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A Visual Information System for Analyzing Rock Slope Displacement Based on Monitored Data

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This study is a discussion of a new visual analysis technique for rock slope displacement. The presentation is based on data obtained from the system for monitoring displacement at a hydropower station in south China. A database technique, a three-dimensional displacement analysis model, and a visualization analysis technique make up the core of this study, and according to these techniques and methods, a set of software for the analytical slope displacement information system was developed.

Key Words : Displacement monitoring system; Visualization analysis technique; Slope displacement information system; Software system

1. INTRODUCTION

A rock slope landslide is a natural disaster. It may lead to endangerment of lives, demolition of equipment, and the loss of property as other natural disasters such as earthquakes, debris flows and mudslides. In fact, even more serious harm may result if a landslide were to occur near a major construction site.

In recent years, with an increase in the number of large-scale construction projects that are built on or inside a rock mass, the potential problem of landslide has become more and more critical. There are several ways to reduce the chances of surface ground control failures: 1) safe geotechnical designs; 2) secondary supports; or 3) monitoring for advance warning of impending failures. Geotechnical designs can be improved to increase factors of safety. Proper bench designs can minimize landslide hazards, and certain supports systems may enhance overall rock mass strength. However, diligent monitoring and examination of slopes for warning of failure is the most important means of protecting lives and property near the landslide side.

The most important purpose of a slope monitoring program is to: 1) maintain safe operational practices; 2) provide advance notice of instability; and 3) provide additional geotechnical information regarding slope behavior.

Slope stability and landslide monitoring involves selecting certain parameters and observing how they change with time. The two most important parameters are groundwater levels and displacement. Slope displacement can be characterized by depth of failure plane(s), direction, magnitude, and rate of the displacement. One or all of these variables may be monitored. Conventional slope monitoring utilizes a single method or a combination of methods. Piezometers allow the determination of water levels; surveying fixed surface monuments, extensometers, inclinometers, and tiltmeters allow determination of direction and rate of slope movement and depth and areal extent of the failure plane; extensometers provide an indication of displacement magnitude. Manually operated probe inclinometers are the most common means of long-term monitoring of slopes.

Critical facilities (dams, quarries, highways, housing developments, etc.) adjacent to unstable slopes have created a need for monitoring systems which can provide immediate warning if movement occurs. An abundant literature exists on the use of monitoring system in analysis of slopes instabilities, e.g. Carpenter, 1992; Shao, 1993; Hua, et al., 1994; Kaufmann, 1996; Liu, et al., 1997; Wang, et al., 1997; Kane, et al., 1999; Matsushima, et al., 2000; Pretorius, et al., 2001.

In general, the number of survey points of a monitoring network is limited by the economic and engineering conditions of a project. The survey points may be used at all times to monitor the displacement of the key positions of the engineering project and to evaluate the entire stability of a slope. This study aims to develop an analytical visualizing software system for monitored data of each point in the entire engineering area.

The work presented here is based on the practice of a monitoring network used at a hydropower station in south China. In this paper, a logical explanation of the structure of the monitoring system will be introduced. After that, a database for the monitoring information, a three-dimensional displacement evaluation model, a software system, and a visualization method for analyzing the field slope displacement will be discussed.

2. ENGINEERING BACKGROUND

The hydropower station consists of three parts: a solid concrete gravity dam, a plant built on the back side of the right bank of the slope, and a third-class consecutive ship lock built on the left bank of the slope. Fig. 1 shows the left bank of the slope near the ship lock is about 500 m long, parallel to the river, and about 165 m high. The geo-engineering of this project is very complex. There are about six typical creep-deformation and sliding masses at the upper reaches of the dam within 1 to 3 km near the storage basin. In order to get the instructions for slope stability, the monitoring system for displacement of the slope, both during excavation and normal operation, was introduced as the primary means for monitoring.

3. MONITORING SYSTEM

Compressive deformation and shear deformation were primary characteristics of displacement in the middle of the slope, and shear slippage was the chief characteristic of displacement at the bottom of the slope. According to these deformation characteristics, the survey points were arranged mainly at key positions in the slope. Furthermore, the survey points were set up on the surface of the slope, in the tunnel walls, and in the drill holes of the rock masses to establish the three-dimensional monitoring network (Liu, et al., 1997).

