tools have been developed. These contributions include *CYCLONE* (Halpin 1973), *TCM* (Moavenzadeh and Markow 1976), *SCRAPESIM* (Clemmins and Willenbrock 1978), *SIREN* (Kavanagh 1985), *RESQUE* (Chang 1986), *COOPS* (Liu 1991), *CIPROS* (Odeh 1992), *DISCO* (Huang and Halpin 1994), *STRABOSCOPE* (Martinez 1996), and *SIMPHONY* (Hajjar and

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AbouRizk 2002). Many successful applications of system simulation technology testify that they are effective tools for planning and improving the performance of a construction process (Halpin 1977; Paulson et al. 1987). These application include: tunneling (Touran 1987), learning development (Hijazi et al. 1992), earth moving and heavy construction (Vanegas et al. 1993; Smith et al. 1995), bridge construction (Huang and Halpin 1994), and pipeline construction (Shi and AbouRizk 1998). The authors (Zhong and Li 2002) have also studied the traffic and transportation systems of complex underground structures using simulation technology. In this paper a new application field is explored. A simulation tools developed based on a *CYCLONE* will be used to analyze concrete dam construction processes.

Despite the widespread application, simulation has not yet been used to its maximum potential in planning construction operations (Huang and Halpin 1994). One reason for this is the difficulty in detecting modeling logic errors in the development stage. Although hierarchical and modular modeling concepts (Zeigler 1987; Odeh 1992) have been proposed to simplify simulation model building, these concepts offer little advantage for simulation modelers to debug models during the development stage. In order to detect error, the modeler has to be both a professional simulationist and a construction engineer. This drawback results in a lack of credibility for the simulation model itself and constitutes a major impediment to the widespread use of simulation technology.

Project managers also struggle with the large amount of output produced in the form of static graphs and tables by the simulation tool. They must determine construction sequence and make decisions by carefully investigating and analyzing a great quantity of tedious data. This deficiency damps those project managers' ardor for utilizing simulation tool.

As the complexity of project construction increases, a project manager will receive increased information and data. The difficulty for the project manager is the efficient organization and management of these vast amounts of data. In particular, there are certain data depicting spatial relationship between construction objects. Most simulation tools are capable of optimizing construction sequences and establishing project plans. However, the tools lack the capability to represent explicitly information involved in the simulated construction process. Project managers are forced to search for design blueprints and data reports that are needed when using simulation tools.

Geographic information system is utilized to overcome the above-mentioned limitations in this paper. Camp and Brown (1993) state GIS as an information management system capable of collecting, storing, retrieving, and manipulating information based on spatial location. Commercial GIS provides the means to handle spatial data, perform spatial analysis, and produce graphic output. Three-dimensional (3D) spatial data are used to represent elements that have physical dimensions in 3D GIS (Turner 1990; Li 1994). Employing time as an attribute of the 3D spatial model, GIS can depict the simulated operations dynamically in a 3D environment as being carried out in the same way as they would be in the real world, which helps to detect performance inconsistencies and obtain insight into the simulated construction operations. The GIS also contains facilities for constructing and importing the triangulated irregular network (TIN) (Miles and Ho 1999). The TIN is useful for representing topographic conditions that dam construction operations are highly dependent on. The volume of cut and fill with TIN can be calculated using the triangulation technique. Spatial and nonspatial queries of the model result are valuable capabilities of GIS to supplement visualization of simulated operations, which is implemented by a data-base engine and a geometric modeling engine (Oloufa and Espino l992).

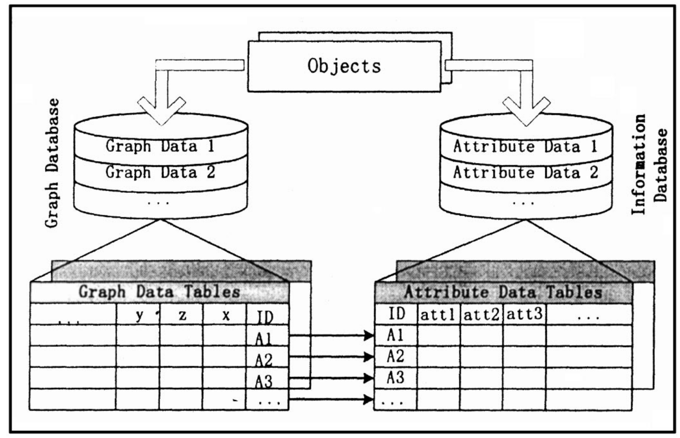

Fig. 1. Schematic diagram of data organization in geographic information system

In the subsequent section, these capabilities of GIS that are used as a supplement to simulation are presented in detail.

