第 35 回岩盤力学に関するシンポジウム講演論文集
（社）土木学会　2006 年 1 月　論文番号 1

Extension of the Underground Space Information Management System: maintenance and 3-D surfaces

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Abstract: This paper presents new additions to the three-dimensional Underground Space Information Management System (USIMS). In the USIMS all types of construction related information is integrated in a 3-D virtual world, facilitating access to the data and allowing investigation of spatial relations. The Information Management System is explained with the aid of the USIMS developed of the Yokotani tunnel in Kyoto prefecture. Two extensions of the USIMS with modules for inspection and maintenance as well as for 3-D surface interpretation are proposed.

Key Words: *Tunnel, Database Management,, Virtual Reality, 3-D visualization, Maintenance, Inspections, Asset Management, Digital Photogrammetry, 3-D surface modeling, Discontinuity identification.*

1. Introduction

Economic, political and societal changes in Japan have forced the construction industry to shift the focus from building new infrastructure to maintaining existing infrastructure. Regular maintenance can extend the life of an engineering structure considerably. This is especially true for tunnels and other underground structures. However, a well carried out maintenance program needs to be implemented. Missing defects can have devastating results.

Underground engineering structures need to be evaluated in the context of the geology around the underground space. This geology is three-dimensional and by its nature mostly unknown, therefore introducing an uncertainty risk. Only during construction the geology is revealed. It is important to register geologic and construction related data and store it for future use. After the completion and commissioning of the underground space, inspections have to be carried out, and repairs made if defects are observed.

At each of these steps large amounts of data are gathered that have to be stored and retrieved at a later stage. This paper presents some new tools that extend the Underground Space Information Management System (USIMS) as presented in Ohnishi, Bruines, Hanaoka and Kimura [2005], with new modules for inspections and maintenance as well as 3-D interpretation and modeling of excavation faces. The developed USIMS is a system that can improve the way data is managed by providing a system that:

- Stores data in a systematical way,
- Provides an intuitive way to retrieve data,
- Is easily extendible to include additional data or data sets,
- Allows for examining 3-D relationships between data,
- Can use datasets to generate new data.

This is mainly achieved by sorting data by location and making the data available in a 3-D world that is a virtual representation of the real underground structure. The user can navigate through this virtual world and access all data at each location. By using one data management system for all datasets, the user can access all data even after many years, which means that no datasets are lost or forgotten.

This paper first presents the USIMS approach as it has been applied to the case of the Yokotani tunnel in Kyoto prefecture. In chapter 3 the maintenance tool is described. Followed by the description of the 3-D surface interpretation and modeling tool in chapter 4. The last chapter discusses the results and makes recommendations for further study.

2. The USIMS: Yokotani tunnel case

The Yokotani tunnel is being constructed as a part of a larger project to improve the infrastructure in the Tanba district of Kyoto prefecture. Under the direction of the Kinki branch of the ministry of land, infrastructure and transport, the Kyoto-juukan highway is being built to shorten the travel time between the city of Miyazu at the Sea of Japan and the city of Kyoto. Because the area is rather mountainous, a number of tunnels have to be constructed. The Yokotani tunnel is part of the Tanba-Ayabe section of the Kyoto-juukan highway and located near the Ayabe-Ankokuji interchange. The total length of the tunnel is 1139 meter and it is being excavated from two directions.

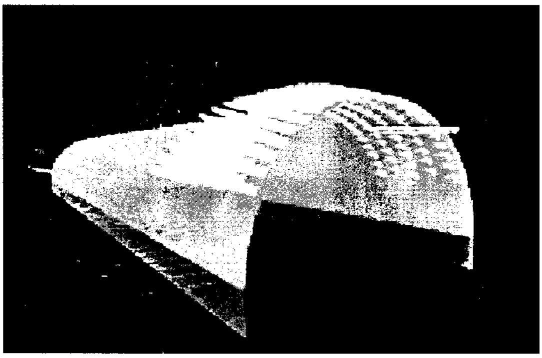

Figure 1: A screen capture showing four of the basic support patterns used in Yokotani tunnel.

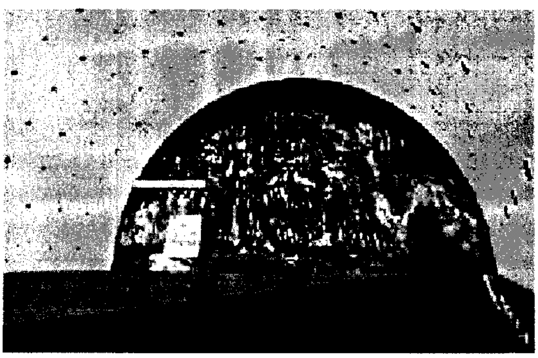

Figure 2: Virtual tunnel as shown in the USIMS. A moveable screen has been included showing the excavation face.