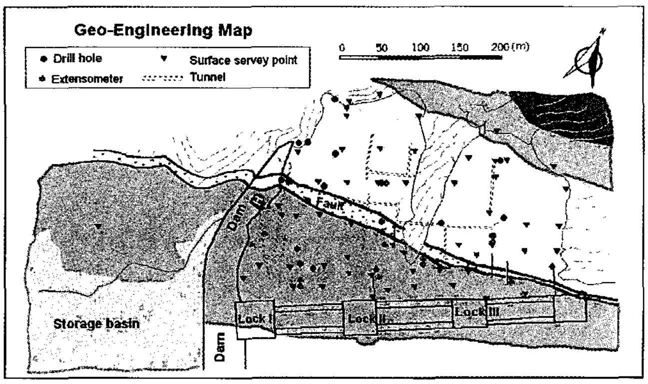


Figure 1 A geo-engineering map of the left slope of a hydropower station in south China

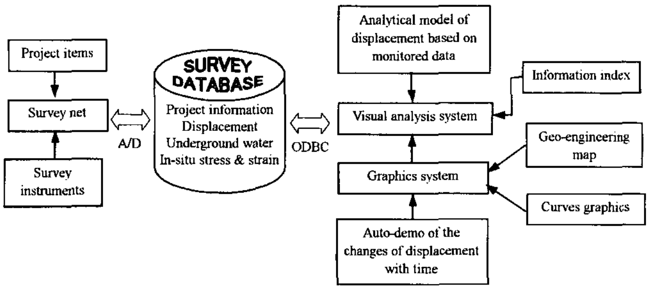


Figure 2 The logical structure of the monitoring and analyzing system

The 64 survey points were laid on six major vertical surface lines on the slope, and each four closest survey points were formed as a group with the shape of a diamond.

Each survey point was set to provide information on both vertical and horizontal displacement. Horizontal displacement of the survey points on the surface was measured by using the triangulation network. Vertical displacement of the survey points was measured by using the circle measuring-line method that is formed by the base point (assuming there is no displacement) and the survey points. Considering the layout of the surface survey points and the distribution of the tunnels excavated prior to the engineering project phase, three measuring lines that included ten tunnels were selected to measure the displacements in the tunnels.

Many of the monitoring methods and apparatuses were adapted to measure the displacement, stress, strain, temperature, and underground water on the left bank of the rock slope. Many of the items were selected to monitor the displacement of the slope, such as horizontal and vertical displacement of the surface, declination and displacement of inner rock masses, as well as displacement of the fault in the tunnels. The apparatuses that were used for monitoring the displacement of the slope included a theodolite, level instrument, range finder, surface inclinometer, multi-points extensometer, drill hole inclinometer, fault monitoring apparatus, and static level instrument. The apparatuses for monitoring the underground water of the slope included a differential resistance osmometer, a measuring weir, a volumeter, and an automatic water level gauge for the drill hole. To measure the strain and stress, the DJ-25 differential resistance strain gauge and a RE-bar stress meter were used.

The monitoring system consisted of three major parts: the monitoring network, the survey database, and the visualization analysis system. The logical structure of the monitoring system is shown in Fig. 2.

4. SURVEY DATABASE

Many survey points were set up on the surface of the slope and in the rock masses. The various elements of the monitoring system were evenly distributed among the survey points. All of the survey points formed a large monitoring network. Therefore, it was very important to establish a database of survey information for sorting, storing, and rapid processing.

Microsoft Access served as the database management system. According to the characteristics of the monitoring information, the information database was constructed with two kinds of data: static and dynamic. Static data were for locations, apparatus properties, and initial data, and dynamic data included the current measurements taken at each survey point.

Two methods were used for collecting the data into the database. The data obtained sequentially from the electric sensor could be input directly into the database by using an Analog to Digital (A/D) technique and a set of program for pre-processing the acquired data, and the data from the other manual apparatus or interrupted apparatus could be input manually into the database by an operator.

5. 3D ANALYSIS MODEL

The primary purpose of establishing the displacement analysis model was to evaluate the displacement of arbitrary position on the surface of the slope and within the rock masses based on the monitored data. By the analytical model, the displacement of any point on the slope could be estimated rapidly, and the analysis results could be shown graphically by using a visualization technique with a microcomputer.

Because the distribution of displacement of the slope depends on the characteristics of the structural properties and randomness of the rock mass, it could, therefore, be described as a regionalized variable in this analysis model. To determine the unknown value of displacement on the non-surveyed point (grid node), some interpolation algorithms were used. Considering the distribution characteristics of the survey points in space, the inverse distance to a power method was used to estimate the displacement of the grid node.

With inverse distance to a power, data are weighted during interpolation such that the influence of one point relative to another declines with distance from the grid node. Weighting is assigned to data through the use of a weighting power that controls how the weighting factors drop off as distance from a grid node increases. The greater the weighting power, the less effect points far from the grid node have during interpolation. As the power increases, the grid node value approaches the value of the nearest point. For a smaller power, the weights are more evenly distributed among the neighboring data points.

Normally, inverse distance to a power behaves as an exact interpolator. The weights assigned to the data points are fractions, and the sum of all the weights is equal to 1.0. When a particular observation is coincident with a grid node, the distance between that observation and the grid node is 0.0, and that observation is given a weight of 1.0, while all other observations are given weights of 0.0. Thus, the grid node is assigned the value of the coincident observation. In order to buffer this behavior, a smoothing parameter is introduced. When a non-zero smoothing parameter is assigned, no point is given an overwhelming weight so that no point is given a weighting factor equal to 1.0.