Geographic Information System Visualization Methodology

Data Management

An appealing feature of GIS is its ability to organize spatial and nonspatial data. Spatial data are used to represent models that possess physical dimensions as one of their major attributes. For instance, the shape, size, and location of a structure will all constitute spatial data, while the structure's name is a nonspatial attribute. In GIS, an object is depicted using spatial data as well as a set of nonspatial attributes that are items of descriptive information. A graph database is created for storing spatial data, such as geometric shapes and topological relationships, while nonspatial attributes are stored in an information database. Graphic data are mapped to attributes of the common identification, which is automatically assigned to the data when stored. Fig. 1 shows a schematic diagram for the organization of spatial and nonspatial data. When users select a model, the information database is accessed according to the appropriate identification. The pertinent information belonging to the model is subsequently retrieved. Coordinate data from the graph database can also be retrieved by the database engine, and then displayed using the geometric modeling engine. This is accomplished with the aid of a program written in GIS programming language.

Three-Dimensional Digital Modeling in Geographic Information System

The 3D model is the basis of visualization. The 3D digital models of the concrete dam construction system in GIS are divided into two categories: a digital terrain model and a digital entity model. A digital terrain model depicts the topographic condition around the construction site itself, in which entity models are laid out. The digital terrain model is represented using a TIN. A TIN consists of a set of nonoverlapping, adjacent triangles defined by a set of discrete, irregularly spaced points. It is useful for representing

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surface that are highly variable and that may contain discontinuities (Camp and Brown 1993). In this study, a TIN is developed from a contour imported from *AutoCAD* file. All TIN operations using topological data are controlled by GIS procedures.

Three-dimensional digital entity models involve structures permanently and temporarily built in a concrete dam construction system. The GIS can model any face with a complex boundary using three types of shapes provided by the program: point, line, and polygon. A structure is then constructed by closing these faces. This representation is adequate for modeling purposes, because only the geometric shape of the structure is of concern. The entity model, as compared to the terrain model, includes time information, which GIS uses to animate the detailed dynamic construction processes in sequence.

The 3D terrain models and entity models can be rendered with realistic textures pasted on their surface in order to represent them with more fidelity. Some functions in the 3D GIS model are in charge of performing the task.

Three-Dimensional Visualization

The GIS facilitates a comprehensive understanding on the part of the user, of the 3D modes, and of the topological relationship between them in many ways. The users may choose to zoom into the specified zone for a closer view. The users also have the option of rotating 3D models around the x, y, or z axes to observe the models more clearly. The models can also be viewed from any direction and from any angle, even flown through along a specified route. A major advantage of GIS is its ability to maintain data associated with a variety of different models in separate layers based on the same geographic referencing system, which can be superimposed spatially to support data queries and analysis.

Animation is a rapid play of a serial of static pictures. Three-dimensional animation visualizes the complex construction processes at any moment and, furthermore, dynamically reflects the spatial transformation and geometric shape change that occurs within the simulation process. The appearance of the model $i, \nu_i(t)$, is determined by the project schedule resulting from simulation. Accordingly, the whole appearance of dam construction system $V(t)$ is made up of all $\nu_i(t)$, namely

$$V(t) = \sum_{i=1}^{n} \nu_i(t) \tag{1}$$

where n=number of total models. The equation $\nu_i = f_i(x_i, y_i, z_i, t)$ illustrates that the shape of model i varies over time. The whole appearance of the dam construction system and its related attributes at any moment are stored in graph and information databases, respectively. When animating, a computer retrieves the shape and attributes of the model in a time order, then continuously renders it on the screen. The complex concrete dam construction processes are thus demonstrated by a rapid display of such serial pictures.

It is significant to note the animation can start and pause during a demonstration as needed in order to permit users to observe the static picture in detail.

Information Inquiry

The GIS provides several convenient methods for retrieving data. For example, the users only need to double click the mouse on a digital model, and the pertinent information will be retrieved and displayed. The graph database engine will respond and output the graph's identification when a 3D model is selected. The information database engine then searches in its database for records with the same identification as the initial digital model. The result is subsequently displayed. If users require more detailed information, such as original design blueprints and reports, the hotlink is a helpful function. Users select the concerned shape, then press the hotlink button, and the needed information will appear in a popup window, as illustrated in Fig. 2. The operation is executed using a procedure developed by the authors. Occasionally the appearance of the construction system state at a specific moment is valuable for users in making a decision. The GIS enables the user to choose the picture directly rather than playing the animation repetitively. The users must simply specify the data they require, and the construction appearance and associated information automatically displays in front of them.