The New Austrian Tunneling Method (NATM) is used to excavate in two steps using a small bench. In total 6 basic support patterns are used, which are based on the ground class. Most of the rock mass around the tunnel is classified as ground class C or D with only three small sections classified ground class B. The support pattern DIII uses inclined bolts in the crown since the overburden is small. The rock bolts used in class DI and DIII are 4 meters long whereas 3 meters rock bolts are used in the classes CI, CII, CI-L-R and B. The support class CI-L-R is used for two specially enlarged sections in the middle of the tunnel that will serve as emergency bays.

The following construction data were available and have been integrated in the information management system:

- Profiles of the different basic support types, including the location of rock bolts,
- Detailed description of approximately 200 excavation faces,
- Photograph corresponding with the detailed descriptions,
- Finally installed support,
- Traceability record of the installed support,
- Traceability record of the installed rock bolts.

The basic profiles of the support types have been used to generate the virtual 3-D model of the tunnel.

Excavation progresses in steps of 1 or 1.2 meter. After each excavation advance the rock mass is characterized, support is installed and relevant construction data recorded. The same sequence has been used to organize the database management system. A detailed description of the rock mass is available for approximately one in four advances. Each of these descriptions includes a photograph of the tunnel face. These pictures have been incorporated in the 3-D virtual tunnel as a moveable screen (figure 2). Data concerning the detailed description, the final support and the traceability record can be selected in a separate navigation frame by clicking on a section of the tunnel wall (see figures 3 and 4). To add data to the USIMS, a folder is created for each type of data. A naming convention for the files need to be agreed upon, after which new data only has to be added to the appropriate folders. A small program then has to be run to update the USIMS. Since the data are opened inside the USIMS in their original format, in this case Excel, the data can be changed without leaving the application or need for an update of the USIMS.

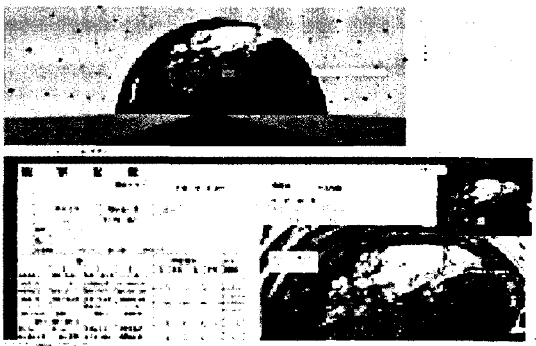

Figure 3: Detailed description of the geology at the excavation face at the time of excavation.

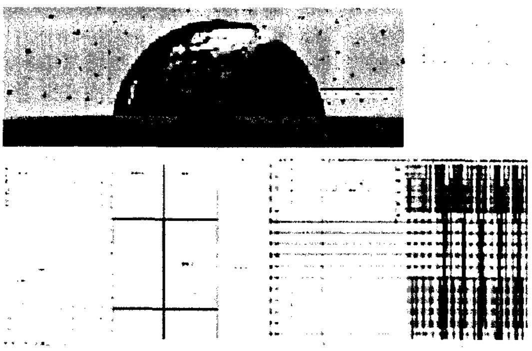

Figure 4: Traceability records of the excavated section including details on the placement of rock bolts, day of installation and data about the materials used.

3. The maintenance module

The example above of the USIMS for the Yokotani tunnel, shows what type of data can be used. These data are important during construction and for accounting purposes. However the importance of these construction data is not limited only to the construction period, but even long after the completion of the tunnel. By comparing the finally installed support data with that of the initially suggested support, expenses can be justified and predictive models can be improved. The traceability record can help to evaluate the performance of different construction crews and can help identify locations of defective materials using batch reference numbers. The description of the data can give important clues as to possible causes of accelerated deterioration. If doubts exist about the characteristics of the rock mass, the photographs can help reevaluate rock masses even if the geology is covered by lining.

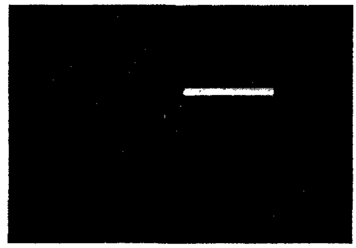

Figure 5: The USIMS for maintenance purposes. At the left side a clickable timeline is included. On the right side the user can navigate to the inspection reports, move to other inspections or look at a picture of the concrete lining, which is shown in the lower window. The central frame shows the condition of the tunnel just after completion of the tunnel.

