METHOD FOR EVALUATING THE HYDRAULIC FUNCTION OF IRRIGATION PIPELINES CONSIDERING RISK DURING LARGE EARTHQUAKES

YOSHIKAZU TANAKA

NARO Institute for Rural Engineering
E-mail: yokka@affrc.go.jp

Abstract— Large earthquakes have damaged the irrigation pipeline facilities. The design standard criteria of pipeline in Ministry of Agriculture, Forestry and Fisheries, Rural Development Bureau in japan has been stipulated how to verify structural functions and implement countermeasures, but does not mention hydraulic safety. This research evaluated the risk to hydraulic functions of irrigation pipelines based on scenarios in the event of a large earthquake to contribute to various hard and soft countermeasures to predict or prevent accidents.

Index Terms— Irrigation pipeline system, Risk reduction process, FMEA , visualization

I. INTRODUCTION

In an irrigation water system, high-pressure irrigation pipelines of up to several dozen kilometers take water from a river, then pumps are used to distribute the irrigation water to paddies, upland fields and orchards. The total length of irrigation pipelines already installed in Japan includes 45,000 km of trunk channels serving beneficiary farms of 100 ha and larger.

In Japan, severe earthquakes have damaged pipeline facilities. Attention first turned to earthquake-resistant pipeline facilities after the Hanshin Awaji Earthquake of 1995. Regarding the earthquake-resistant design of irrigation pipelines, the technical document in the design standard “Pipelines”, which was revised in 2009, presents a procedure for verifying structural safety considering earthquake motion which is very large but occurs rarely (Level 2) [1]. The document stipulates how to verify structural functions and implement countermeasures, but does not mention hydraulic safety, even though it is important to also fully study the risk to hydraulic functions. The reason is that many reports on damage caused by past large earthquakes to pipeline facilities state that leaking water from a damaged facility has caused further damage to the facility and harmed the surrounding farmland. Past research has shown that hydrodynamic pressure caused by earthquake motion (hydrodynamic pressure during an earthquake) can cause a great change of the pressure head, equivalent to water hammer pressure caused by the abrupt closure of a valve. Furthermore, a loss of electric power, which is likely to occur after a large earthquake, or a human operating error, could
result in water hammer pressure caused by the abrupt stoppage of a pump or sudden closure of a valve. It is necessary to hypothesize and study scenarios of such risk to hydraulic functions posed by various accidents during a large earthquake disaster.

This research evaluated the risk to hydraulic functions of irrigation pipelines based on scenarios in the event of a large earthquake to contribute to various hard and soft countermeasures to predict or prevent accidents.

We propose a method of risk management for hydraulic functions of irrigation pipelines with reference to a risk reduction process in machinery, which is a pioneer in the risk management field. This paper outlines the software developed to support this work. The software consists of three components: software for evaluating the risk reduction process, software for numerical analysis of exceedance phenomena in pipelines during large earthquakes, and software for visualizing the numerical analysis results along with other information.

II. RISK MANAGEMENT METHOD FOR HYDRAULIC FUNCTIONS OF IRRIGATION PIPELINES

A. Risk reduction process

This section examines the extent to which methods reduce the risk to hydraulic functions during a large earthquake, using Failure Modes and Effects Analysis (FMEA), which is also used for managing the risk to machines [2]. FMEA hypothesizes the potential failure mode during use of all constituent components of systems that are designed and studies the impact of the accident on superstructure components, sub-systems and system functions, to identify weak points, give advice on appropriate countermeasures, and prevent accidents. Our purpose is to use FMEA to evaluate the risk to all facilities of an irrigation pipeline and to reduce this risk. Fig. 1 shows the steps in the risk reduction process of the proposed risk management method.

The risk reduction process estimates risk by calculating critical evaluation scores for a variety of hypothetical failure modes for all facilities in an irrigation pipeline, and repeatedly considers taking a variety of hard and soft countermeasures to reduce this critical evaluation score, and finally, eliminating the risk.

