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VR-based education system for inspection of concrete bridges

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Abstract. In this study, a novel education system for inspection of concrete bridges is presented. The new education approach uses virtual reality (VR) and three-dimensional computer graphics (3DCG) in training engineers to become bridge inspection specialists. The slow time-dependent deterioration of concrete bridges can be reproduced on the computer screen in any chosen time frame, thus providing the trainees with illustrative and educative insight into the deterioration problem. In the proposed VR/3DCG approach a three-dimensional model of concrete bridge, including surfaces, viewpoints and walkthrough paths is created. With the help of this virtual bridge model, an experienced bridge inspection specialist teaches the different deterioration phenomena of concrete bridges to the trainees. The new system was tested, and the inspection results from the case bridge showed that in comparison with the traditional Japanese bridge inspection education system, the new system gives better results. In addition to the improvement of quality of bridge inspections, the new VR/3DCG system-based education brings along some other, more intangible benefits.

Keywords: bridge inspection; virtual reality (VR); computer graphics; inspection education; bridge management; high quality; civil engineering.

1. Introduction

Bridge management is facing serious challenges in the near future. The number of deteriorating bridges is increasing, but at the same time, the resources for management of existing infrastructure are decreasing. In many high-tech countries, the whole civil engineering sector is seen as low-tech

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business, and consequently it does not attract new talents. The ageing of the bridge engineers and lack of new ones is becoming a serious problem. Bridge inspection and diagnosis of deterioration, as a crucial part of bridge management, are suffering from the current trend. Many efforts have been made to make young people to see civil engineering as future business. One of the most promising attempts is to increase high-tech in the sector. It has been noted that with the help of the newest IT applications not only the attractiveness but also the effectiveness of the civil engineering sector can be improved. Effectiveness means also reduced costs, which the bridge owner organizations vividly appreciate.

Virtual reality (VR)/three-dimensional computer graphics (3DCG) is a technology that creates a virtual three-dimensional space in a computer to visually reproduce the texture and movement of objects. Due to the significant improvement of the performance of computers, and price reduction of software and various peripheral equipments in recent years, VR/3DCG is rapidly becoming widely used for various purposes including scientific simulation and entertainment. It is also used in civil engineering for such purposes as aesthetic evaluation during planning and design phases, analytical simulations, and damage detection with real-time health monitoring. In this study a VR/3DCG-based education system is proposed to meet the education challenges of bridge inspection in Japan. International perspective is offered by describing the bridge inspection education system in Finland where the challenges of bridge management resemble the Japanese ones. Huge number of bridges is coming to the critical age, budget limitations are tight, and the ageing of population will be causing labor shortage in the near future.

2. Bridge inspection views in Finland and in Japan

In Finland the bridge management differs from the Japanese practice. The bridge management system has been working effectively for years. The more than 14000 bridges on public roads in Finland are owned and managed by Finnish Road Administration, but the inspection, maintenance and repair works are ordered from private companies. All the bridges are visually inspected once in every five years and the results are inserted into the bridge database. If the visual inspection gives reason for more in-depth inspection, a special inspection is carried out (Tiehallinto 2004).

The visual (or general) inspections of bridges in Finland are carried out by especially trained bridge inspectors. Every authorized inspector has a license from Finnish Road Administration to execute general inspections. To get the license, a person must have building or civil engineering background (technician degree or higher), take part in three days theory education and two days field education, and pass the examinations organized by Finnish Road Administration. The authorized bridge inspectors must take part every year in the quality control or further training to keep the license valid (Dietrich 2004).

As the whole education, from requirements to examinations is strictly managed and controlled by Finnish Road Administration, the quality of Finnish bridge inspection is high. Naturally the education material and methods are being updated constantly, but so far there have not been discussions about replacing field education by virtual reality methods in Finland. New ways of further improving the bridge management in Finland include for example new service models, which make room for the innovations of maintenance contractors without compromising the quality of bridge maintenance. As the bridge inspections have reached a high and steady level, no big alterations are expected in that sector (Tiehallinto 2005). With the Finnish volumes, 14000 bridges and under one hundred authorized inspectors, this management policy can be deemed logical and reasonable, and it has proven efficient.

The situation is different when the volumes are bigger, and if there are many bridge owner organizations. In case of Japan, there are (depending on the definition of bridge) many hundreds of thousands of road bridges, owned by four different operators: national government, prefectural government, cities or private highway corporations. Nation-wide, established bridge inspection or bridge management systems do not exist. The bridges owned by the highway corporations are under regular inspections and good maintenance to guarantee the satisfaction of the paying road users, but on free national and prefectural roads, there are bridges that have not been inspected at all, and consequently the bridge registers do not have detailed up-to-date information of those bridges. The bridge inspection directions of national government are very thorough, but to run inspections in accordance with those regulations is very expensive. The highway corporations have their own tailored inspection manuals, but these organizations have a steady income flow from the road users to execute inspections and maintenance works. The importance of high quality inspections in bridge management is recognized on all levels in Japan, but budgets are too stringent to follow the national inspection directions.

