Dam earthquake resistance and related technologies

1. Outline of Research and Activities

Background, History, and Outline of Research

Events and changes in society	○ 1995 Hyogoken-Nanbu Earthquake (Great Hanshin-Awaji Earthquake) ○ 1995-2001 Recommendations on Seismic Standards for Civil Engineering Structures / Guidelines for Seismic Design of Civil Engineering Structures (JSCE) ➤ Consideration of two levels of seismic motion Introduction of limit state design method, etc. ○ 2000 Tottori Prefecture Western Earthquake ➤ Largest earthquake ground motion ever observed at a dam foundation	○ 2004 Niigata Prefecture Chuetsu Earthquake ➤ Relatively noticeable damage in multiple fill dams	○ 2011 Off the Pacific Coast of Tohoku Earthquake (Great East Japan Earthquake) ➤ Damage from a break in an old agricultural reservoir	○ 2016 Kumamoto Earthquake
Actions of the MLIT	○ 1976 River management facilities, etc. Enactment of the Structural Ordinance and the Enforcement Regulations ➤ Legislated seismic standards for dams based on the conventional seismic intensity method. ○ 1991 Seismic Design Guidelines for Fill Dam (Draft) was published. ➤ Introduction of Seismic Design Methods Considering Dynamic Response ○ 1997 Technical Standard for River Erosion Control (Design) established.	○ 2001 NILIM established. ○ 2002 "Basics of Design for Civil Engineering and Architecture" published. ➤ Clearly stated seismic performance set limits, conditions, design methods, etc. ○ 2002-2005 "Earthquake Resistance Study Group" ➤ Study on the technical guideline on the seismic performance verification method for dams against large earthquakes ○ 2005 Draft Guideline for Seismic Performance Verification of Dams against Large-Scale Earthquakes (Draft) was published.	○ 2005- Started a trial seismic performance verification of dams against large-scale earthquakes (dams managed by the MLIT nationwide)	○ 2013-2016 NILIM, PWRI Reorganization ➤ Research organization in the field of dam structures unified into NILIM

Research & Activities

(Former Public Works Research Institute)

- ☐ Accumulation of research on the advancement of structural and seismic design methods for dams
- ☐ Accumulation of knowledge through seismic surveys
- ☐ Technical support for on-site construction and management dams

◆ **Phase 1**

Research on seismic performance verification methods of dams

➤ Research on methods for verifying the seismic performance of dams against large-scale earthquakes

◆ **Phase 2**

Operation and further improvement of the seismic performance verification method

➤ Responding to technical issues associated with trial operation of seismic performance verification for large-scale earthquakes

➤ Accumulation of knowledge through seismic surveys, etc.

➤ Technical support to the site in the event of an earthquake

➤ Technical support for nationwide seismic performance verification (trial)

Main Results (Phase 1)

- ☐ Drafting of the Draft Guidelines for Seismic Performance Verification of Dams against Large-Scale Earthquakes (technical guideline development)
- ・Method of setting level 2 earthquake ground motions
- ・Requirements for seismic performance
- ・Verification analysis method for dam main body
- ・Analysis method for verification of related structures (gates, etc.)

Main Results (Phase 2)

- ☐ Nationwide progress in seismic performance verification
- ☐ Incorporation of new knowledge (e.g., improvement of earthquake motion estimation formulas)
- ☐ Addressing practical issues (e.g., system identification methods for earthquake response analysis)

◆ **Phase 3**

Development of related research on earthquake countermeasure technology

Main Results (Partially implemented)

- ☐ Deformation monitoring techniques
- ☐ Crisis management methods in the event of an earthquake
- ☐ Seismic reinforcement techniques

◆ **Research on methods for verifying seismic performance of dams (Phase 1)**

[Background and Issues] In the 1995 Great Hanshin-Awaji Earthquake in southern Hyogo Prefecture, dam facilities suffered only minor damage, but various other structures were severely damaged. This led to an increase in public interest in the earthquake resistance of structures, and accelerated a fundamental review of earthquake resistance standards for various civil engineering structures, including the introduction of a two-stage design method that takes into account both conventional design earthquake motion and higher levels of earthquake motion, the clarification of earthquake resistance performance for each earthquake motion level, and the introduction of the limit state design method. The introduction of the limit state design method, for example, accelerated the trend toward a fundamental revision of seismic codes. Under these circumstances, and given that the nationwide seismic observation system for dams has been enhanced, there has been an increasing number of observed cases of seismic motion exceeding the design seismic intensity (the magnitude of seismic force (ratio to gravity) to be considered in the design) specified in the domestic structural standards based on the seismic intensity method (Government Ordinance for Structural Standards for River Administration Facilities and Ministry of Construction Ordinance for Structural Standards for River Administration Facilities). This has led to a strong demand for the development of a method that can rationally explain the seismic resistance of individual dams against large-scale earthquakes. Therefore, it was decided to develop a method for evaluating seismic performance against large-scale earthquakes that actively incorporates numerical analysis techniques, such as the estimation of seismic response using the dynamic analysis method, which was already becoming popular.