Before starting to estimate risk, the failure mode is defined in order to determine what kinds of failures to evaluate at the risk analysis stage. Meanwhile, evaluation items for many standards used to evaluate failure modes are decided. Generally, this involves weighting evaluation scores in evaluation standards within each evaluation item and deciding on the relative weighting among the many evaluation items which exist.

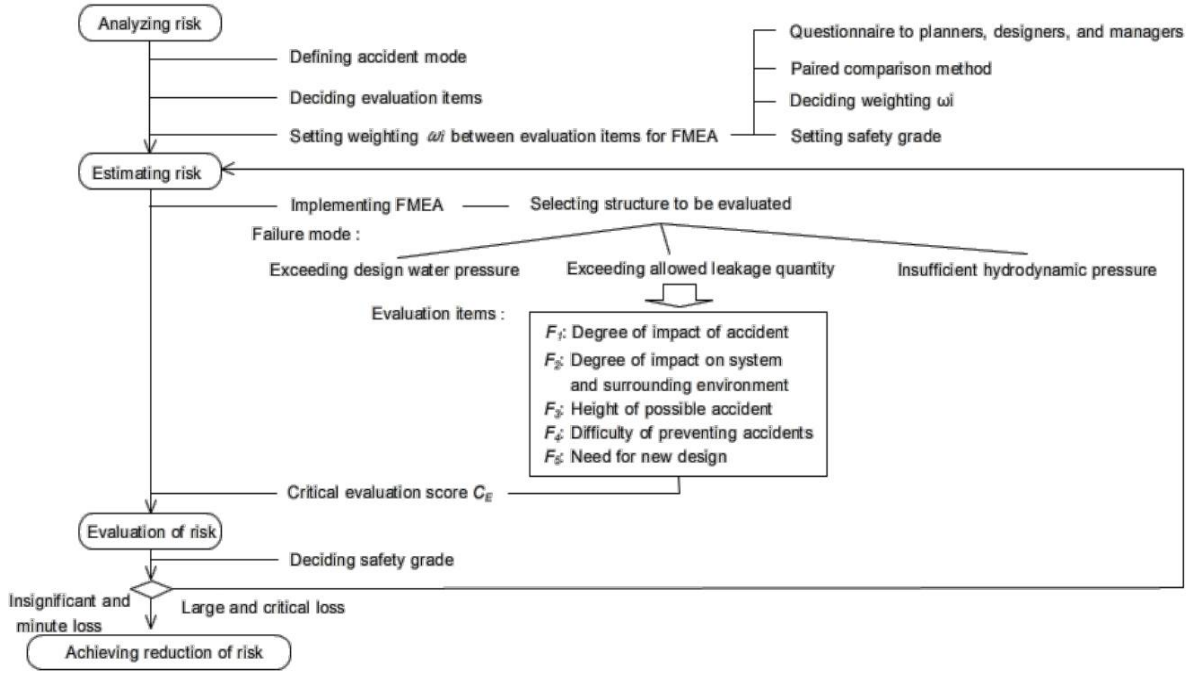

Fig.1 Process of risk reduction for hydraulic function of an irrigation pipeline

For this study, failure modes were defined as exceeding the design water pressure, exceeding the allowed leakage quantity, and insufficient hydrodynamic pressure. Five failure mode evaluation items were set: degree of impact of the accident, degree of impact on the system and surrounding environment, possibility of occurrence, difficulty of prevention, and possibility of a new design. If each evaluation score is represented by F1, F2, F3, F4, and F5, according to equation (1), the criticality score CE for risk evaluation is given by

$$C_E = (F_1 \times F_2 \times F_3 \times F_4 \times F_5)^{\frac{1}{5}} \quad (1)$$

In order to quantify the relative importance of these evaluation items, the relative weight of each evaluation item must be set. The relative importance of the evaluation items are set as weights, which were obtained by quantifying the evaluation norms of the person setting the weights. Therefore, the impact on the criticality score of each evaluation item in the estimation of risk is the evaluation score Fi for which the weight ωi evaluated by such person in advance was weighted on the evaluation score Pi of each evaluation item.

$$F_i = \omega_i \times P_i \quad (2)$$

When the evaluation result indicates that the risk is unacceptable for the safety grade, soft and hard countermeasures are taken and the process of estimating risk is repeated. When the result indicates that the safety grade is only slightly lowered, finally the risk is reduced and the process is completed.