Therefore, cheaper ways of inspecting and maintaining bridges have been and are constantly being sought after. Wada and others (2002) developed a system for building 3D models of structures using digital images, making nonlinear finite element analyses and visualizing analyses results. Mikami and others (2003) developed a system for training steel and concrete bridge inspection engineers based on e-learning. For developing the system, an adequate analysis was made of the characteristics of inspection engineers, education environment, and definition of skills to be obtained and of methods of evaluating the achievement. The education program is divided into the basic and regular inspection courses. By introducing these kinds of innovations, the problems of bridge inspection and maintenance in Japan are expected to be alleviated.

3. VR/3DCG-based education formula

3.1. Background

Traditional on-site training requires time and money. The transportation to the bridge site and back can be organized with a reasonable budget, but more expensive is the group training on the bridge site. Reaching the concrete surface of the deck, girders, piers and abutments of a bridge crossing a river, ravine or railway is not cheap or easy, especially when every trainee should be able to tangibly experience, see and hear what the inspection instructor is teaching. If the on-site training is to be carried out properly, it needs traffic interruptions, special equipment (e.g. for river crossing or under-deck inspection), and many safety considerations, in addition to a good weather and a lot of time. The proposed VR/3DCG education system alleviates these problems considerably, by creating virtual bridge environment in a lecture hall and displaying the long life cycle of the bridge in a short time frame. However, it must be noted that no matter how efficient the education with virtual models is, the final maturation to the bridge inspection profession evolves as the on-the-job-experience accumulates with time. The main objective of the proposed method is to get the trainees on as high level as possible from the very beginning of their career, with a cost efficient way. The quality of the inspectors cannot be over-emphasized in bridge management, because they give the input to the database, which is the base of the long-term optimization and decision making of any modern bridge management system (Rissanen 2005).

3.2. Outline of education program

In Japan, "regular inspection", the key component of bridge inspection, is generally followed by "comprehensive evaluation and diagnosis of the bridge by visual inspection" and "determination of the need of a detailed investigation based on the inspection results". Bridge inspection is thus divided into two major tasks, namely "inspection" and "diagnosis". The proposed education program is also divided into inspection and diagnosis tasks, i.e., "VR/3DCG system-based training of maintenance engineers focused on inspection" and "VR/3DCG system-based training of maintenance engineers focused on diagnosis", respectively.

The education task "training of maintenance engineers focused on inspection" is aimed at providing engineers with skills to accurately inspect bridges. Potential trainees are engineers who are likely to be involved in bridge inspections (as one part of their job), but who at the present have insufficient knowledge and experience about the domain. The course is designed to enable trainees to acquire the basic knowledge about inspection, verification of damage condition and recognition of typical damage. The objective is to guarantee high level of inspection results and to minimize the dispersion of inspection results obtained by different inspectors.

The education task "training of maintenance engineers focused on diagnosis" intends to provide the attendees with skills for accurate bridge diagnosis during maintenance. The course is aimed at enabling engineers to accurately inspect bridges, verify damages, estimate causes of deterioration, determine the level of damage and design remedial measures. The candidates of this diagnosis course are engineers who are likely to be deeply involved in bridge maintenance. The candidates have basic knowledge about maintenance and they have already experience about inspection assignments. Education about the causes of damage and deterioration is conducted in accordance with "Bridge Inspection Manual" (Public Works Research Institute 1988) and "Guidelines for Determining Cracking" (Kinki Technical Office of Kinki Regional Construction Bureau 1998).

The VR/3DCG system-based training of maintenance engineers focused either on inspection or on diagnosis is carried out using a five-step procedure. First, the education policy is defined, and details of education are determined accordingly. Then the education details are visualized using the VR/3DCG technology, the instructor teaches the trainees, and finally the trainees take an examination to verify their achievement. The examination results are taken into account in subsequent courses to continuously improve the education.

3.3. Education procedure for training of maintenance engineers focused on inspection

Step 1 Define education policy

Bridge engineers with field experience in bridge inspections for at least ten years can be considered as capable of giving education to the trainees. The course provides basic knowledge about inspection, verification of damage condition and recognition of typical damage. Education can be conducted in one or several sessions, depending on the need.

Step 2 Determine education details

The points of emphasis in education are determined in this phase. The inspection course covers the different bridge members, the typical damage types and the damage types that are easily overlooked, and those possible weak points that were found in previous inspection courses. The bridge members that are considered important from the maintenance viewpoint, include deck, girders, piers and abutments. An example of damage that may be easily overlooked is cracking. Cracking appears in varying size in different locations on concrete surface, so even experienced engineers may fail to notice it. Untrained engineers have naturally more difficulties in handling cracking. This point is especially taken into account during education. The critical types of damage to concrete structures defined in this step are cracking, spalling, corrosion of reinforcement, water leakage and free lime.