The equation used for inverse distance to a power is:

$$w_j = \frac{\sum_{i=1}^{n} \frac{w_i}{h_{ij}^{\beta}}}{\sum_{i=1}^{n} \frac{1}{h_{ij}^{\beta}}} \qquad (1)$$

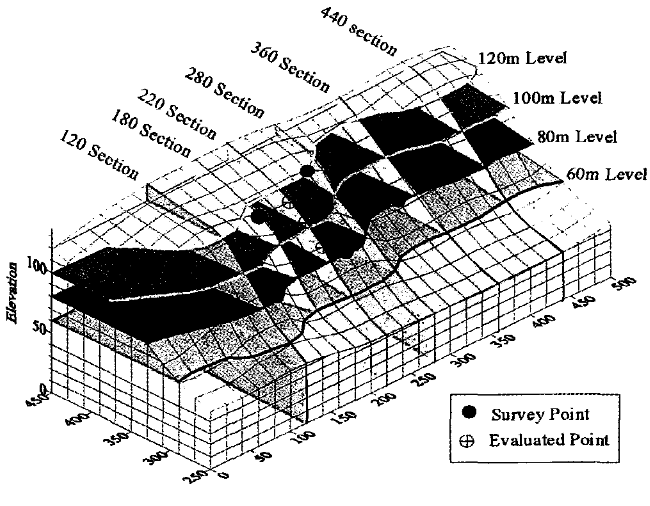


Figure 3 The analysis model of slope displacement

and $$h_{ij} = \sqrt{d_{ij}^2 + \delta^2} \qquad (2)$$

where, h_{ij} is the effective separation distance between jth grid node and the ith neighboring survey point; w_j is the interpolated value for jth grid node; w_i are the neighboring survey points; d_{ij} is the distance between jth grid node and the ith neighboring survey point; β is the weighting power (the power parameter), and δ is the smoothing parameter.

The displacement is expressed as a vector. It has not only the magnitude but also the direction. In order to determine the Gdisplacement at a grid node, the known displacement vector should be firstly divided into three coordination components along the axis directions. After that, the unknown values of displacement components at the grid node should be estimated using the inverse distance to a power interpolation algorithm, and finally, the Gcomponents of the magnitude and direction to the displacement of each point should be compounded.

Sphere and ellipsoid searching are the two primary methods for searching the spatial data. The sphere searching is applied to search the isotropic data, and ellipsoid for the anisotropic data. There are two methods for sphere searching: closest-point and Gsector. The closest-point method is used for estimating data of a grid node at the radius center of a sphere in the data searching range. In this case, data searching starts from the closest point of a survey point to the next closest point and finishes when all of the necessary points are discovered. With the sector method, the searching sphere is divided into several sectors, and the data search is carried out by sector. When the search is completed on all of the sectors, the whole search is finished. Ellipsoid searching is also used for determining the data of an unknown point as the center of the target ellipsoid. Using a variogram analysis, parameters of an ellipsoid can be determined. These parameters include sizes and direction of the ellipsoid. With this method, the power factor of these points will be equal when the data points lie on the same ellipsoid surface. When the number of the survey points is insufficient and the sector searching method is applied for estimating the value of the unknown points, then it will require a greater searching range, which leads to a lesser degree of accuracy.

In the closest-point method, the data searching range is determined by using a step-by-step moving algorithm. According to the average degree of closing of the survey points, the data from the known data points are searched from the closest point until all of the required survey points has been found out.

The minimum radius of the searching sphere can be determined with the following formula:

according to $$\frac{4}{3}\pi r^3 = k\left(\frac{V}{N}\right) \qquad (3)$$

then $$r_{\min} = \sqrt[3]{\frac{3kV}{4\pi N}} \qquad (4)$$

where k is the number of the required points; r is the radius of the dynamic searching sphere; V is the total volume of the slope; and N is the number of survey points.

When the minimum radius is determined, it first has to be judged whether these known data points are sufficient in number for estimating the value at grid node, and if not, the searching radius will be increasing until all of the demands are satisfied.

In order to study the stability of the key positions of the slope, six vertical cross-sections and four horizontal cross-sections were selected as important positions for evaluating the characteristics of displacement (shown in Fig. 3).

6. VISUALIZATION ANALYSIS

For scientific analysis, the core of the visualization analysis is the automatic processing of the data, which enables the user to view the analysis in graph form on the computer monitor.

The data and process flow in the visualization analysis is shown in Fig. 4. This figure shows that the database of the survey information is the foundation of the data processing. All of the information correlated with the analysis process comes from the database. In the entire displacement analysis of the slope, the analysis model is the most important. Furthermore, the graphics system are developed for input, edit, storage, and displaying the basic geo-engineering map or the analysis results. The information index for each survey point includes the data type for each survey point. When the type is selected, the number and the name of the survey point will be shown in a list box. When one of the points is selected, the varying curves for the monitored data, such as the displacement and the level of underground water, will automatically be shown in the graphic area.