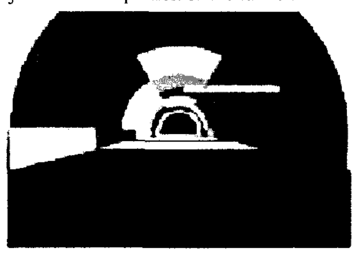

Figure 6: shows the condition of the tunnel after 20 years of service. A number of sections need to be monitored or repaired.

This capability to reevaluate the data is especially important when problems arise in the future. To recognize and mitigate problems before they arise inspections have to be carried out. By having direct access to construction data, causes of defects can be identified. To aid in the interpretation we have developed a module which allows the inclusion and visualization the inspection results. Inspections have to be carried out at regular intervals. For this reason a navigation frame that allows the selection of results for specific inspections over time has been added. By clicking on the time line the user can switch between different inspections. Like in the USIMS for the Yokotani tunnel presented above, the different parts of the tunnel are clickable and give access to the inspection reports and photos. In the example shown in figures 5 and 6 the inspections results have been compiled in a soundness value for each section. In this case the soundness value is scaled between 0 and 50. These numerical values are converted to five different classes, which suggest specific responses, ranging from no action needed, continued monitoring, preventive maintenance and repair, to reinforcement. By moving the cursor over each section the soundness value is displayed. Each class has also been assigned a color that is shown in the 3-D representation, ranging from green for intact, to red for severely deteriorated conditions.

Deterioration can take place in different ways and can be gradual or stepwise depending on different causes. Deterioration can lead to more deterioration, making the process an accelerated one. The costs are also on a curve, the costs for serious repairs or reinforcement are easily an order of magnitude bigger than simple maintenance and small repairs. Early identification of deterioration is therefore of the utmost importance. There is however a trade off. Inspections also come at a cost which can be rather elevated in case of for instance highway tunnels where the traffic needs to be diverted for inspection purposes. The USIMS can be a valuable asset management tool. To make a good inspection and maintenance program it is important to identify how fast and with what spread deterioration takes place. When accelerated deterioration is observed at one location, other locations can be checked within the USIMS to determine if similar rock conditions or materials are used and therefore a higher probability of deterioration can be expected. Once the different areas requiring repairs have been identified, the USIMS can be used to plan repair works by showing the 3-D distribution of problem areas.

4. The excavation face module

A tunnel is constructed in steps. A typical step would involve the excavation of that section, the installation of rockbolts, the application of shotcrete and possibly steel support. At a later stage final support or lining is usually installed. In this process there is only little time for the observation and description of the rockmass. To prevent the collapse of the tunnel the initial lining has to be installed, which usually means that the rockmass is no longer visible. Before the initial support is installed however, the excavated area might be too dangerous to allow access. This often means that valuable information about the rockmass is not recorded.

Photography can be an important tool in these cases. Photographs can be taken from a relative distance keeping the investigators out of harms way. Photographs can be taken very fast. Using photographs of the same object from different angles, the 3-D structure of an excavation surface can be recreated.

Discontinuities are some of the most important features in determining the behavior of a rock mass. They influence the flow of groundwater into the tunnel and are the most important mechanical weaknesses in a rockmass. An important problem is that of keyblocks. An unfavorable system of discontinuities can form blocks that can easily dislocate and severely disrupt construction. To measure the discontinuities by hand however is a lengthy process for which there is usually not enough time. The excavation face might also be too dangerous or difficult to access. Photographic interpretation will minimize the impact on the excavation cycle.

Two different directions are pursued to improve this process with the use of an USIMS. It is possible to project pictures of the underground space on any surface in the USIMS. If a discontinuity is visible on more than one flat surface, three points will be enough to define the plane. This idea has been implemented in the USIMS. Figure 7 shows a hypothetical tunnel with in the lower right corner geometrical data. The first three numbers show the x, y and z coordinate of the point on the tunnel wall the cursor is currently pointing to. In this example three locations on the tunnel wall have been selected. Their coordinates are shown in lines 4, 5 and 6. After three coordinates have been selected, a circular disc is added to the 3-D representation. The center of the disc is the arithmetic mean of the coordinates of the three points and is shown on the 7th line. Subtraction of one point from the two others gives two vectors. The cross product of these two vectors will give the normal of the disc and is shown in the 8th line in the navigation. The radius of the disc in this example is chosen as 5 meters. With this information the disc object is added to the 3-D model. This process can be repeated so that more discontinuities can be added. By looking at the system of discontinuities generated in this way, keyblocks that could exist because of the intersection of large discontinuities visible on the photographs, can be identified as shown in figure 8.