Step 3 Conduct VR/3DCG system-based education

Education is conducted using the VR/3DCG system, according to the definitions made in Step 1 and Step 2. With the VR/3DCG model of the bridge on the screen, the instructor teaches the trainees and gives explanations in the interactive education session.

Step 4 Examination

The examination concentrates on the contents of the education that is received in Step 3. A virtual VR/3DCG model of bridge is displayed and used for the test.

Step 5 Review test results

After the examination, the answers are checked, and the instructor reviews the results of the test. The answer sheets are returned to the trainees, and a "feedback session" with the VR/3DCG model is held. The feedback session concentrates on those parts that caused difficulties in the examination. The results of the examination are taken into account in subsequent education courses, thus enhancing the effectiveness of the VR/3DCG system-based education.

3.4. Education procedure for training of maintenance engineers focused on diagnosis

Step 1 Define education policy

An authorized concrete diagnosis engineer educates engineers who have two to three years of experience in field inspection. The education concentrates on estimation of the causes of deterioration, identification and determination of the degree of damage and planning of remedial measures.

Step 2 Determine education details

The diagnosis course emphasizes those points that the experienced engineers take into consideration during bridge inspection and diagnosis. The types of damage that should be dealt with in education are determined.

Steps 3 to 5

Steps 3 to 5 are the same as those in the training of maintenance engineers focused on inspection.

4. Outline of the VR/3DCG system

4.1. VR/3DCG system composition

The VR/3DCG system consists of "modeling" and "3D drawing" subsystems, as presented in Fig. 1.

The "modeling" subsystem computes the 3D coordinates of a bridge and generates an image of damage. The "3D drawing" subsystem displays a generated 3D model on the screen. The bridge specifications are input to the modeling subsystem as numerical data, and inspection image data are read into the subsystem in the bitmap format. A 3DCG model is made from the bridge

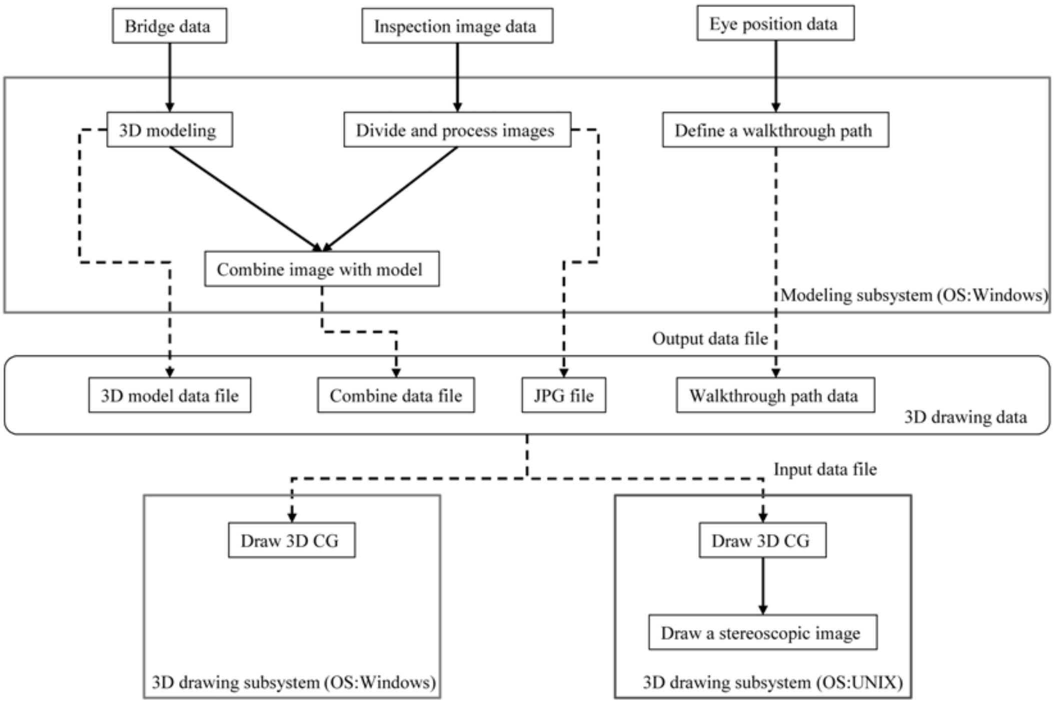

Fig. 1 VR/3DCG system components

specifications. The bitmap data is divided and processed. Images are pasted on appropriate surfaces of members of the 3DCG model. Additionally, a walkthrough path and time-series representation can be specified wherever necessary. The modeling subsystem incorporates the walkthrough path and time-series representation and outputs data to draw a 3D image. The 3D drawing subsystem is composed of applications working on two different platforms: Windows and UNIX. The application running under UNIX is also capable of stereoscopic representation.

