Inspection of dams after earthquakes

Martin Wieland[1], Norihiso Matsumoto[2], Ian Landon-Jones[3], Donald Babbitt[4]

(1. Chairman, ICOLD Committee on Seismic Aspects of Dam Design, Poyry Energy Ltd., Zurich, Switzerland; 2. Vice-President of ICOLD, Advisor, Japan Dam Engineering Center, Minato, Tokyo, Japan; 3. General Manager of Dam Safety, Sydney Catchment Authority, Sydney, Australia; 4. Dam Consultant, Sacramento, California, USA)

Abstract: Earthquakes may cause damage to dams in different ways: ① strong ground shaking; ② movements along faults and other discontinuities in the footprint of a dam; ③ permanent loss of freeboard and water waves generated by fault movements in reservoir; ④ impulsive waves due to mass movements into the reservoir. Major earthquakes may affect large areas and large numbers of dams. This was demonstrated by the 2001 Bhuj earthquake in India, where some 240 dams (mainly small embankment dams) were damaged and needed repair and strengthening. Also during the magnitude 8 Wenchuan earthquake in Sichuan province in China of May 12, 2008, over 1580 dams and reservoirs were affected to different extents. Moreover, after the magnitude 7.2 Iwate-Miyagi Nairiku earthquake, which occurred in Japan on June 14, 2008, 134 dams were inspected. Therefore, in order to assess the safety of dams affected by earthquakes a thorough investigation is usually required by the dam safety authorities. This is done best by using checklists. In 2008 the 20 year old ICOLD Guideline on the Inspection of Dams Following Earthquakes was completely revised including the checklists for the inspection of embankment and concrete dams. The present paper provides a summary of the new features of this guideline and it is hoped that the checklists provided will be used not only for the inspection of dams after earthquakes but also for the general inspection of dams.

Key words: dam safety; dam inspection; strong motion instrumentation; earthquake damage

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Biography: Martin Wieland (1948－), male, PhD. He has been engaged in dam and earthquake engineering. E-mail: martin.wieland@poyry.com.

水库大坝地震后特别检查

摘 要：地震可以不同方式对水库大坝造成破坏：①强烈的地振动；②坝基沿断层或其他间断面的位移；③水库内断层活动引起波浪使大坝失去超高；④岩体向水库运动形成冲击波。大地震影响的范围较广，可能影响的水库大坝数量也较多，如2001年发生的印度Bhuj地震，有240多座水库大坝（主要为小型的土石坝）因遭受破坏而需要除险加固。另外，2008年5月12日发生在四川汶川的8级地震，有1580多座水库大坝遭受到不同程度的破坏。2008年6月14日日本Iwate-Miyagi Nairiku 7.2级地震发生后，对其涉及的134座水库大坝进行了地震后特别检查。通常，负责大坝安全的部门需要通过调查对震损水库的安全状况进行评估，进行调查时最好使用检查表。2008年国际大坝委员会对使用了20 a的地震后水坝检查导则进行了全面修订，其中包括土石坝及混凝土坝的震后检查表。介绍了导则修改后的特点，并希望提供的检查表不仅应用于水库大坝的震后检查，也可应用于水库大坝一般检查。

关键词：大坝安全；大坝检查；强振仪；地震破坏

0 Introduction

The recent earthquakes in China and Japan have shown that a large number of dams may have to be inspected following a major earthquake. It was reported that the May 12, 2008 Wenchuan earthquake in Sichuan province in China with a magnitude of 8.0 may have affected some 1580 dams, which had to be checked (Fig. 1), and after the magnitude 7.2 Iwate-Miyagi Nairiku earthquake in Japan of June 14, 2008 134 dams had to be inspected within a short period of time. To perform such inspections efficiently and thoroughly checklists are of great help. This was also realised by the International Commission on Large Dams (ICOLD), which in 1988 published a guideline on Inspection of Dams Following Earthquakes (ICOLD, 2008)[1]. This guideline may have

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been rarely used as rather few earthquakes have occurred, which involved a large number of dams. The January 25, 2001 Bhuj earthquake in Gujarat province in India was probably the first event where a large number of dams was damaged. After the earthuake some 240 dams needed repair or rehabilitation (Fig. 2).