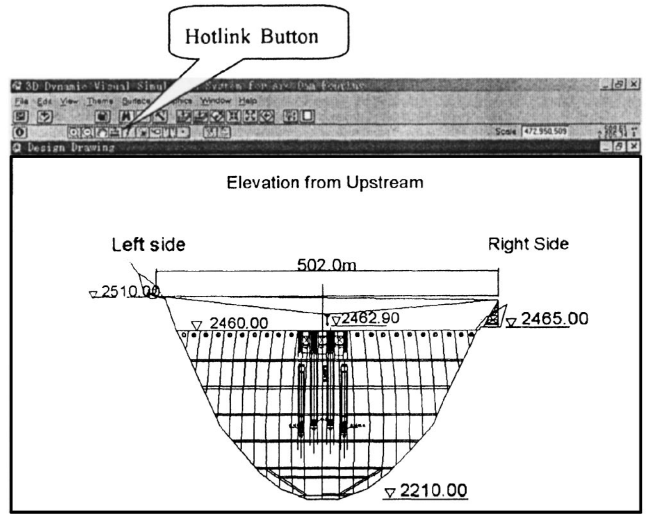

Fig. 2. Inquired information by hotline

Simulation of Concrete Dam Construction

Concrete Dam Construction Processes

Generally, the concrete dam construction process consists of three main tasks: producing concrete, transporting concrete, and pouring concrete, as illustrated in Fig. 3. As the third task plays a more important role in the total process, and is far more complex than the other two tasks, this paper will focus on it. The third task is further divided into two parallel processes. The first process is the conveyance of concrete from a concrete load site to the specified dam block ready for construction. The other process includes preparation work (such as dismantling or erecting a molding board, installing water cooling pipes, or setting up a rebar), unloading concrete into a molding board, spreading the concrete, consolidating the concrete, and curing the concrete. The only intersecting job of the two processes is unloading the concrete into a molding board. Construction operations are carried out in open environments, making them susceptible to such factors as weather conditions and work efficiency, which are hard to predict or control. Thus work in a dam construction system usually has a stochastic duration.

The volume of a concrete dam is often many millions of cubic meters. For example, 12.38 million m^3 makes up only one half of the concrete dam at the Three-Gorges hydropower station. Thus it

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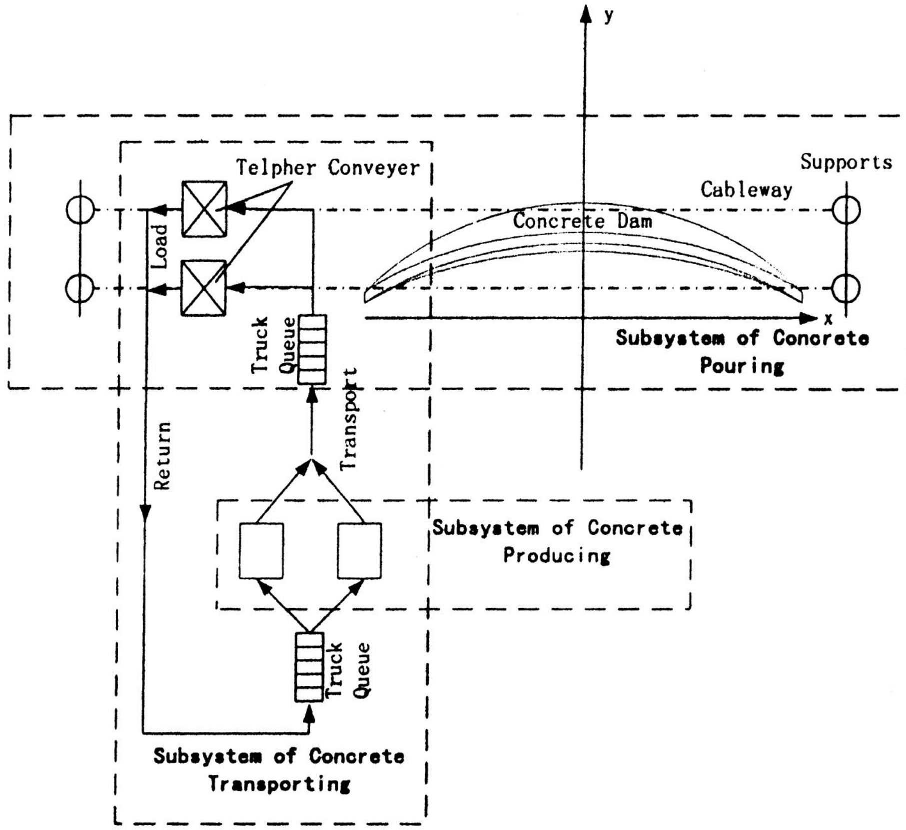