Many items are presented in this visualization analysis technique. They include: (1) formation of the contour lines of the displacement on the typical vertical cross-sections and horizontal cross-sections of the geo-engineering project map, (2) creation and display of the displacement lines on the slope surface both in the directions of vertical cross-section and horizontal cross-section, (3) display of the displacement vectors of the original survey points and the evaluated points on the slope border, (4) display of the line of underground water level, (5) index of the properties and physical meaning of each graphic element in the analysis results, (6) automatic demonstration of the analysis

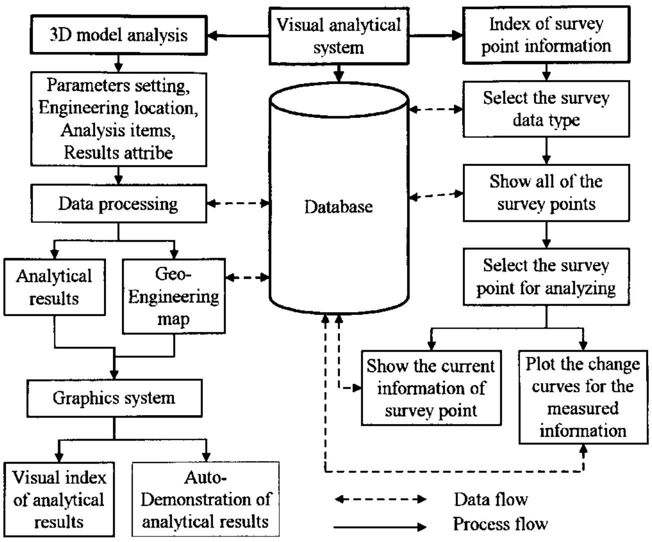


Figure 4 A visual analytical process of the slope displacement

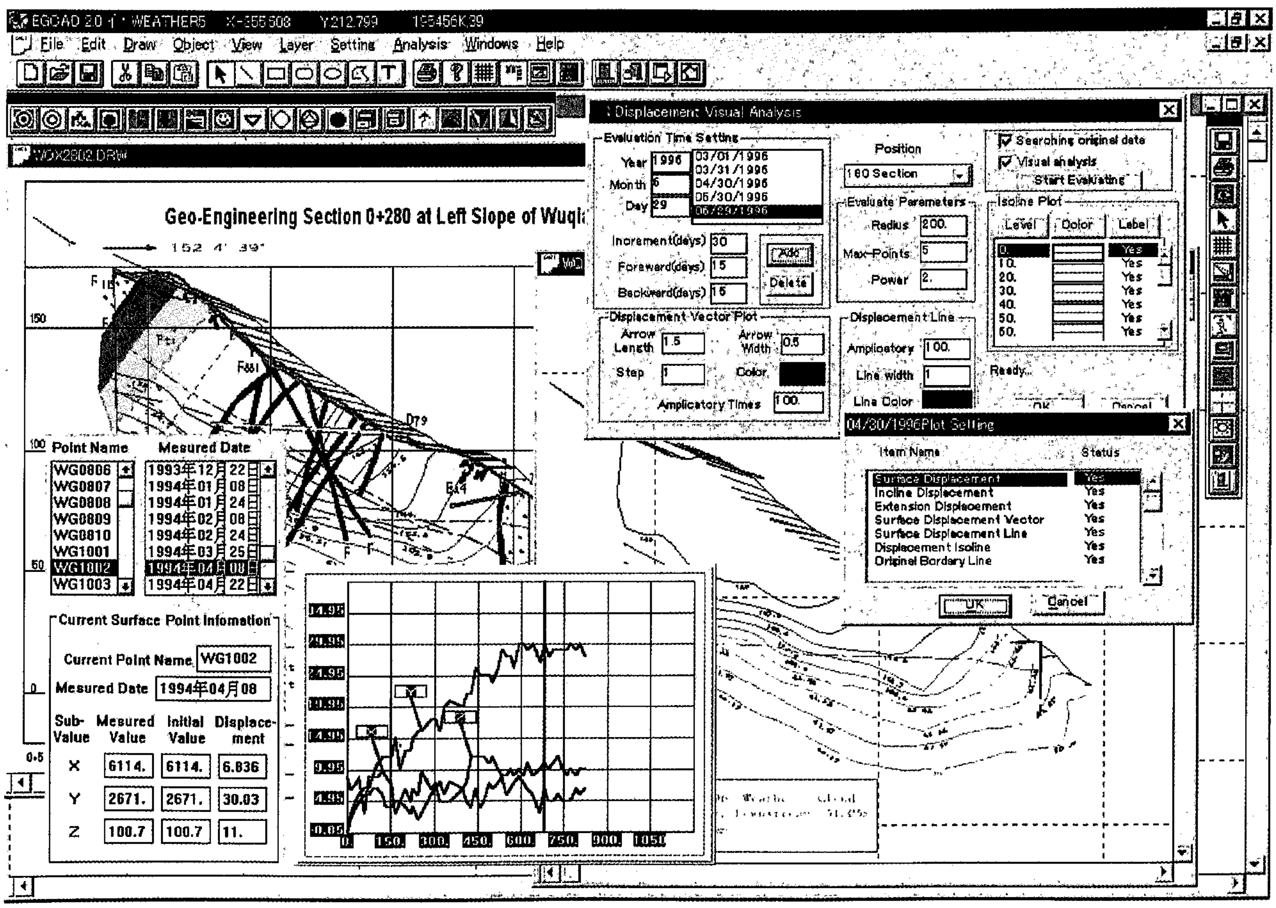
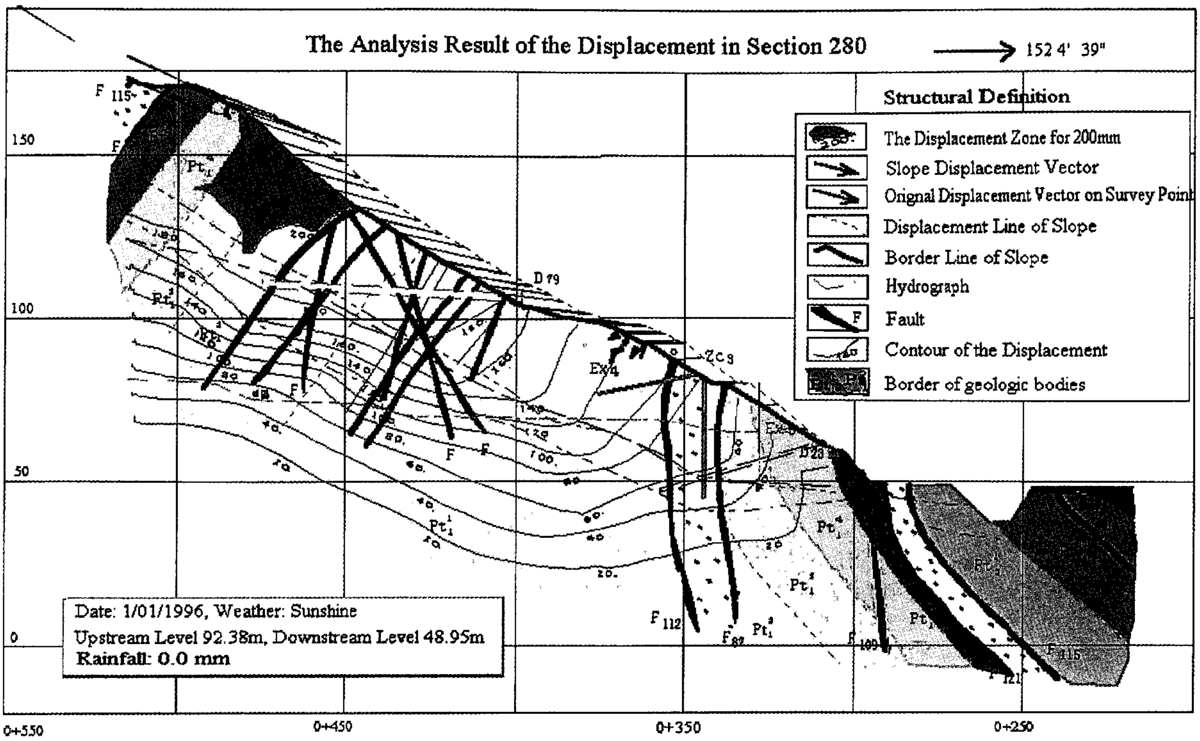
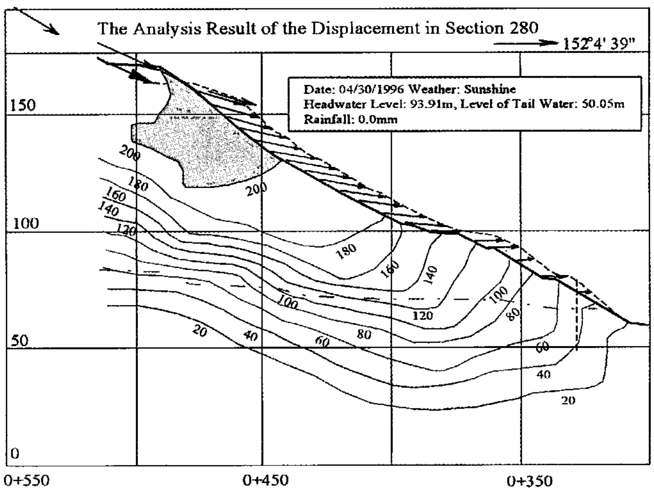


Figure 5 A typical interface of EGCAD system



(a)