Fig. 1 Damage of concrete face of Zipingpu concrete face rockfill dam caused by the 2008 Wenchuan earthquake, China

(a)

(b)

Fig. 2 Typical damage of embankment dams caused by the 2001 Bhuj earthquake, Gujarat, India

After an earthquake it is always necessary to make a safety assessment of the dams affected by the earthquake. A systematic and consistent safety assessment is only possible with a sound checklist. Of course the assessment must be performed by experienced engineers. Due to the urgency of such inspections it is necessary that several engineers or teams perform such inspections. However, this has the disadvantage that the damage and safety assessment may not be fully consistent among different teams and engineers inspecting different dams.

The present paper gives a brief summary of the revised guideline (ICOLD, 2008), that was approved at the ICOLD Annual Meeting in Sofia, Bulgaria in June 2008. However, the emphasis will be on the checklists and their dissemination. We also hope that these checklists will become better known so they will also be applied for the inspection of the dams affected by the Wenchuan earthquake in China.

The revised Guideline on the Inspection of Dams Following Earthquakes was prepared by the ICOLD Committee on Seismic Aspects of Dam Design, which comprises representatives from 29 different countries from all continents. The participation of representatives from many countries is of great help in the dissemination of the latest information on seismic aspects of dams and in particular the earthquake safety of large storage dams.

1 Inspection of dams

The list of contents of the revised ICOLD Guideline on the Inspection of Dams Following Earthquakes is as follows:

(1) Earthquake Preparedness and Planning.

(2) Earthquake Detection and Alarms: ① Seismic Data Collection; ② Earthquake Warnings and Recommendations.

(3) Immediate Inspection Following Earthquake: ① When Communication Links Are in Place; ② When Communication Links Are not Available.

(4) Followup Engineering Inspection: ①Possible Modes and Causes of Failure.Abutment and Foundation Deficiencies, Spillway and Outlet Works, Seepage, Defective or Inferior Materials, Concrete Dam Overstressing, Reservoir Margin Defects; ②Features to Be Inspected after Earthquake. Embankment Dams (Figs. 1 and 2), Concrete and Masonry Dams (Fig. 3), Abutments and Foundation, Reservoir, Landslides (Fig. 4), Appurtenant Structures (Fig. 5).

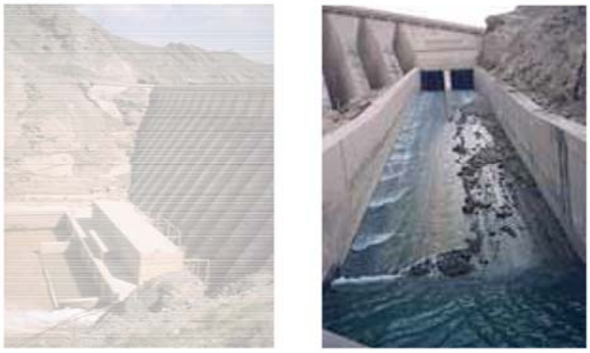

Fig. 3 Damage of Sefid Rud buttress dam caused by the 1990 Manjil (magnitude 7.5) earthquake, Iran

The new sections of the revised Bulletin 62 are Earthquake Preparedness, Planning, and Earthquake Detection and Alarms and Effects of Earthquakes on

Leakage and Uplift Pressures.