[Research Summary and Main Results] Around 2001, when NILIM was established, we began to identify issues in the current structural standards in solving the above-mentioned problems, and we started to examine measures from both technical and institutional perspectives. In addition to the seismic design based on a combination of empirical design seismic intensity and safety factors under the current structural standards, it was decided to establish a new framework for evaluating the seismic performance of dams designed in accordance with these standards against the maximum earthquake motion (Level 2 earthquake motion) that can be expected at each dam site. We worked together with the Public Works Research Institute and others to consider its specific contents. The main items studied were: (1) a specific method for setting the Level 2 earthquake motion, (2) the details of the seismic performance required of dams in response to Level 2 earthquake motion, and (3) a specific method for evaluating the seismic performance of the dam body and related structures (gate equipment, etc.) based on these items. The contents were compiled through deliberations from 2002 to 2005 at study groups including experts and government officials, and became the "Guidelines for Seismic Safety Evaluation of Dams (Draft)" (hereinafter referred to as the "Draft Guidelines") published by the Ministry of Land, Infrastructure, Transport and Tourism in March 2005.

◆ **Operation and further improvement of the seismic performance evaluation method (Phase 2)**

[Background and Issues] Based on the aforementioned draft guidelines, trial verification of seismic performance began in FY 2005 at dams managed by the Ministry of Land, Infrastructure, Transport, and Tourism (MLIT) nationwide. However, in order to ensure that the evaluation was appropriately conducted at individual dams with various topographical and geological conditions and structural characteristics, it was necessary to provide continuous and detailed technical support to each dam administrator, etc. In addition, new knowledge gained in the course of the trials, as well as issues related to practical handling, needed to be considered. It was also required to respond to new findings obtained in the course of the trials and to address issues that arose in the practical handling.

[Research Summary and Main Results] NILIM, in collaboration with the Public Works Research Institute, compiled and published a series of technical documents[1)] to assist practitioners in evaluating the seismic performance of dams. In addition, NILIM has continuously provided technical support to individual dams by utilizing the knowledge obtained through field surveys conducted in the past when earthquakes occurred. In 2011, we improved the seismic motion estimation equation used to set the Level 2 seismic motion by using a large number of seismic motion observation records obtained during the Great East Japan Earthquake (2011 off the Pacific coast of Tohoku Earthquake). We have also been conducting research to further improve the technology for estimating the seismic response of dams, including seismic performance evaluation, by developing a system identification method that more accurately sets the analytical parameters required for seismic response analysis based on measured response records.

◆ **Development of related earthquake countermeasure technology research (Phase 3)**

[Background and Issues] In order to ensure the safety of dams against earthquakes, it is necessary to develop and disseminate related technologies in various aspects, including crisis management, such as rapid prediction of the effects of earthquakes, and countermeasure technologies, such as methods to improve earthquake resistance.

[Research Summary and Main Results] As a new dam monitoring method that can be used to detect abnormalities during earthquakes, we recently developed a technology that uses satellite data and vibration data, and have confirmed the effectiveness of this technology. In addition, we are also developing technology to immediately estimate the impact of an earthquake on individual dams based on information on the epicenter of the earthquake. In terms of countermeasure technologies, we have been studying methods to improve (reinforce) the seismic resistance of dams, of which there are few examples in Japan.

2. Main Research Results

◆ **Research on methods for evaluating seismic performance of dams (Phase 1)**

In order to evaluate the seismic performance of dams against large earthquakes, it is first necessary to set the Level 2 earthquake motion to be considered in the evaluation. For this purpose, we clarified the method and procedure for setting Level 2 earthquake motions for each dam site based on information on earthquakes that are expected to occur on nearby active faults and oceanic plate boundaries. In addition, since it is necessary to set the minimum strength of earthquake ground motions to be considered for earthquakes in the inland crust, considering the possibility of the existence of unknown active faults around the site, a response spectrum (Figure-1) that defines the lower limit of Level 2 earthquake ground motions was also set to address this possibility.