4.2. Generation of the 3D model

Step 1 Input data for the superstructure

Data is input to generate the superstructure of the 3DCG model. The number of main girders, number of spans, span lengths, number of panels in each span and panel lengths, girder spacing, cross section, shape of main girder, shape of transverse members and other parameters are input. An example of the screen for defining the shape of the superstructure cross section is shown in Fig. 2.

Step 2 Input data for the substructure

In this step, data is input to generate the substructure of the 3DCG model. Input parameters include for example profiles and cross sections of abutments and piers.

Step 3 Compute 3D coordinates

The 3D coordinates are computed for the superstructure and substructure based on the data input in Step 1 and Step 2.

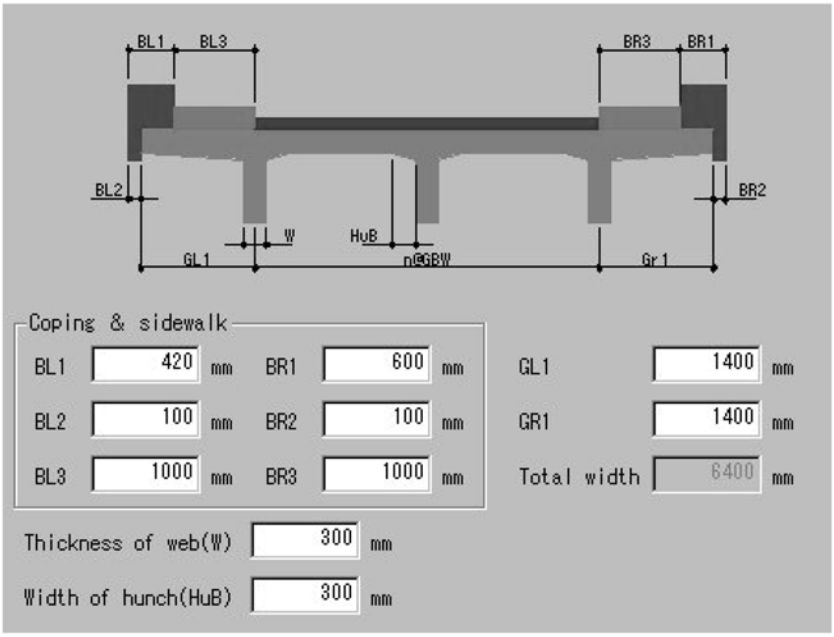

Fig. 2 Screen for defining bridge superstructure cross section

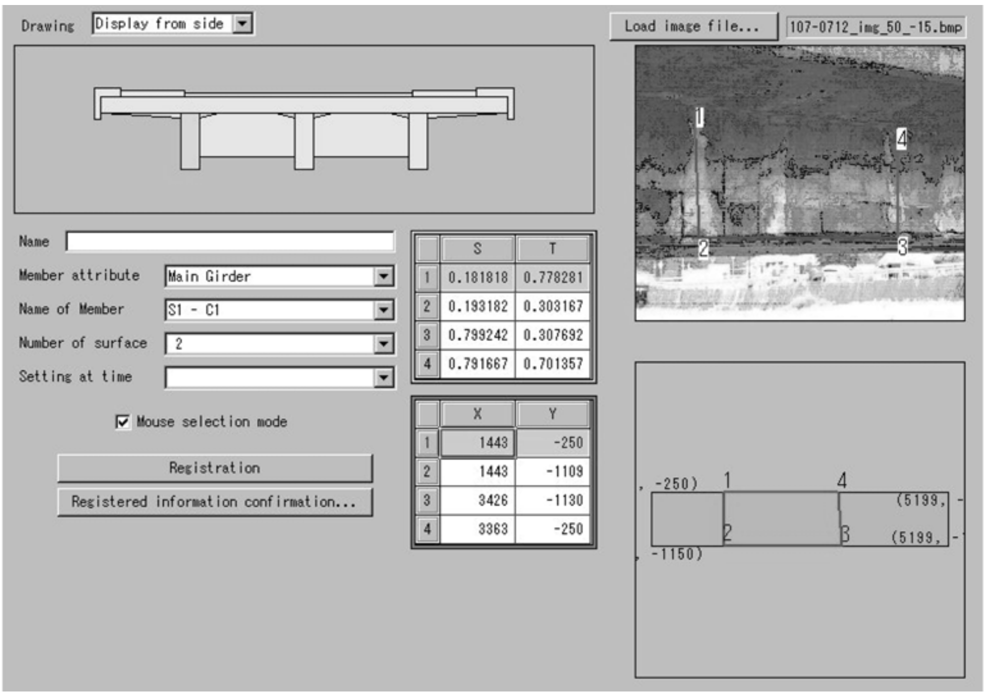

Fig. 3 Sample screen for combining the image with the model

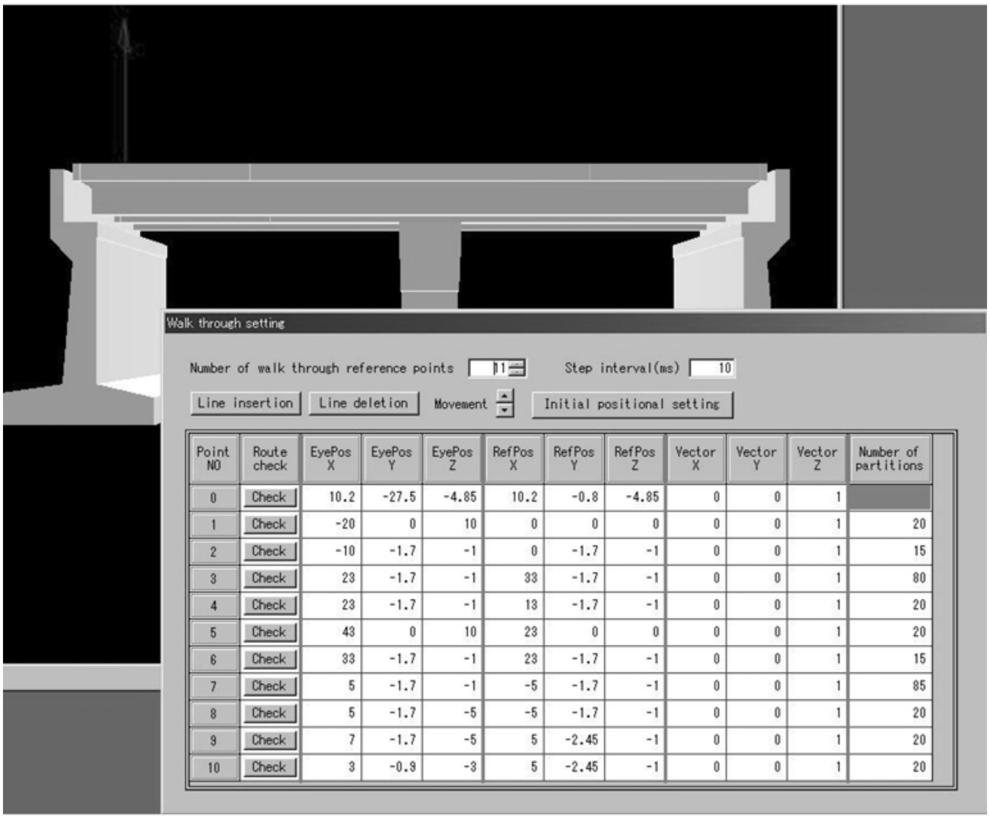

Fig. 4 Sample screen for defining a walkthrough path

Step 4 Combine image data with the model

In this step, the 3D model is combined with image data. The location in the model where image data is to be pasted and the coordinates of the image are specified. An example of the screen for inputting these specifications is shown in Fig. 3.

Step 5 Define a walkthrough path

In this step, settings are made for animation. The walkthrough path is defined by inputting the eye position, reference point and vertical vector component. An example of the screen for making these settings is shown in Fig. 4.

4.3. Three-dimensional CG drawing