Fig. 4 Rockfall damage of Sefid Rud buttress dam caused by the 1990 Manjil earthquake, Iran

Fig. 5 Switchyard damage of Sefid Rud buttress dam caused by the 1990 Manjil earthquake, Iran

2 Features to be inspected after earthquake

All features should be inspected to determine whether there are any changes that may have been a result of the earthquake. Sketches, photographs or videos may help to describe the nature and extent of any damage. Photographs should be obtained as soon as possible of any visible results from the seismic activity. These records will be invaluable in determining if there is additional distress developing in the structures. Measurements and readings should be taken of all instrumentation installed in the dam and foundation and in the immediate area. Additional precise surveys, temporary strong-motion seismographs, and other instrumentation may be desirable to monitor structures and individual damage locations. Special steps need to be taken to ensure that records from the seismographs are properly extracted and given to those responsible for their interpretation. The following is an extract from the revised Bulletin 62 (ICOLD, 2008).

2.1 Embankment dams

The external surfaces of an embankment dam can often provide clues to the behaviour of the interior of the structure. Liquefaction is a special problem for susceptible embankment dams and foundations as a result of earthquake shaking. For this reason, a thorough examination of all exposed surfaces of the dam should be made.

The embankment should be carefully examined for any evidence of displacement, cracks, sinkholes, springs, sand boils and wet spots. Any of these conditions may be in a developing mode and, if they worsen and are not corrected, ultimately could lead to failure of the embankment.

Surface displacement on an embankment often can be detected by visual examination. Sighting along the line of embankment roads, parapet walls, utility lines, guardrails, longitudinal conduits, or other lineaments parallel or concentric to the embankment axis can sometimes identify surface movements of the embankment. The crest should be examined for depressions and crack patterns that could indicate sliding, settlement, or bulging movements. The upstream and downstream slopes and areas downstream of the embankment should be examined for any sign of bulging, depressions, or other variance from smooth, uniform face planes. If a permanent system of monuments for measurement of movement exists, and if any movement is suspected, a resurvey should be made without delay.

Cracks on the surface of an embankment can be indicative of potentially unsafe conditions. Surface cracks are often caused by desiccation and shrinkage of materials near the surface of the embankment; however, the depth and orientation of the cracks should be determined for a better understanding of their cause. The depth and extent of cracks can be observed by first filling the cracks with dye and then excavating. Otherwise it can be difficult to identify the extent of cracking. Openings or escarpments on the embankment crest or slopes can identify slides and a close examination of these areas should be made to outline the location and extent of the slide mass. Surface cracks near the embankment-abutment contacts, and contacts with other structures can be an indication of settlement of the embankment and, if severe enough, a path for seepage can develop along the contact. Therefore, these locations must be thoroughly examined. Cracks can also indicate differential settlement between embankment zones. Trenches are often excavated by machine or by hand to determine the depth of cracking.

The downstream face and toe of the dam, as well as areas downstream of the embankment, and natural abutments should be examined for wet spots, boils, depressions, sinkholes, or springs, which may indicate concentrated or excessive seepage through the dam or abutments. Any of these conditions may be in a developing mode and, if they worsen and are not corrected, ultimately could lead to failure of the embankment. Other indicators of seepage are soft spots, deposits from evaporation of water, abnormal growth or vegetation and, in colder climates, ice accumulation or areas where rapid snowmelt occurs. Seepage water should be examined for any suspended solids (turbidity) and, if solutioning is suspected, samples of the seepage and reservoir water should be collected for chemical analyses. Seepage also should be tested for taste and temperature to help identify its source. If saturated areas are located, they should be studied to determine if the wet spot(s) are a result of surface moisture, embankment seepage, or other sources. Wet areas, springs, and boils should be located accurately and mapped for comparison with future inspections. Seepage should be measured and monitored on an increased frequency to ensure that an adverse trend does not develop which could lead to an unsafe condition.

Drainage systems should be inspected for increased or decreased flow and for any obstructions which could plug the drains.

In addition to verifying anticipated embankment and foundation performance, instrumentation also can be an indicator of developing unsafe conditions. Readings should be made frequently, if earthquake shaking has changed the historical steady state readings. Earthquakes can cause increases in pore piezometric levels by shaking-caused soil volume reduction and/or shearing, and indirectly by earthquake compacted soils transferring loads to stiffer soils.