B. Defining the failure modes

The following are the hydraulic phenomena which are the grounds for exceeding the allowed leakage quantity, exceeding the design water pressure and insufficient hydrodynamic pressure, which are defined as the failure modes in this study.

B.1 Exceeding the allowed leakage quantity

Leakage having high water pressure from inside a pipeline, sweeps away backfill material and surface ground, results in large depression of the ground surface [3]-[5].

B.2 Exceeding the design water pressure

It is assumed that in an earthquake, unexpected emergency shut-downs, such as the sudden shut-down of pumps, will occur as a result of power failures. When a pump is shut down in an emergency, the water hammer pressure causes negative pressure inside a pipeline, and if it is lower than the saturated vapor pressure, a void forms inside the pipeline, and the separated water columns may then recombine, greatly increasing the pressure inside the pipeline [6]. Earthquake motion also directly causes water hammer pressure, called hydrodynamic pressure during an earthquake. The hydrodynamic pressure during an earthquake was logically deduced by [7]. By chance, [8] also observed hydrodynamic pressure during the Tokachi Offshore earthquake. The observations showed that the peak value of the water hammer pressure was about 30% of

the hydrostatic pressure, but could be even larger if the sampling cycle is measured correctly. Later, [9] predicted by numerical hydraulic analysis that the water hammer pressure cannot be ignored.

B.3 Insufficient hydrodynamic pressure

When a leak occurs, air pockets are formed inside the pipeline at elevations above the leak location, which may reduce the quantity of water carried because of insufficient hydrodynamic pressure.

C. Setting the scenarios

Two-stage scenarios hypothesizing a large earthquake are prepared: a damage scenario and a countermeasure scenario. The damage scenario establishes what kinds of damage occur during a large earthquake, while the countermeasure scenario establishes what kinds of hard and soft countermeasures are taken. Firstly, the risk reduction process is carried out once based on the damage scenario. If the result shows that the risk is unacceptable, a countermeasure scenario is set and the risk reduction process is repeated as many times as necessary to reduce the risk to an acceptable level.

D. Weighting evaluation items

The paired comparison method was used for weighting. This involves quantifying all evaluation items by evaluating
the relative degrees of importance of pairs of all evaluation items by a round-robin process [10]. Fig. 2 shows part of a paired comparison table used for a questionnaire survey of persons who assign weightings.

From the results of this paired comparison table questionnaire, a paired comparison matrix is prepared, and the calculated eigenvector becomes the weight of the evaluation item. The results of computing weights by multiple weighting persons are then averaged to obtain the final weights of the evaluation items. Thus, the weight computation method involves selecting the weighting persons, conducting a questionnaire survey and compiling the responses. Engineers of the land improvement district that manages the irrigation pipeline facilities are appropriate weighting persons.

III. SUPPORT SOFTWARE FOR RISK MANAGEMENT METHOD

The support software consists of (1) FMEA evaluation software, (2) information visualization software, and (3) numerical hydraulic analysis software. (1) is a web application used to enter evaluation scores for each evaluation item based on the risk reduction process and to share the evaluations results within each group, (2) is software that visualizes the information needed to decide

Question 1: What are the degrees of impact when evaluating the risk of an accident on a trunk pipeline system in a large earthquake? Please mark a circle "○" closest to your opinion for the following questions.

		Left side is extremely large	Left side is very large	Left side is large	Left side is somewhat large	Almost the same	Right side is somewhat large	Right side is large	Right side is very large	Right side is extremely large	
Q1	Degree of impact of accident										Degree of impact on system and surrounding environment
Q2	Degree of impact of accident										Height of possible occurrence of accident
Q3	Degree of impact of accident										Difficulty of preventing accident
Q4	Degree of impact of accident										Need for new design
Q5	Degree of impact on system and surrounding environment										Height of possible occurrence of accident
Q6	Degree of impact on system and surrounding environment										Difficulty of preventing accident
Q7	Degree of impact on system and surrounding environment										Need for new design
Q8	Height of possible occurrence of accident										Difficulty of preventing accident
Q9	Height of possible occurrence of accident										Need for new design
Q10	Difficulty of preventing accident										Need for new design

Fig.2 Example of paired comparison method

evaluation scores for each evaluation item, and (3) is software that analyzes hydraulic phenomena based on the damage and countermeasure scenarios.