The 3DCG image is drawn by reading the data on the model, model combined with the image of damage and walkthrough path. The 3D drawing system is designed to work either on Windows or UNIX. Working on both systems is important because it is beneficial to verify the created model using Windows, and use image processing functions on a large scale (such as stereoscopy and drawing on a screen) using UNIX, which is fit for image processing.

5. Verification of effectiveness of the system

5.1. Method of verification

To verify the effectiveness of the proposed education system, it was compared with the traditional education system in Japan. First, a group of engineers was trained using the proposed VR/3DCG system. Then these engineers inspected an existing bridge. The same bridge was inspected also by another group of engineers, trained by using the traditional education system. The obtained inspection results of both groups were compared with the inspection results obtained by a specialist (authorized concrete structure diagnosis engineer) and with each other. Both groups of engineers consisted of eight members. All the members had been inspecting bridges several times before the training and the verification test. Before the training, the group configurations were made according to the knowledge of the trainees, so that the members in both groups had the same level of knowledge and experience. After this the other group received VR/3DCG system-based education and the other group traditional education.

5.2. Pre-inspection education using the proposed VR/3DCG system

The training of the group receiving VR/3DCG system-based education was carried out in accordance with the procedure described in chapter 3.3. "Education Procedure for Training of Maintenance Engineers Focused on Inspection".