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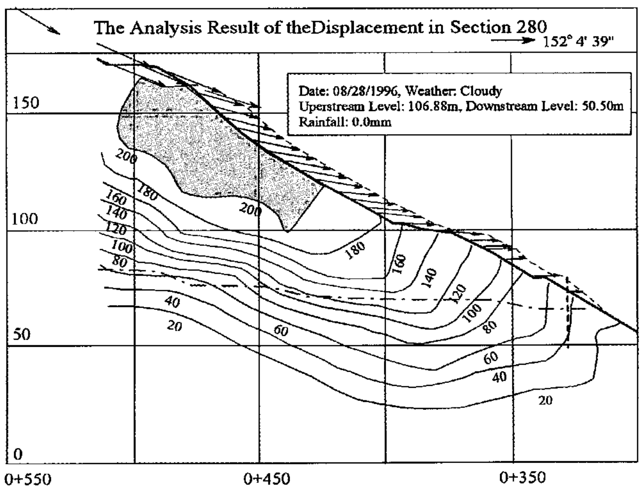

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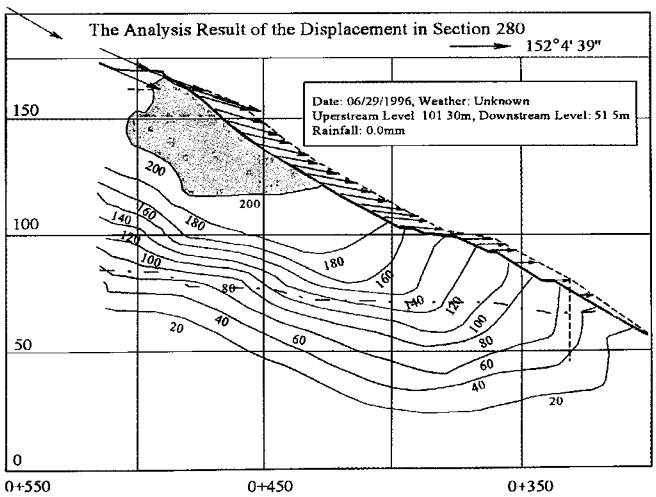
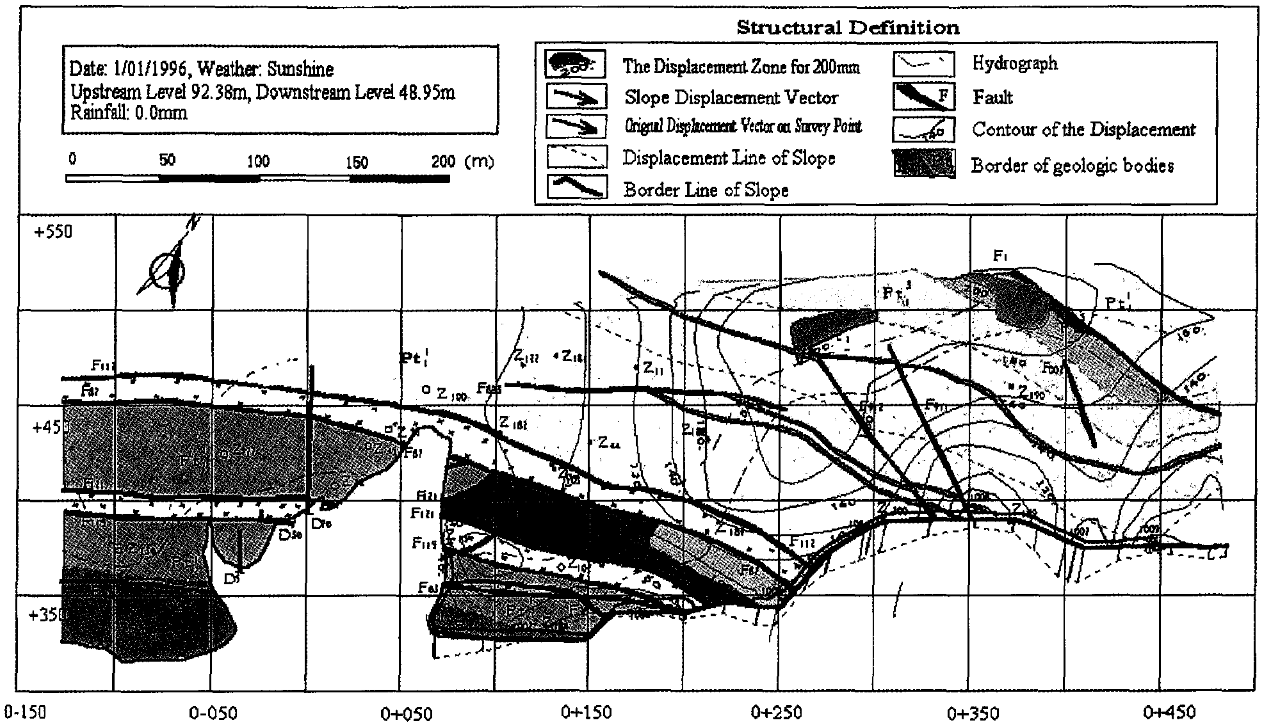