It also clarified the seismic performance of dams to be secured against Level 2 earthquake motion by stipulating that “even if the dam is damaged, its water storage function shall be maintained, and the damage that occurs shall be limited to the extent that it can be repaired.” This means that damage to the dam itself is acceptable as long as it is limited and does not cause damage to downstream areas.

As a specific evaluation method for the dam body and related structures, a seismic response analysis method that considers the damage process was introduced (Figure-2). Nonlinear dynamic analysis (Figure-3) that can take into account cracks and joint openings in the dam body is used for concrete dams; plastic deformation analysis that can estimate the settlement of the embankment is used for fill dams; and seismic response analysis that can take into account plasticization of the members is used for gate facilities. Based on the results of the seismic analysis, the following checks were made: for concrete dams, the presence or absence of instability due to cracks that would break up the upper and lower surfaces of the dam body; for fill dams, the presence or absence of large settlement or seepage failure that would cause overflow of stored water; and for gate facilities, the presence or absence of damage that would cause excessive outflow of stored water. The basic concept of judgment in confirming whether or not the dam has the required seismic performance was clarified.

All of the above contents are positioned in the “Guidelines for Seismic Safety Evaluation of Dams (Draft)” and are being used in trials of seismic performance evaluation at dams nationwide.

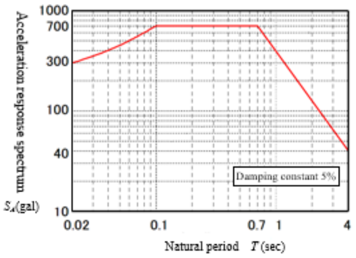

Figure-1 Lower limit acceleration response spectrum for verification[1)](for horizontal motion) *Some revisions have since been made.

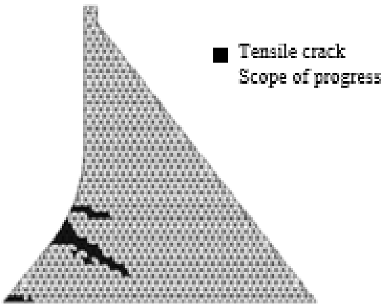

Figure-3 Example of nonlinear dynamic analysis of dam body considering damage process (gravity-type concrete dam)[1)]

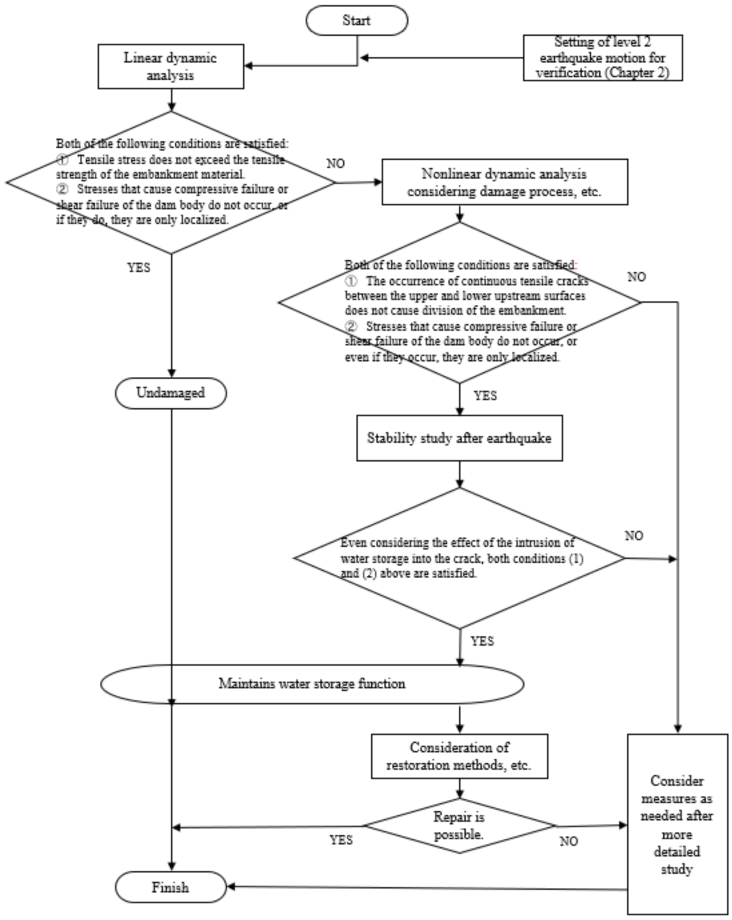

Figure-2 Procedure for seismic performance evaluation of dam main body[1)]

(In the case of gravity-type concrete dams)

◆ **Operation and further improvement of the seismic performance evaluation method (Phase 2)**

In conjunction with the start of the trial seismic performance evaluations of dams based on the draft guidelines, NILIM has prepared and published technical materials[1] that provide more practical handling and examples, while continuing to respond to technical consultations from the dam site offices. As a result, the nationwide trial seismic performance evaluations have progressed.