2.2 Concrete and masonry dams

Concrete dams encompass a variety of structures which include gravity, slab and buttress, multiple arch, and single arch dams. Masonry dams may be considered as gravity structures with many joints. Regardless of the type, all dams are subject to the same basic considerations with respect to safety.

The dam should be checked for indications of excessive stress and strain as well as signs of instability. Most dams have survey points and/or plumblines for regularly scheduled measurements of movement within the dam, the results of which can be plotted to determine the behavioural trend. There are obvious indications of movement which can be noted during an inspection. A gravity or masonry dam usually can be checked by sighting along the parapets or handrails from one abutment to the other. Each contraction joint or row of masonry blocks should be examined for evidence of differential movement between adjacent blocks. The joints should be examined for evidence of excessive expansion or contraction and excessive movement. The foundation contacts should be examined for any evidence of differential movement between the dam and the foundation.

All cracks and spalls on the dam faces and in the galleries should be examined. Gravity dams would more likely show new cracking in the upper part of the dam, and arch dams near the abutment and top arch. Gallery cracks should be examined to see if they coincide with face cracks. Cracks and spalls noted during past inspections should be examined for any change of condition. New cracks and spalls should be noted and examined to determine the type, such as tension or crushing and the reasons for their existence. They should be marked and measured so that any changes can be detected during subsequent inspections.

Seepage should be examined to determine the possible sources such as poor bond on lift lines, waterstop failure, structural cracks, and erosion of mortar. The quantity of seepage should be compared with previously observed quantities to determine if there has been any significant change in the flow for similar reservoir elevations.

Drain and weep holes should be checked to determine if they are open and functioning as designed. Drains in the foundation and the dam should be examined to determine if there have been significant changes in their flow.

2.3 Abutments and foundation

Critical areas of the abutments and foundations are usually covered and not available for direct inspection. Inspection of upstream portions of the abutments and foundation is normally not possible because of reservoir storage. Therefore, physical examination is typically limited to the downstream abutment contacts, toe of the dam and foundations of some appurtenant structures. Grouting and drainage tunnels also may be available for inspection. Reaction of structures often reflects foundation changes.

Indications of harmful seepage may be quite obvious or very subtle. Changes in measured flow from monitored drains, whether increases or decreases, are immediately suspect. Another indication of changes might be increased frequency of sump pump operation. The presence of suspended particles in seepage water is evidence that piping is taking place and is cause for immediate concern. Joint opening caused by earthquake shaking can rupture grout curtains. On the other hand, small increases in seepage (less than one litre/second - but this would depend on the individual size and nature of dam) are common and are apparently caused by minor opening of rock joints or dislodging or movement of fines in fractures.

Temporary changes (both increases and decreases) in seepage and piezometric pressures are common and should normally start to return to pre-earthquake levels within a few hours after the earthquake however in some cases they may be permanent or take a long time to reverse. Refer to Appendix 4 for case histories of impact of earthquakes on leakage and uplift pressures in Japan.

When the possibility of solutioning exists, samples of reservoir and seepage water should be collected for water quality analyses. Such analyses can identify the soluble material. If the rate of seepage can be determined, the rate of solutioning can be estimated.

2.4 Reservoir

The reservoir basin usually does not directly affect the stability of the dam; however, the reservoir should be examined for features which may compromise the safe operation of the dam and reservoir. Immediately upstream of the dam and its abutments the reservoir surface should be inspected for indications of abnormal flow patterns that may indicate gross leakage is taking place. These may include whirlpools or an unusual flow pattern.

The region around the reservoir should be examined for indications of problems which might affect the safety of the dam or reservoir. Landforms and regional geologic structures should be assessed. Areas of mineral, coal, gas, oil, and groundwater extractions should be examined. The region should be checked for subsidence indications such as sinkholes, trenches, and settlement of highways and structures. The reaction of other structures on the same formation may provide information on the possible behaviour of the dam and appurtenances. Whenever an inspection is made, the elevation of the reservoir should be recorded.