Step 1 Define education policy

The education course focused on providing the trainees with basic knowledge about bridge inspection, with ability to verify damage condition and to recognize typical damages. For verification purpose, the education concentrated especially on improving the perception of damages,

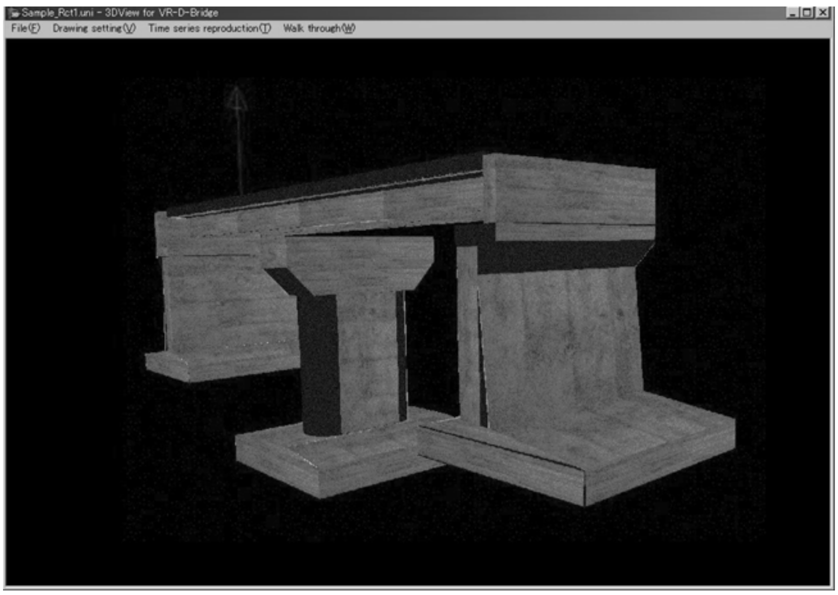

Fig. 5 Bridge model for education

thus wading into the prevailing situation where damages are too often overlooked.

Step 2 Determine education details

The course focused on cracking, one of the leading and most critical types of damage in bridges. Cracking serves as a parameter for evaluating the durability and load bearing capacity of structures. The cause of cracking may sometimes be estimated according to the location or shape of the cracking. Cracking occurs at varying locations, and in varying shapes and sizes, so it is overlooked in Japanese bridge inspection practice more frequently than any other type of damage. The trainees were educated about the bridge members vulnerable to cracking and about the locations where cracking is expected to occur, based on the opinions of experienced engineers.

Step 3 Conduct VR/3DCG system-based education

A 3DCG model was generated for the education described above. A 3DCG model of a two-span continuous girder bridge was based on the technical data of the "Old Kotougawa Bridge". The type of superstructure of the model bridge is reinforced concrete T-girder with three girders over two spans. The substructure consists of the abutments and the intermediate pier, the shapes of which resemble inverted T. The model is shown in Fig. 5. The trainees were instructed to specify in the 3DCG model displayed on the screen the locations vulnerable to cracking, and the bridge members that were likely to be overlooked.

5.3. Pre-inspection education using conventional material

The conventional education provided the other group of trainees with knowledge about the bridge members and locations that were likely to be affected by cracking, based on "Bridge Inspection Manual" (Public Works Research Institute, 1988) and "Guidelines for Determining Cracking" (Kinki

Fig. 6 The bridge that was used in the inspection verification test

Technical Office of Kinki Regional Construction Bureau 1998). Copies of drawings showing the typical crack patterns and the bridge members and locations vulnerable to cracking were distributed to the trainees to supplement the oral tuition. No 3D material was used in the education of this group.

5.4. Post-education bridge inspection test

A bridge over a river in Ube city (in Yamaguchi prefecture, Western Japan) was inspected after the education. The four-span continuous T-girder bridge with reinforced concrete slabs and five main girders was constructed in March 1960 and has been in service ever since. No official specifications of the bridge were available. There was evidence that the deck slab had been repaired once. The bridge, located near the seacoast, suffered from considerable salt damage. The facade of the bridge is shown in Fig. 6.

The group that took a course based on the VR/3DCG system, and the other group that used conventional material for education, inspected the bridge separately. An authorized concrete structure diagnosis engineer (authorized by JCI-Japan Concrete Institute) also inspected the bridge to prepare the model inspection results. The results of the bridge inspection, obtained by the two groups of engineers and the authorized concrete structure diagnosis engineer, were compared. The inspection results for the main girders are presented in Fig. 7, and for the deck slab in Fig. 8. The letters from A to H in Figs. 7 and 8 represent the individual engineers in both groups, and SD means standard deviation of the results.