A. FMEA evaluation software

This software supports the risk reduction process explained in Section Ⅱ.A. The software is designed to repeat the risk reduction process by repeatedly storing all information concerning each facility of the evaluated pipeline and the risk reduction process in a database and performing searching and editing.

Briefly, the procedure is as follows. First, the screen shown in Fig. 3 is used to search for the evaluation results of a certain damage scenario. If there is no suitable damage scenario for evaluating a certain facility, the screen shown in Fig. 4 is used instead to prepare a new damage scenario. This is done by selecting conditions for the damage scenario from a list or adding such conditions to the list. The failure mode of the facility to be evaluated is then assessed under this damage scenario. When studying evaluation items to obtain evaluation scores, it is possible to decide evaluation scores by selecting the radio button.

When the evaluation of the five evaluation items does not result in an allowable risk, the evaluation is performed again considering the countermeasure scenario. A countermeasure scenario is prepared and evaluated using the screen shown in Fig. 5. The software thus repeats the FMEA risk reduction process.

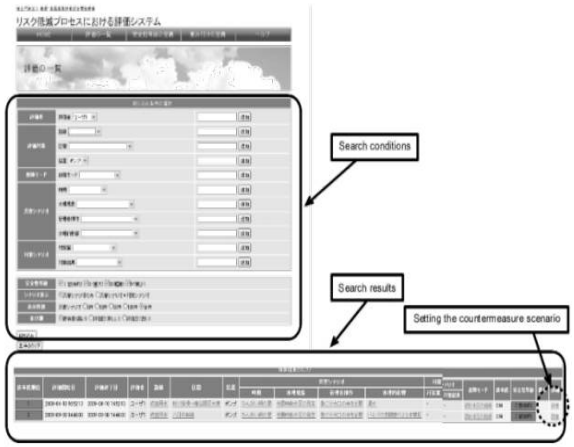

Fig.3 Narrowed search based on the evaluated damage scenario

B. Information visualization software

When deciding evaluation scores in the risk reduction process, information to help the engineers make judgments is required. Google Earth was used to be able to view geographical information needed to evaluate risk using a simple geographical information system.

Google Earth can superimpose images on a map. This is used to help the engineers make decisions by superimposing information about the facilities of an irrigation pipeline on geographical information needed to evaluate evaluation items.

Fig. 6, for example, shows the results of downloading images of the distribution of probability of being subjected



Fig.4 Damage scenario setting and evaluation score entry Screen

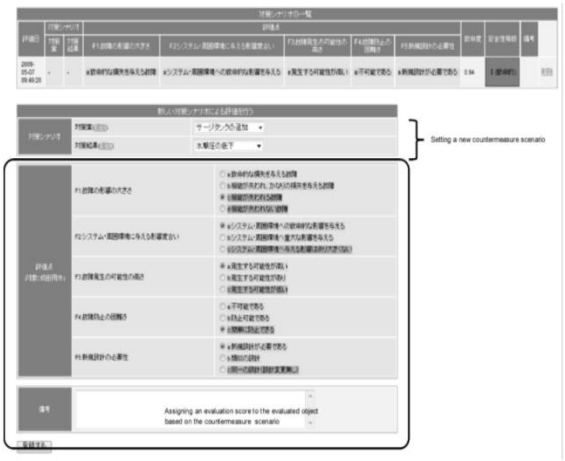

Fig.5 Countermeasure scenario setting and evaluation score entry screen

to shaking of seismic intensity of 6 or higher during the next 30 years from J-SHIS of the National Research Institute for Earth Science and Disaster Prevention (http://www.j-shis. bosai.go.jp/), applying it to a Google Earth screen and superimposing it on irrigation pipeline facility information. Using this method, diverse map information including a 25,000 digital map, dips, dip classification maps, topography classification maps, surface soil maps, land use status maps, and disaster prevention maps released by prefectures was organized.