Fig. 3. Schematics diagram of concrete dam construction system

is impossible to construct a dam as a whole. When concrete is cured it generates a great quantity of heat, which can cause tension stress that may generate cracks in the concrete structure. Therefore concrete construction must be implemented in small quantities and on a large surface area in order to emit heat as quickly as possible. Another constraint comes from limitations in equipment. Most kinds of equipment are designed to transport concrete only hundreds of cubic meters each hour or even less. However, concrete must be unloaded, spread, and consolidated immediately before it solidifies. The solidification time is usually 3–6 h. It is beyond the equipment's capability to transport millions of cubic meters of concrete in several hours. All the limitations force concrete dams to be divided into dam blocks. As an example, an arch dam is separated into segments using crevices along the dam's center axis, as showed in Fig. 4. As the dam rises up, the crevices will be filled with concrete in order to interlock all the dam segments. One segment is constructed layer by layer, while a layer is constructed in the concrete solidification time. A dam block comprises several layers that are constructed in same period of time. A dam block is a basic unit for dam construction.

Concrete dam construction is a repetitive process, as the dam is built by constructing all the dam blocks in a certain sequence. Similarly to the foregoing description, the construction process of each dam block consists of typical–load–transport–unload–return cycles involving the transportation of concrete from the load site to a specified dam block. Therefore, the process is abstracted as a queuing system, in which telpher conveyers act as servers and dam blocks as clients. The following section discusses the system model thoroughly.

Simulation Model

In Fig. 5, the concrete dam construction is represented using a simulation model, in which the elements are same as *CYCLONE*. At the beginning, a telpher conveyer is waiting to transport concrete. To load the telpher conveyer, a completed dam block should be available. The telpher conveyer must transport concrete n times to finish a dam block. The volume of the dam block and the capacity of its conveyers determine the value of n. After the telpher conveyer is loaded, it travels along a cableway to the site where the dam block is located. Then, it slowly descends to the top of the dam block and unloads the concrete. After unloading,

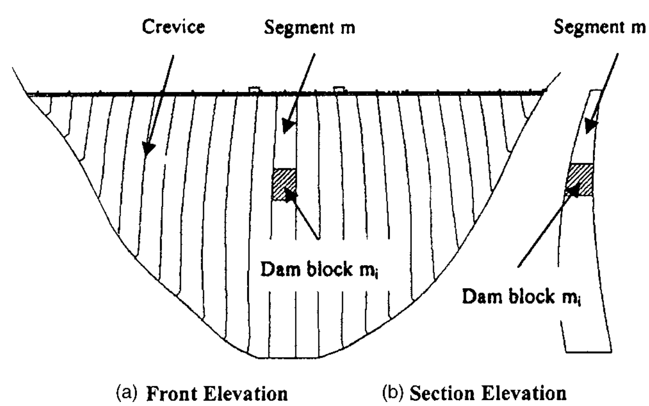

Fig. 4. Schematic diagram of dam block

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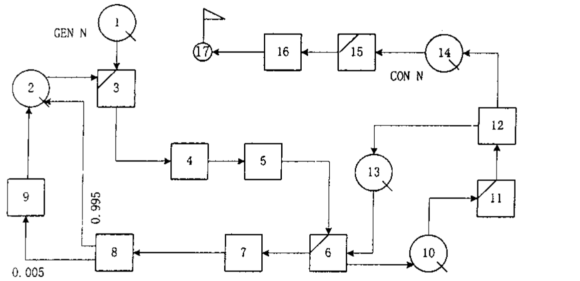

Fig. 5. Simulation model

the telpher conveyer moves up and returns to the load site. Simultaneously, concrete is spread and consolidated. The process repeats itself *n* times until the dam block is finished. Then the conveyer returns and enters the queue. There is a 0.5% probability that maintenance will be done prior to the conveyer entering the queue for reload. After the dam block is finished, it is cured. The molding board will be dismantled when it reaches a certain rigidity. After that, the dam may be constructed. When all dam blocks are finished, the concrete dam construction process is complete.

It should be noted that the queue Node 1 and queue Node 2 have different queuing disciplines. Queue 2 is a first in first out node. When the telpher conveyer returns to the loading site, it enters the queue at the end. Queue 1, on the other hand, is a priority queue. A dam block, meeting all the following constraints, has a priority coefficient of one, while dam blocks, failing to meet the following constraints, possess a priority coefficient of zero.