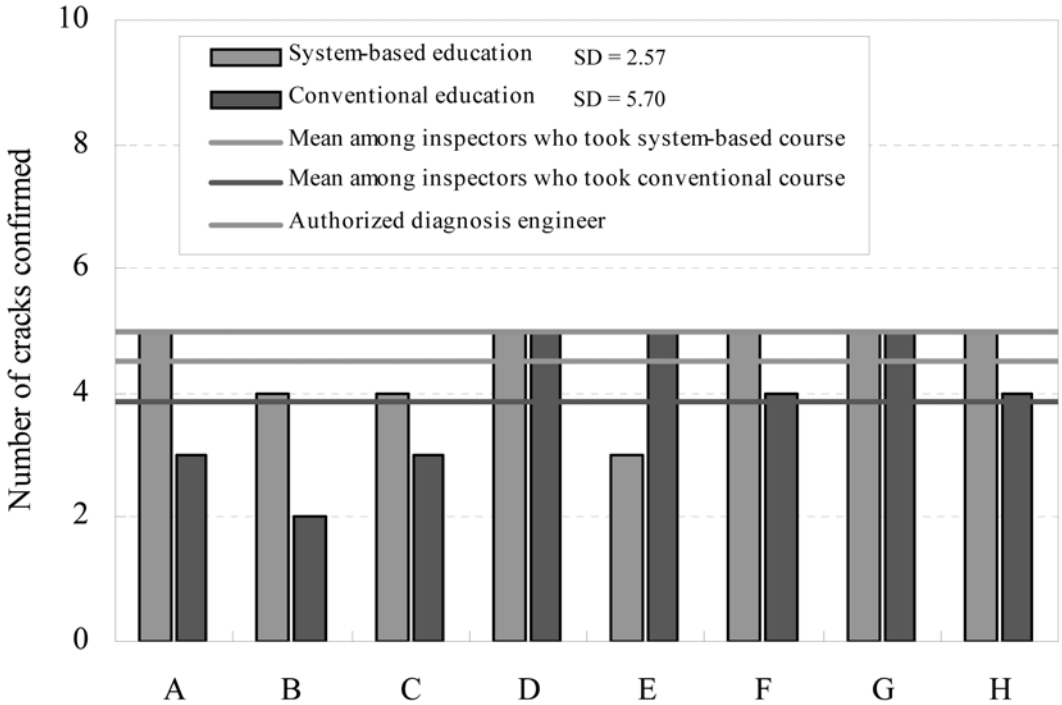

Fig. 7 Verification test results for crack discovery in main girders

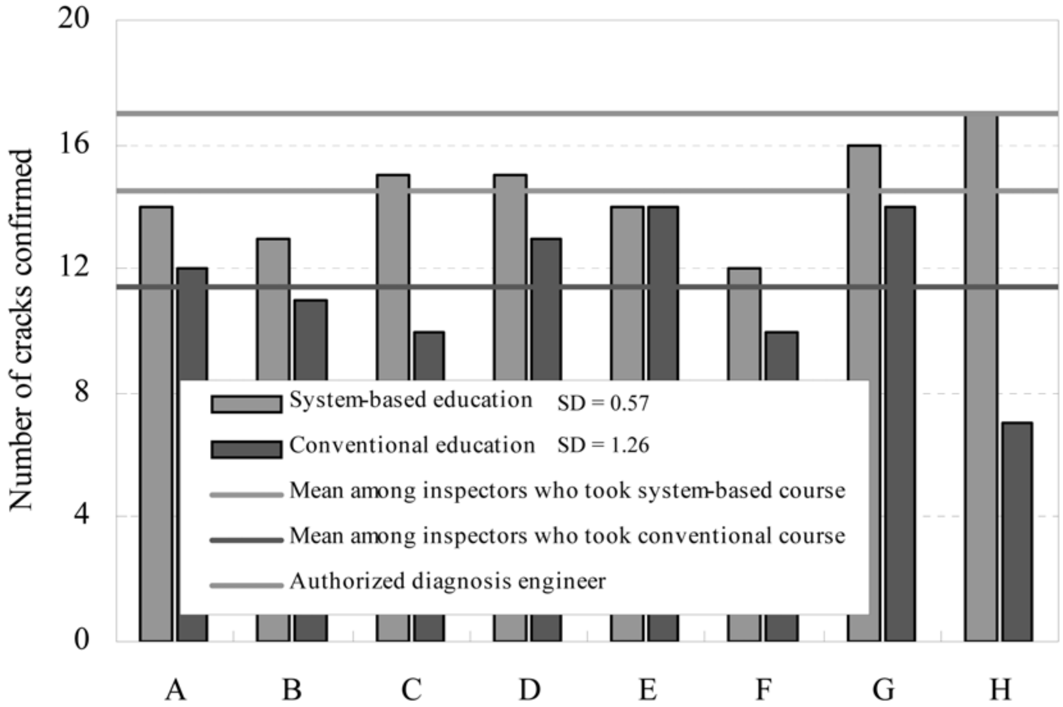

Fig. 8 Verification test results for crack discovery in deck slab

5.5. Discussion

The results of the small-scale verification test reveal that of the two inspection groups, the inspection results of the engineers trained with the VR/3DCG system are closer to the model inspection results. The inspection results of the engineers trained with conventional method are notably lower than the inspection results of the engineers trained with the VR/3DCG system. In addition, the results of the verification test show that the variation of the individual inspection results is much bigger (standard deviation roughly double) in the group of engineers who received conventional training. A conclusion might be drawn, that by using the proposed VR/3DCG system-based education the quality of bridge inspections can be clearly improved and harmonized, when compared to the current practice in Japan. However, before making too straightforward conclusions it must be noted that the verification test was very small-scale, focusing only on crack discovery, and many factors of uncertainty were included in the test. For example, there were only eight members in both test groups, so in terms of statistical reliability the experiment cannot be deemed absolutely probative, but only indicative. As human beings were tested in the experiment, the possibility of Hawthorne effect cannot be ruled out. Also, the test was carried out only once. Therefore, the real indisputable result of the verification test was that it clearly showed that the perception of cracks *could* be enhanced by using the new VR/3DCG system. This should encourage the bridge management researchers to develop the methodology further, and to search for wider synergy in bridge management sector. With the current tight budgets, synergy is highly appreciated.

The first advantage of the new VR/3DCG system-based education formula is the improvement of bridge inspection quality, but in addition to that, the education formula can bring other, synergetic benefits. For example, the model used in the VR/3DCG system-based education can be easily stored in digital form into a database. As the modeling, image processing, prediction etc. techniques keep developing, in the future there will be more and more of these models stored in the database, finally representing all the bridge types of the national bridge stock. The final (but at the moment still utopian) goal would be a situation, where *all* actual bridges of the national bridge stock would have a VR/3DCG model, with correct materials, dimensions, deterioration history, condition, environmental and other loading, with real time updating, etc.

Another possible synergetic benefit of the VR/3DCG system-based education is demographic-related: as the ageing of population is becoming a serious challenge in Japan and in many Western countries, there will be a lack of qualified workforce in many sectors of society (Rissanen 2005). At present, the civil engineering sector in these countries is seen as non-interesting low technology business. With introduction of high technology (like the proposed VR/3DCG system), the attractiveness of bridge and civil engineering sector can be increased among talented young people, thus enhancing the sufficiency of qualified workforce in the future.