Google Earth is also used as a data entry screen or output display screen for the numerical hydraulic analysis software as described later. This makes the results of the analysis visually easier to understand, enabling engineers to more easily evaluate the risk to hydraulic functions of irrigation pipeline facilities.

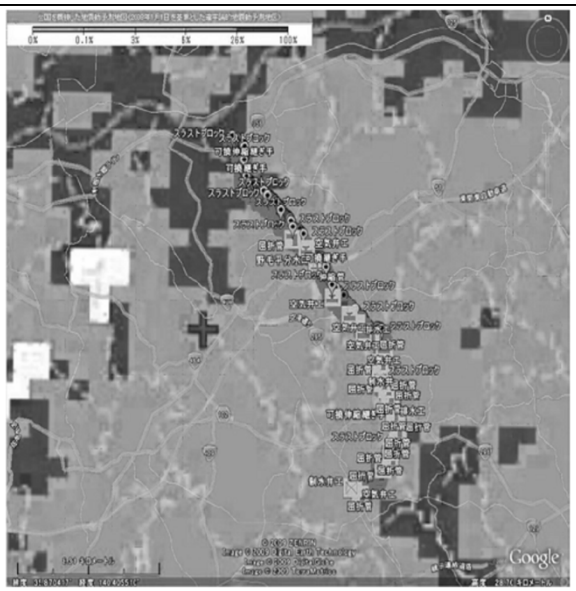

Fig.6 Superimposing earthquake motion prediction information with route data of an irrigation pipeline (Using image data from J-SHIS of the National Research Institute for Earth Science and Disaster Prevention and Google Earth of Google Corp.)

C. Numerical hydraulic analysis software

For estimating the risk to hydraulic functions, instead of relying only on records of past accidents that affected hydraulic functions, the results of numerical hydraulic analysis of facilities to be evaluated based on damage scenarios are also useful. Therefore, the software supports the series of tasks for performing numerical hydraulic analysis.

C.1 Constituent parts of the software

As shown in Fig. 7, the software consists of three parts: pre-processing, numerical analysis, and post-processing.

Pre-processing is done by engineers entering route information data using a Google Earth screen, then converting the prepared KML file into numerical analysis entry data. KML is an abbreviation for Keyhole Markup Language, which is a mark-up language of XML used to control geographical information in a computer program. Numerical analysis enters information about the irrigation pipeline to be calculated from the KML file, to numerically analyze the hydraulic phenomena. Post-processing converts

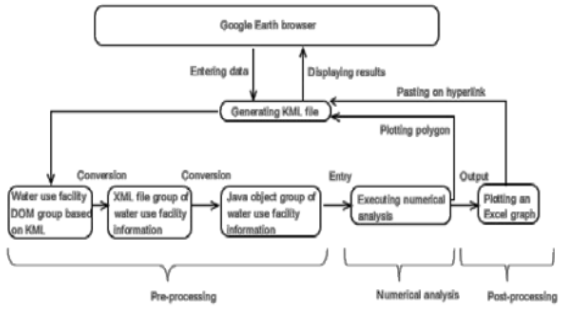

Fig.7 Constituent parts of the numerical hydraulic analysis system

the results of the numerical analysis so that they can be
displayed as polygon shapes on Google Earth.

C.2 Numerical analysis

C.2.1 Calculating leakage and air pocket capacity

Leaks occur when pipes separate caused by permanent displacement by earthquake motion or earthquakes. Their likely locations are decided by considering the possibility of liquefaction phenomena or slope collapse based on the results of earthquake motion predictions, soil investigations, and accident histories.

Facility managers predict the likelihood of a water stoppage in the event of a large earthquake, so the final leakage quantity is assumed to be in a hydrostatic state without considering the volume supplied from upstream, and so the total leakage is roughly equal to the volume of the pipeline above the elevation of the leak location, excluding sections where leaks do not occur because of the longitudinal section of the pipeline.