Constraints

1. A new dam block can be constructed only when the dam block under it reaches a certain rigidity. If it does not, the priority coefficient becomes zero.
2. A dam block must maintain the least difference in height with adjacent dam blocks in order to emit heat as quickly as possible. However, the height difference between dam blocks cannot extend beyond the maximum allowance. Should such a condition arise, many tasks such as erecting and dismantling molding boards would be limited by spatial restrictions and would result in a decline in productivity. If a dam block violates any one of the limitations, its priority coefficient becomes zeros.
3. In order to ensure construction safety, the distance between any two Telpher conveyers cannot be less than the distance that has been predetermined to be least safe. Therefore, a selected dam block must be located a safe distance from the dam blocks being constructed at that moment. Should this not be the case, the priority coefficient becomes zero.
4. To avoid disturbing other dam blocks, a given dam block may be selected on the premise that its adjacent dam segments are not being constructed at that specific moment. If the dam block is selected improperly, however, the priority coefficient becomes zero.
5. If there are several dam blocks meeting all of the above-mentioned constraints, the lowest dam block is selected in order to average the rising height of each dam segment. The other dam blocks' priority coefficients are set as zero.
6. There remain certain specified constraints that must be observed in addition to the five above-mentioned constraints. These additional constraints vary depending upon the project. Therefore, the construction constraints must be analyzed specifically before modeling.

Attention must be given to queue Node 1 that the priorities of the dam blocks vary with time. The priorities of the dam blocks should be recalculated each time Telpher conveyer gets ready and a waits an available dam block.

Duration of Simulation Activity

To make the simulation realistic, the collection of simulation activity durations has been investigated. Through interviews with construction engineers and an analysis of analog construction projects, these set were collected. Loading and unloading times were calculated as normal distributions based upon the collected data and using a normal curve-fitting algorithm. The spreading, consolidating, curing, and dismantling mold board times are likewise calculated as normal distributions. Transport and return times are calculated using an empirical equation

$$\text{Transport or return (min)} = \frac{\text{Hor Distance}}{\text{Hor Velocity}} + \theta_h \tag{2}$$

where Hor Distance=horizontal distance from load site to the site of ready dam block; HorVelocity=horizontal velocity of a telpher conveyer along the cableway; and θ_h= stochastic variable with a normal distribution.

Similarly, the descend or ascend times are calculated using an empirical equation.

$$\text{Descend or ascend time (min)} = \frac{\text{Ver Distance}}{\text{Ver Velocity}} + \theta_v \tag{3}$$

where VerDistance=vertical distance from load site to the site of a ready dam block; VerVelocity=vertical velocity of telpher conveyer; θ_v=stochastic variable with a normal distribution; and both θ_h and θ_v represent the stochastic essence of the transportation process.

Geographic Information System-Based Visual Simulation System

The GIS-based visual simulation system (GVSS) was developed with GIS and *Visual C++*. It provides a platform that implements simulation and 3D dynamic demonstration in an integrated environment. A depiction of the overall environment is presented in Fig. 6.

Integration Methodology of Geographic Information System and Simulation

There are two ways by which the integration of GIS and simulation can be achieved. The first is the. "melting Pot" approach in which the functionalities of the two tools are combined into one. The advantages are numerous, but the required investment of the development is prohibitively high. The second approach to the integration involves sharing information between the two distinct

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Table 1. Stochastic Duration of Activities

Activities or variable	Type	Expected value (min)	Standard deviation
Activity 3	normal distribution	1.1	0.3
θ_h	normal distribution	0.3	0.05
θ_v	normal distribution	0.2	0.05
Activity 6	normal distribution	1.5	0.3
Activity 12	normal distribution	2.5	1.2
Activity 13	normal distribution	5.5	1.0
Activity 16	normal distribution	4,320.0	180
Activity 17	normal distribution	2,880.0	80.0

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systems by extending each of them. This approach is cost effective, as most GIS and simulation tools are extendable. In this paper, the latter method is adopted.

Data Collection and Management Module

The input data includes topographic data, shape and size of structures, and the layout of the construction system. Topographic data are usually imported using data files produced with *AutoCAD*. Spreadsheets are another way to input data. Inputting data through the keyboard is also permitted. The input shape data and properties are stored separately in graph and information databases. In particular, GIS can exchange data with *Visual C++* through the extended function. *Visual C++* is the programming language used to develop the simulation program that will generate detailed information regarding dam construction processes. This includes the construction sequence of dam blocks, the start time and construction duration of each dam block, the efficiency of equipment, and the monthly intensity of concrete construction. The results are saved in spreadsheets, which are employed by GIS.