(c)

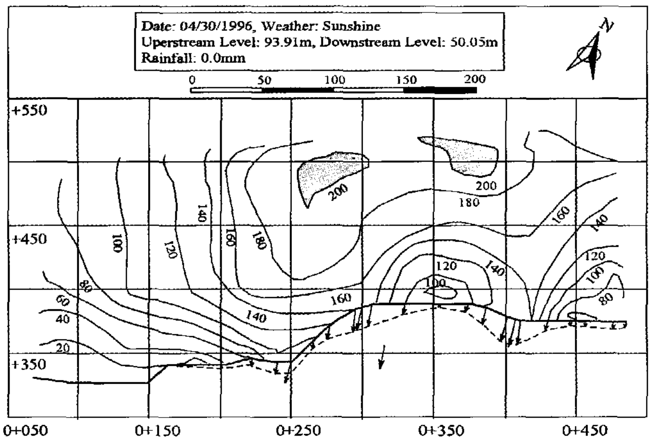
Figure 6 The analysis result of the displacement in a vertical cross-section

results for five different monitoring times, (7) hiding and display of the graphic layers and modification of the attributes of the graphic elements, and (8) coupling of the displacement analysis results and the original geo-engineering map. At the same time, the visualization index of the original survey points is shown in the pattern of the data table and change curves of monitored data with time.

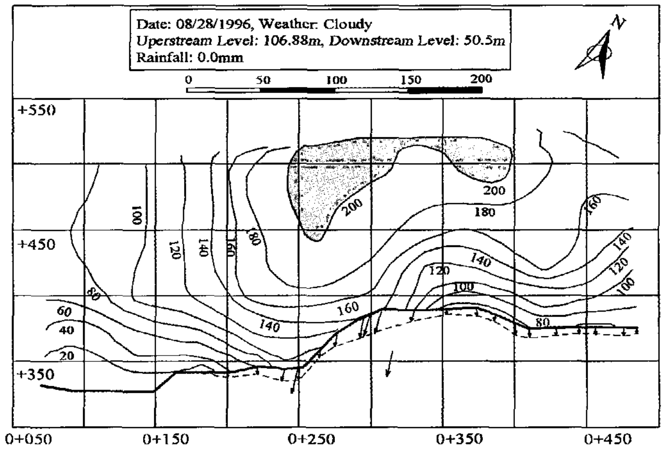
An especially significant characteristic of this study is that a maximum of five sets of monitored data can be evaluated simultaneously, and the results of this data can be stored in graphic layers. The special features of the graph software permit the displacement to automatically show variances occurring at a variety of times.



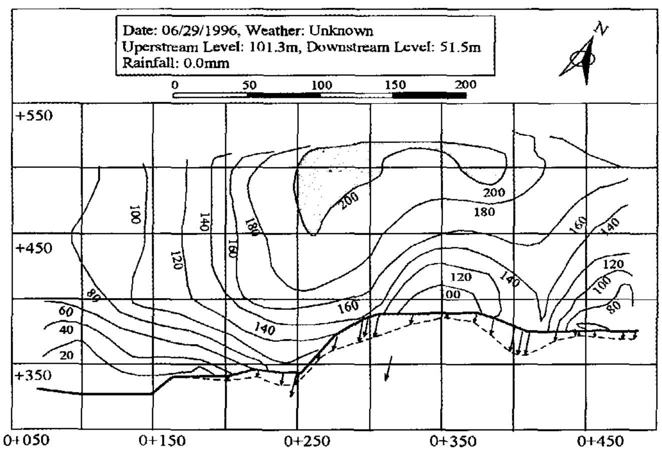
(a)



(b)



(d)



(c)

Figure 7 The analysis result of the displacement in a horizontal cross-section

With the graph layering options, any of the graph elements located in a different layer can be shown or hidden in the display.

7. SOFTWARE SYSTEM "EGCAD"

A software system named "EGCAD" was developed for the purpose of analyzing rock slope displacement visually based on monitored data at the hydropower station by using Microsoft Visual C++6.0 software developing tools. The Open Database Connection (ODBC) technique was used for accessing the database.

The EGCAD system mainly consists of three modules, i.e. graphics module, 3D modeling module and information index module.

The graphics module provides a user-friendly interface and graphics environment. The primary functions of this module include to:

1) Provide a graphics platform for input, edit, storage and output the original geoengineering maps.

2) Provide an interface of graphics data for displaying the analyzed results of displacement with multi-patterns of graphics.

3) Use layers and objects techniques to manage the graphics elements, furthermore, provides a set of tools for demonstrating the changes of displacement with time automatically.

4) Plot the variation curves of monitored data for each survey point.