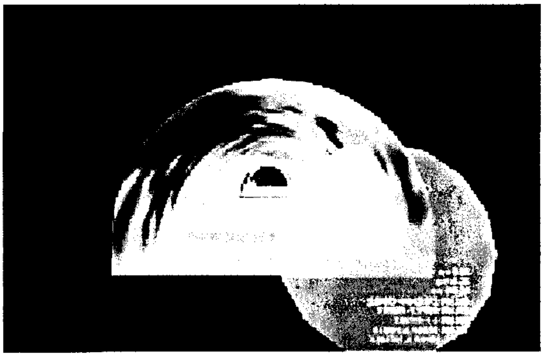

Figure 7: By selecting three points on the tunnel wall a discontinuity is generated.

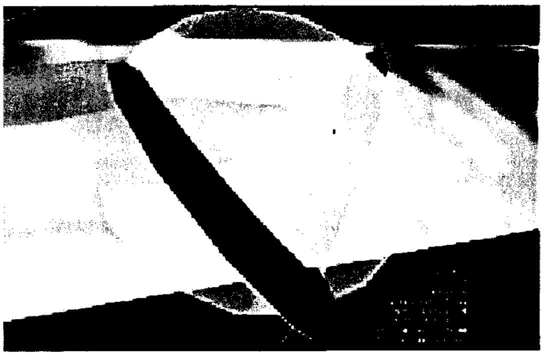

Figure 8: Intersecting discontinuities can form keyblocks.

The approach shown above uses the 3-D shape of the engineering structure to develop the idealized discontinuities. Much more information could be extracted if also the small scale irregularities of the excavation could be used. For this purpose a 3-D representation of the excavation faces is needed. This can be achieved by taking multiple pictures of the same object from different directions. The following basic steps have to be made:

- A number of pictures of the object of concern from different directions are taken.
- The exact locations of a number of reference points are determined as well as certain parameters of the camera and lenses used.
- Match points on the different pictures are identified.
- If the exact positions of the camera are not known, then they can be determined with the data mentioned before.
- With the above information the 3-D coordinates of all the match points can be identified.

To obtain the 3-D coordinates different approaches can be used. At our group a methodology has been developed that uses a large number of photographs from unknown positions. The advantage of this methodology is that pictures can be taken "free hand" while still yielding very accurate 3-D results in the order of millimeters so that even small displacements of slopes or within tunnels can be detected. To display the 3-D picture and to be able to use the discontinuity tool described above, additional steps have to be taken:

- The 3-D data from the stereogrammetry only consists of the two dimensional coordinates of the match points on the pictures and the corresponding coordinates in 3-D space. These data first have to be converted to the suitable format used in the USIMS.
- Since the USIMS works with triangular areas, these have to be first generated. To do this Delauney triangulation is performed on the two dimensional coordinates from the picture. These points are then assigned the corresponding 3-D coordinates.
- Using these points and the triangles a three-dimensional surface can be made, on which the picture can be projected.

At the time of writing this paper this methodology has been applied to construct a 3-D surface of a rock slope, because of the absence of suitable data from tunnel excavation faces.

Figure 9: 3-D model of rock slope with generated discontinuities.

The rock slope has been equipped with a large number of reflecting targets. A large number of pictures have been taken from different angles. After processing the data the 3-D coordinates of these points have been determined. For this model only a single photograph was needed together with the 3-D coordinates. Following the procedure described above and after adding the discontinuity selector the slope surface shown in figure 9 resulted. By selecting three points on a surface of the slope a discontinuity is generated. Since the triangles in this 3-D surface represent existing rock surfaces, it is no longer necessary to select the three points on at least two different surfaces, although it is still possible.

5. Discussion

Introducing the idea of an underground information system to inspections and maintenance of underground system is in our opinion a good idea. A USIMS can help to optimize the process of inspections and maintenance and can be of great help to identify causes for accelerated deterioration. The maintenance system will however not reach it full potential if the construction related data are not included. Only the concept could be presented in this paper, since gathering maintenance data is a long process and most of these data are considered confidential. In the future we hope to find maintenance data and develop a fully functional example.

The discontinuity identification tool presented in this paper is fully functional. Some improvements i.e. stereonet generation of the results can be implemented without too much difficulty. However the USIMS has been developed using internet tools, this means easy accessibility for all users but has the disadvantage that recording obtained interpretations is difficult. It might be preferable that in the future the USIMS is implemented as a stand-alone application. At the moment the photographs taken of the excavated rock mass at tunnel construction sites are usually limited to the excavation front, however photographs from the tunnel walls might be more helpful for easily determining discontinuity orientations of major features.

The development of 3-D surfaces is a very promising application. There are however some technical issues that will need further research. One of the most important being the identification of enough match points on stereo pairs of photographs to get a network dense enough to later determine all important discontinuities.

References

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Acknowledgements

This research has been made possible partly by the Japan Society for the Promotion of Science.