Simulation Module

The simulation tool has been demonstrated as useful in the decision-making process. The tool helps to predict the construction rate in the preparation phase of construction. After modeling different construction conditions using GVSS, the most reasonable and economical scheme of equipment set can be determined. Correspondingly, other parameters, such as construction sequence of dam blocks, monthly intensity of concrete construction, and construction appearance at the middle and end of each year, may be obtained. The data are valuable for project managers to plan schedules.

Three-Dimensional Animation Module

Three-Dimensional animation addresses the deficiencies discussed in review. It helps to detect logic errors in the models. For example, through 3D animation, a developer can easily observe if any adjacent segments will retain a height difference. If they do not, the dam block queuing discipline is not reasonable.

The complex processes of dam construction are dynamically demonstrated in 3D animation, which provides a powerful tool for quickly and comprehensively understanding the complicated construction process. As a result, it facilitates the exchange of ideas between managers and technicians, avoiding misunderstanding and obfuscation. Even nonprofessionals can join the discussion and give some insightful advice.

Table 3. Construction Durations under Various Schemes

Schemes	Number of Telpher conveyers	Generating electricity date	Construction completion date
1	2	Dec 21, 2009	Dec 6, 2010
2	3	Sep 3, 2009	Aug 12, 2010
3	4	Aug 27, 2009	Aug 3, 2010

Information Query Module

If users need more information to support their opinion, they can find it by clicking on the graph or specifying simple data. Efficient organization and management of vast amounts of data involved in project construction relieves managers from the heavy task of handling data. Project managers will no longer be required to search for design blueprints or data reports needed as a result of the implementation of the simulation tool.

Reporting Module

The reporting module organizes a great deal of data produced by the simulation module. Some of the data are saved in specifically formatted reports. The remainder of the data may be kept in sheets for further analysis. Charts are also a straightforward method of interpreting simulation output.

Case Study

Project Description

An actual hydroelectric project, located on the Yellow River in northwest China, is used here as an example. The arch dam is 250 m high with the dam's crown at 2,460.0 m and its base at 2,210.0 m. It is divided into 24 segments and 1,644 dam blocks, with a total volume of 2.342 million m^3. Some dam blocks close to the base have three layers that are 0.5 m thick, while others have six layers. The maximum volume of a dam block is 1,653 m^3, the minimum volume is 1,021 m^3.

Telpher conveyers with a volume of 9 m^3 are utilized to transport concrete. The conveyers' horizontal velocity is 450 m/min

Table 2. Suitable Construction Days of Each Month

(a)						(b)					
January (days)	February (days)	March (days)	April (days)	May (days)	June (days)	July (days)	August (days)	Sept (days)	October (days)	November (days)	December (days)
15	10	18	27	27	25	25	27	27	27	27	25

Note: The work time of every day is 18 h.

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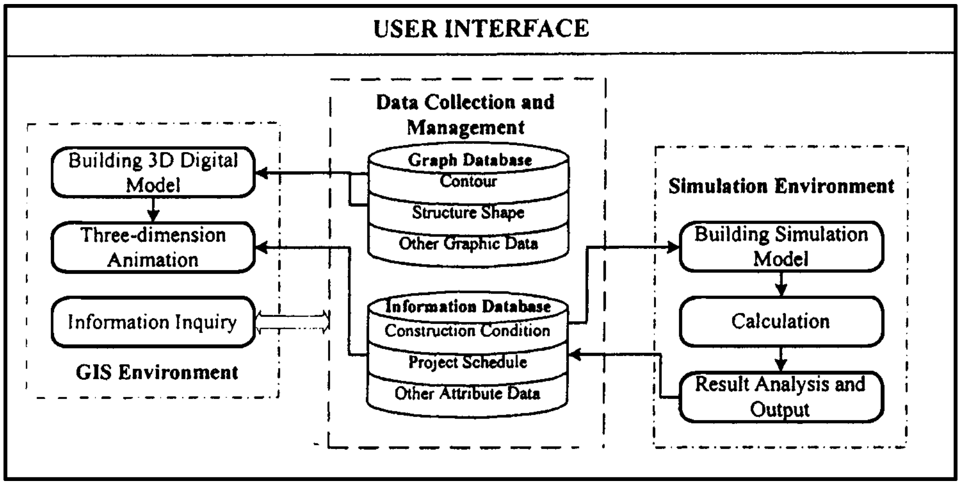

Fig. 6. Structure of geographic information system visual information system

with a vertical velocity of 180 m/min. When the Telpher conveyer returns, it has a 0.5% potential of receiving a thorough maintenance within 7 days.

A vast amount of data are collected and used to calculate the duration of simulation activity. The distribution type, expected duration, and standard deviation of stochastic activities are summarized in Table 1.