Figure-4 Safety confirmation at a dam subjected to strong shaking (Kumamoto Earthquake, 2016)[3]

In addition, many seismic motion records were obtained at dam sites following the Great East Japan Earthquake of 2011 (2011 off the Pacific coast of Tohoku Earthquake), and the seismic motion estimation formula (distance attenuation formula for dams) has been improved[2] based on these records.

In response to practical issues that have been identified through the trial seismic performance evaluations, research is underway to enable more accurate estimation of the dynamic behavior of dams during strong earthquakes, including the use of system identification methods based on autoregressive models to accurately set analytical parameters such as damping constants that affect the results of seismic response analysis.

On the other hand, we are also actively providing technical support to dam managers, such as on-site safety confirmation at the time of an earthquake (Figure-4) and advice on restoration methods, in an effort to understand on-site needs and provide them with knowledge in the course of our research activities.

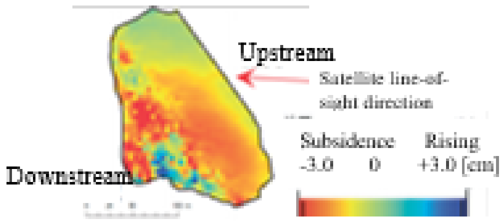

Figure-5 Distribution of displacement (settlement) of fill dam obtained from satellite SAR data before and after a large-scale earthquake[4]

◆ **Development of related earthquake protection technology research (Phase 3)**

For the purpose of rationalization and advancement of safety management of dams, including during earthquakes, we have developed displacement monitoring technology utilizing satellite SAR (Synthetic Aperture Radar) data[4] and have confirmed that even areal displacement of a few millimeters in a rockfill dam can be detected (Figure-5). In addition, research[5] has been conducted on the detection of structural damage using vibration monitoring, which captures changes in the vibration characteristics of dams during strong earthquakes based on seismic motion and constant microtremor data. In terms of technology to improve seismic resistance, we have been clarifying the effects of seismic reinforcement works such as dam body anchoring and dam body thickness on concrete dams through analytical studies,[6] assuming that further studies will be required as seismic surveys progress in the future.

3. List of Related Reports and Technical Documents

1) "Technical Note on Seismic Performance Evaluation of Dams against Large Earthquake," NILIM Technical Note No. 244, 2005
https://www.nilim.go.jp/lab/bcg/siryou/tnn/tnn0244.htm
2) Takashi Sasaki and Takeshi Ito: Attenuation Relationship of Earthquake Motion at Dam Foundation in Consideration of Tohoku Earthquake, Journal of Earthquake Engineering, 16(4), pp. 80-92, 2016
3) Activities of the NILIM in the 2016 Kumamoto Earthquake (River and Dam Field)
http://www.nilim.go.jp/lab/bcg/siryou/tnn/tnn0967.htm

4) Hiroyuki Sato, Masafumi Kondo, Toshihide Kobori, Aoi Onodera: External Deformation Monitoring of Nineteen Rock Fill Dams Using Satellite SAR Data, Civil Engineering Journal, 59(9), pp. 36-41, 2017
5) Masafumi Kondo, Toshihide Kobori and Takashi Sasaki: Seismic Effects on Vibration Characteristics of Concrete Dams, J-STAGE, 27(4), pp. 265-278, 2017
6) "Research on Reinforcement Method of Dams," NILIM Yearbook (FY2016 Summary of results of surveys, tests, and research) http://www.nilim.go.jp/lab/bcg/siryou/nenpou/kn28/kn28web004.pdf

4. Future Outlook

In the future, we would like to further improve the reliability of technologies for evaluating the seismic performance of dams through the accumulation of earthquake ground motion observation data and the improvement of response analysis technology, and to make these technologies available for use in risk management during earthquakes, together with real-time earthquake information and monitoring data. Another future task is to establish a design method for seismic reinforcement of dams, of which there are few examples in Japan, as well as a structural design and maintenance method that can more reasonably take into account various uncertain factors, including earthquakes, and their effects.