These intangible synergetic benefits must not be overlooked when developing new high-tech methods. The proposed VR/3DCG system-based education is likely to be able to improve bridge inspection quality, but in addition to that, it seems to entail a wider positive "overall effect" on the bridge inspection sector. However, this overall effect is not easy to measure quantitatively.

6. Conclusions

Bridge inspection has a key role in bridge management. The quality of inspections must be as high as possible, and the variation between inspections results obtained by individual inspectors must be as low as possible. If these two goals are not achieved, the bridge management system does not give reliable results. Therefore, the education of bridge inspectors is a crucial issue in today's bridge management. Many countries have high standard inspector training and education systems, which have proven efficient. In Japan, the education of bridge inspectors is not yet systematized on national level, but the importance of the quality of bridge inspections has been recognized. Within the Japanese constraints (e.g. decentralized ownership of bridges, tight maintenance budgets, large volume of bridges and ageing of population), the challenge of establishing an efficient inspection education system is not easy to answer.

In this study, the above challenge is met with the help of virtual reality (VR) and three-dimensional computer graphics (3DCG). First, a three-dimensional virtual model of a concrete bridge is generated by using data of a real or a hypothetical bridge. Then the VR/3DCG model is displayed to the inspection trainees, and an authorized bridge inspection specialist conducts the interactive education session. The slow process of deterioration can be reproduced on the model in chosen time frame, thus elucidating the problem areas and making the teaching more powerful. The trainees can take part in the creation of the model, or the teacher can use existing models from a database. The VR/3DCG models used in the education are stored into the database for the future purposes.

The proposed VR/3DCG system-based education was tested with two groups of engineers to find out its feasibility in real life. The test showed clearly that the group of engineers that received VR/3DCG system-based education obtained better results than the group of engineers that received traditional education. Although the test was very small-scale and it was carried out only once, it can be concluded, that the VR/3DCG system-based education is a very promising bridge inspection education method. The next step will be to develop the system further, to include also other materials besides concrete, all types of bridges and all types of deterioration. In addition, it would be useful to test the method in countries where the bridge inspection education is already on high level and harmonized. Positive results (i.e. improvements in the inspection results after the VR/3DCG system-based education) from those countries would clearly confirm that the method has potential, and that the endeavors to develop the VR/3DCG method further and to integrate it to the bridge management practice in Japan are to be encouraged. In the future, resources should also be allocated to study the positive "overall effect" that VR/3DCG and other high-tech innovations bring along to the bridge management sector.

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