As previously mentioned, only when a dam block has been finished and its molding board dismantled, is it possible for a new dam block to be constructed on it. Moreover, the maximum and minimum height differences between adjacent segments are 12 and 4 m respectively. Any two Telpher conveyers must keep at least 10 m off for safe operation. The span of the Telpher conveyer is 502 m. Other parameters may to reference Fig. 2.

The climate condition affects construction progress greatly, especially for concrete construction. The precipitation and temperature are two vital factors postponing the project. As a normal principle, either when precipitation is up to 10 mm/h or when the temperature is lower than −20°C (Celsius temperature scale) the concrete construction should stop. Suitable construction days for each month, statistically, are provided through design reporting, and are shown in Table 2. The project starts on October 1, 2006.

Result Analysis

Three schemes with different numbers of telpher conveyers are investigated. Table 3 gives the construction duration and the time when the dam reaches the height necessary for generating electricity. Scheme 2 uses three Telpher conveyers, one more than Scheme 1. As a result, the construction duration is shortened by almost 4 months. First of all, Scheme 2 allows electricity to be generated almost 4 months earlier than Scheme 1. This will bring about enormous economic benefits. Excessive equipment, however, only results in a waste of resources. This is why Scheme 3 is abandoned. Although one more Telpher conveyer is employed, the construction duration is almost the same as that of Scheme 2. Furthermore, electricity may be generated only a few days ahead of the time offered in Scheme 2. For those reasons, Scheme 2 is recommended here.

The other simulation results include monthly intensity of concrete construction, construction appearance at the middle and end of each year, and three-dimensional construction process demonstrations. The monthly intensity of concrete construction as shown in Fig. 7 helps to make decisions regarding the project schedule and to arrange laborers and materials. Due to the vari-

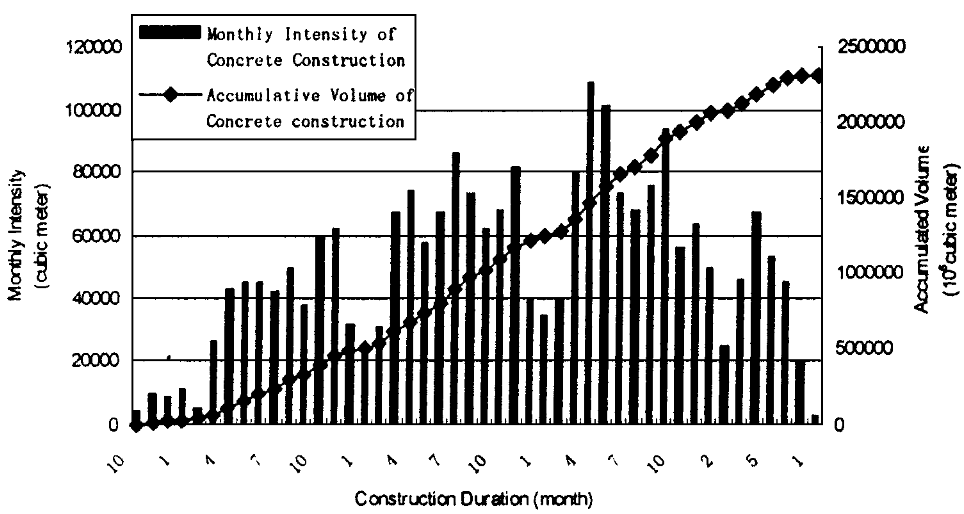

Fig. 7. Monthly intensity of concrete construction and accumulative volume of concrete construction