The time-series change of the leakage quantity is greatly influenced by the state of damage to the pipeline at the leak location, because if leak opening area is large, the leakage flow rate is high. Therefore, to calculate the leak flow rate, first the size of the opening area at the leak location is hypothesized, then the hourly leak quantity is calculated based on Torricelli's theorem, which considers the friction loss. Simultaneously, the capacity of the air pocket is hypothesized to be that created only by the leak quantity in the part at the highest elevation in the pipeline section where the leak occurred.

C.2.2 Calculation of water hammer pressure by underwater separation and reintegration with the water hammer phenomenon

The non-constant hydraulic phenomena inside the pipeline is numerically analyzed following the basic equations (3) and (4) assuming that the water inside the pipe and the pipe body are elastic bodies.

$$g\frac{\partial H}{\partial x}+\frac{\partial V}{\partial t}+V\frac{\partial V}{\partial x}+\frac{fV^2}{2D}=0 \quad (3)$$

$$\frac{a^2}{g}\frac{\partial V}{\partial x}+\frac{\partial H}{\partial t}+V\left(\frac{\partial H}{\partial x}+\sin\alpha\right)=0 \quad (4)$$

where, H: pressure head, V: average velocity inside the pipe, t: time, x: pipeline length, f : coefficient of friction loss, D: pipe diameter, α: pipe gradient, and a: propagation velocity. The analysis method used was the method of characteristic curves. The model of the water hammer pressure ΔH based on water column separation and reintegration was the vapor cavity model [6].

$$\Delta H=\frac{a}{2gA}(Q_{in}-Q_{out}) \quad (5)$$

average outflow from the cavity section, and A: pipe section area.

C.2.3 Calculating the hydrodynamic pressure during an earthquake

The hydrodynamic pressure during an earthquake is, when the earthquake motion vibrates in the pipe axis direction, the maximum value σmax and is given by the following equation [7]:

$$\sigma_{\max} = \frac{\beta g T k}{2\pi a\left(1+2\frac{kr}{Ee}\right)} \quad (6)$$

where, β: seismic intensity (ratio of earthquake acceleration to acceleration due to gravity), g: acceleration due to gravity, T: cycle of vibration, k: modulus of elasticity by volume of water, r: pipe radius (internal diameter), E: elastic modulus of pipe material, e: thickness of pipe, and a: propagation velocity of pressure waves inside pipe.

$$a = \sqrt{\frac{g}{\omega}\frac{k}{1+2\frac{rk}{Ee}}} \quad (7)$$

where, ω is the unit weight of water.

Equation (6) was used to obtain an equation that also calculates hydrodynamic pressure during an earthquake for valves, dead-ends of pipes, bends, T-shaped pipes, and reducers.

C.3 Pre-processing

Pre-processing helps to prepare entry data for the numerical analysis. Here, entry data includes the initial conditions for the water-carrying facilities and boundary conditions of ancillary facilities of irrigation pipelines. As there are many kinds of ancillary facilities, data entry is complex. This work must be done efficiently because it is necessary when changing the damage scenario or countermeasure scenario. By specifying meta-data information for water-carrying facilities and ancillary facilities of a pipeline and, based on this specification, using an XML file containing initial conditions for water-carrying facilities and boundary conditions as ancillary conditions for data entry, the numerical simulation solver can smoothly read in entry data. To reduce the work of entering data in the XML file of ancillary facilities, a system for entering data using a Google Earth screen was built. For example, as shown in Fig. 8, a user can prepare data by forming place-marks for ancillary facilities on a map and editing the XML file that is displayed on the explanation tag of the popup dialog box.