The 3D modeling module estimates the displacement of each grid node in the geo-engineering horizontal cross-sections or vertical cross-sections using the interpolation algorithm of the inverse distance to a power method. The primary functions of this module include to:

1) Seek monitored data from survey database.

2) Estimate the value of displacement at each grid node.

3) Create contours and vectors of displacement, and forms movement lines of slope.

4) Create and output the graphics data into the graphics system.

The information index module provides a user-friendly interface for seeking all information of each survey point and displaying the changes of monitored data with time.

A typical interface of EGCAD is shown in Fig. 5.

8. CASE ANALYSIS OF THE SLOPE DISPLACEMENT

A typical result of the displacement analyzed for a vertical cross-section in the slope is shown in Figure 6. In Fig. 6 (a), (b), (c), and (d), the items monitored at a variety of times are shown through the duration of a monitoring period.

Figure 6(a), shows the details of the basic geo-engineering map, which highlights the geologic boundaries, faults, excavated tunnels, and survey points of the slope. In order to simplify and clarify the graph, the basic geo-engineering map was hidden intentionally in Fig. 6 (b)-(d). The analytical results shown in Fig. 6 (a)-(d) came from four different monitoring dates: January 1, April 30, June 29, and August 28, 1996. In each figure, a bold solid line inclining to the right shows the original surface line of the slope. The displacement of each survey point and evaluated point that occurred within the elapsed time during the construction of the slope was shown as a fine solid (red in the color display) line of the displacement vector with the length and direction. In addition, a fine dotted line indicated by the envelope on the tips of the displacement vectors shows the movement line on the surface of the slope. The contour lines of the displacement with a step of 20 mm are shown as fine solid lines on the entire vertical cross-section of the slope. With Fig. 6, it was difficult to compare the amount of displacement with these contour lines at different times in the monitoring process. Therefore, in order to make it easier to compare the difference in the displacement, the region where the displacement exceeds 200 mm was filled with a pattern of light gray dots in the monotone graph (green in the color display). With these figures, it was clear that the displacement in the top area of the slope was remarkably huge, and that the value was increasing with the elapsed time. The increment was even more remarkable in the monsoon season from June to August 1996.

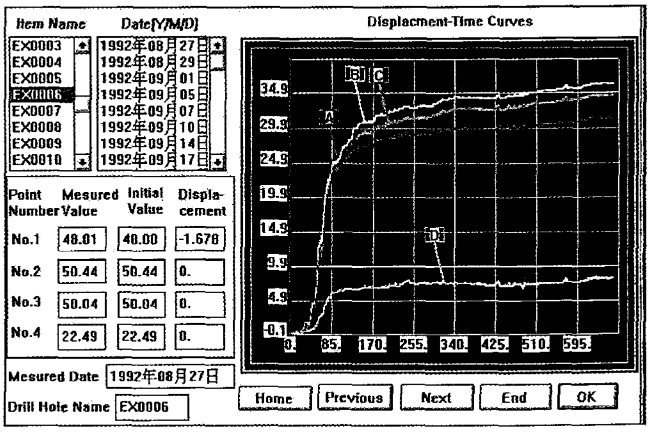


Figure 8 A typical interface for the survey points information index

Typical results of the displacement analyzed for a horizontal cross-section in the slope are shown in Fig. 7(a), (b), (c), and (d), respectively. In this Figure, the monitoring items are shown for four different times, which coincide with the monitoring times shown in Fig. 6. In these figures, the regions where the displacement exceeds 200 mm are also marked with a pattern of light gray dots. It is clear that the regions marked with the light gray dots in these figures increase with elapsed time and that varying patterns are shown with the same tendency as those shown in the vertical cross-section in Fig. 6.

The change in displacement with time measured by using the extensometer, are displayed graphically in Fig. 8. The other information of the survey point are also shown as an information index table in this figure. All of the information of the survey points, such as the surface displacement of the slope, the drill hole inclination, and the level of the underground water, can be shown by using a similar data index interface in this system.

9. CONCLUSION

It is very important to prevent a landslide disaster on a natural slope at the site of an engineering project. Therefore, the establishme00nt of a monitoring network and system for observing displacement and other mechanical conditions of a construction-site slope is also very important. The primary purpose of this monitoring
information system was to facilitate the analysis of information of the slope in a manner that is scientific, accurate, and rapid. Furthermore, the system is to allow for the results to be simply described. Therefore, the visualization analysis method was very useful. And the survey information database was served as a foundation for displacement analysis. According to the characteristics of structure and randomness of slope displacement, a regionalized variable analysis method was adopted to establish a three-dimensional analysis model. A graphic system based on a visualization technique can be used to display the results. This graphic system has capabilities for input, edit, and store the analyzed data on geo-engineering maps. Furthermore, it can be used to display the displacement of a slope, index the information of the survey points, and automatically demonstrate analytical results of slope displacement.

The analytical information system for rock slope displacement developed in this study is realized to analyze and display for rock slope information rapidly, accurately and automatically.

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