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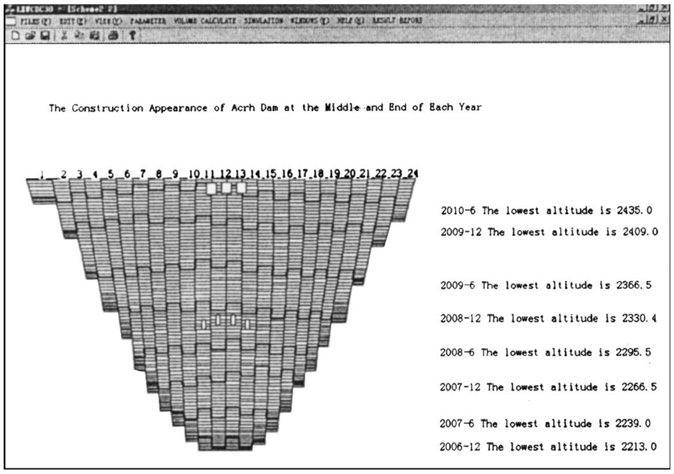
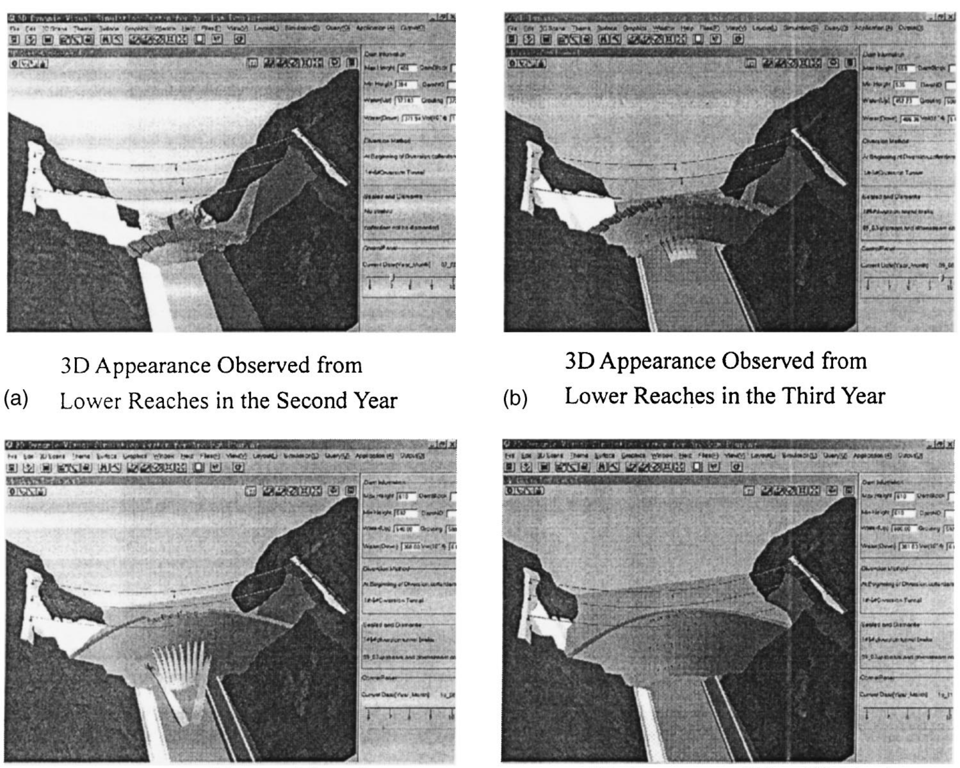


Fig. 8. Construction appearances a middle and end of each year

ance of suitable construction days each month, the monthly intensity of concrete construction varies periodically. Meanwhile, the maximum and average monthly intensities of each year increase significantly. Topographic conditions affect the intensity as well. The V-like valley, where the arch dam is located, is deep and steep. Thus in the beginning phase there are only a few dam segments due to a limitation of space. The dam blocks become bottlenecked and Telpher conveyers must wait for an available dam block. As the arch dam rises up, the valley broadens and more dam segments may be constructed. Likewise, the monthly intensity of concrete construction increases. However, as more and more segments reach the expected height in the last phase, the monthly intensity of concrete construction declines. The construction progress is displayed in Fig. 8. The bold lines represent the construction appearance at the middle and end of each year. The serrated appearance results from dam blocks selected using the second and fourth constraints mentioned in the previous section. More appearances can be obtained through query. Three-dimensional demonstration provides a powerful tool for quickly and comprehensively understanding the complicated processes. Fig. 9 illustrates the 3D animation of arch dam construction process and the relevant construction information generated by GVSS.

Conclusion

The GIS-based visual simulation methodology is presented in this paper. It is a new method for dynamically and graphically simulating the complex construction process. The corresponding software, GVSS, is developed and put into use in an actual hydroelectric project in China. An optimum scheme is selected after simulating the three potential construction schemes. The other parameters such as the efficiencies of equipment, the monthly intensity of concrete construction, and annual concrete construction volume are illustrated using tables and charts. The construction appearance at the middle and end of each year, through one of the simulation outputs, is helpful for engineers to learn the construction rate quickly. Meanwhile, the complex processes of dam construction are dynamically demonstrated through 3D animation, providing a powerful tool for quickly and comprehensively understanding the complicated process. The GIS-based visual simulation methodology and the corresponding GVSS



(a) 3D Appearance Observed from Lower Reaches in the Second Year

(b) 3D Appearance Observed from Lower Reaches in the Third Year

(c) 3D Appearance Observed from Lower Reaches in the Last Year

(d) 3D Appearance When Finished

Fig. 9. Three-dimensional of Arch Dam construction processes and relevant construction information

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software are very useful for the design and management of concrete dam construction.

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