C.4 Post-processing

As shown in Fig. 9, the results of the numerical hydraulic analysis are displayed on Google Earth. The CSV file output by the numerical analysis solver is converted to KML format and the maximum values of the pressure head of each facility of the pipeline are displayed as polygons. Of the three polygons, the red lines are routes, the white lines are the design water pressure, and the blue lines are the maximum values of the pressure head in the results of numerical analysis. The graph of the time-series change of the pressure head can be confirmed based on the



Fig.8 Data entry using Google Earth (Using Google Earth from Google)

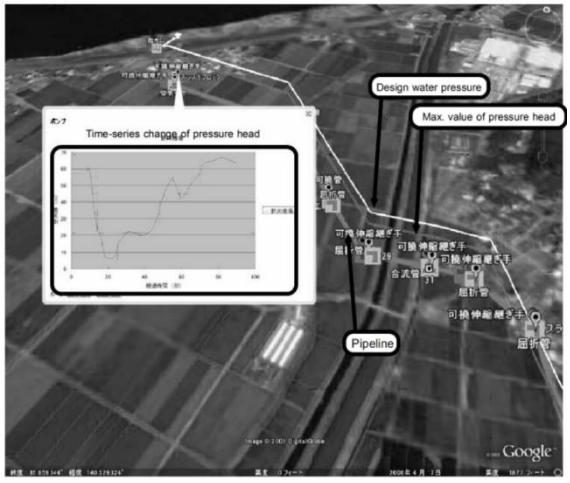

Fig.9 Sample display of results of analysis of water hammer pressure and hydrodynamic pressure during an earthquake (Using Google Earth from Google)

explanatory notes of the pipeline ancillary facilities. This result is used by engineers to study the occurrence of damage to hydraulic functions and its impact on the surrounding environment.

CONCLUSION

This study proposed a method for risk management of hydraulic functions, which have not been studied until now, in the seismic design of irrigation pipelines in Japan. Software for using this method on a PC was also developed.

The software and how it has been used by engineers of land improvement districts in target regions in the past were also explained. Field engineers must still verify whether the system can be fully introduced.

It is important to note that the developed software converts data to KML files at the pre-processing and post-processing stages, but is a program independent of Google

Earth. Google Earth is freeware, but should be used in line with a contract with Google.

REFERENCES

[1]. [1] Ministry of Agriculture, Forestry and Fisheries, Rural Development Bureau, Rural Infrastructure Department, Design Division (2009): Planning and design standards and operation of land improvement projects, commentary and design, "Pipelines", 322-378, (in Japanese)

[2]. M. Mukaiden (2007): Basic concept of safe design, Japanese Standards Association, 11-109, (in japanese)

[3]. Akita Prefecture Agriculture Administration Bureau (1985): 1983 Middle Japan Sea Earthquake – Damage to and restoration of farmland and agricultural facilities –, 32-342, (in japanese)

[4]. Hyogo Prefecture: Nanbu Earthquake Technical Study Committee (1996): Hyogo Nanbu Earthquake of 1995, Report on the technical study of farmland and agricultural use facilities, 119-130, (in japanese)

[5]. 2003 Tokachi offshore earthquake damage survey report, Special Edition (2003): Monthly Journal of the Civil Engineering Research Institute of Hokkaido, 52-55, (in japanese)

[6]. Y. Nara, M. Saito, H. Inagaki, T. Nakazono, Y. Akiyoshi (2003):A Method to Design Pumping Pipeline Considering Water Column Separation Phenomenon, Japan Rainwater Catchment Systems Association, 9, 1, 25-36

[7]. Y. Nakagawa (1969): Theoretical research on water hammer pressure in water transport pipe during earthquakes, Journal of the Japan Waterworks Association, No. 416, 26-35, (in japanese)

[8]. Y. Hideshima (2005): Water hammer pressure of a pipeline observed during the 2003 Tokachi Offshore Earthquake, Drainage and Reclamation Engineering in Hokkaido, No. 27, 50-55, (in japanese)

[9]. K. Ueya, J. Tokui , K. Abe, K. Hasegawa, H. Tagashira, Y. Hideshima (2004): Analysis of water hammer pressure observed at "The Tokachi-Oki Earthquake 2003", Abstracts of the Conferences of the Japanese Society of Irrigation, Drainage and Rural Engineering, Japan, 800-801

[10]. E. Kinoshita (1996): Basic decision-making made simple, Kindai Kagaku Sha Co., Ltd., 55-94, (in japanese)

★★★