The reservoir basin surfaces should be examined for depressions, sinkholes, or erosion of natural surfaces or reservoir linings. The reservoir basin should also be inspected for excessive siltation, which can adversely affect the loading of the dam or obstruct the inlet channels to the spillway or outlet works.

The drainage basins in areas adjacent to but on the outside of the reservoir rim should be examined. Any new springs or seepage areas may indicate that reservoir water is passing through the reservoir rim. Such seepage also may cause land instability in these areas.

2.5 Landslides

Landslides, as used herein, include all forms of mass movement that can affect the dam, appurtenances, reservoir, or access routes. They include active, inactive, and potential slide areas which can range from minor slope ravelling to large volume movements. In addition to slide phenomenon, the inspection also should determine if there has been any toppling or sliding of intact rock blocks or masses. These can occur not only in the reservoir but also in the abutments of the dam and above powerhouses. Landslides might form natural dams on tributary streams or cause waves on reservoir surfaces.

At least one team member should be knowledgeable about landslide causes, mechanisms, characteristics, symptoms, and treatment. Slide areas often can be identified by escarpments, leaning trees, hillside distortions, or misalignment of linear features.

2.6 Appurtenant structures

All appurtenant structures that could affect the safe operation of the dam should be examined. These structures include the spillway, outlet works, power outlets and powerplants, and canal outlets. Inspection of critical components such as spillway gates or bottom outlets may not be adequate to verify their operability and in these cases these components should be physically tested and exercised.

2.7 Inlet and outlet channels

Practically every hydraulic structure is served by inlet and outlet channels composed of cut or fill slopes of soil or rock. Most soil- or rock-lined spillways have a concrete or solid rock control section to reduce seepage or erosion potential past the dam. Outlet works inlet channels are usually submerged and may require special underwater investigation. Channel protection adjacent to the energy dissipation structure should be examined to determine if it is performing as designed. Special attention should be given to the possibility that the material may wash either out of the channel or back into the structure during operation.

The channels should have stable slopes and be free of sloughs, slides and debris, and should be examined for evidence of sinkholes, boils, or piping. The channels should provide satisfactory clearance around intake and terminal structures so the structures can operate hydraulically as designed.

The outflow water should be examined for the presence of rock and soil or concrete fragments, which may mean that the conduit has been breached and embankment or foundation material is being eroded. On the other hand, the source of turbidity may only be reservoir sediments that were stirred up by earthquake shaking. Repeated observations are usually necessary to identify the source of turbidity.

2.8 Dam safety critical plant

Dam safety critical plant, such as gates and valves required by dams to provide flood protection and to reduce loads on the dam after the earthquake shaking should be inspected for operability. Abnormally high leakage from gates and valves may indicate distortion and warping precluding their use. Structural elements should be examined for buckling and damage. Operating equipment such as winches, hydraulic systems, control systems and their support structures, such as spillway bridge decks and spillway piers, should be inspected for any damage that may render the gates or lifting equipment inoperable. Similarly the condition of backup power supplies should be included in the post earthquake inspection schedules.

2.9 Penstocks

In some cases penstock failure or significant leakage from penstocks may lead to erosive damage to an earth dam downstream face or its toe that has safety implications for the dam. The condition of these penstocks and their controlling intake gates should be inspected to confirm satisfactory conditions.

3 Checklist for post-earthquake safety inspection of embankment dams

The members of an inspection team must be aware of the modes of failure of embankment dams.

In embankment dams (including canal embankments), earthquake impacts can include large deformations, settlement and/or cracking. Most cracking is longitudinal, normally found on the dam crest, but traverse cracking has occurred mainly near the abutments.

The main items to be looked at during the inspection of embankment dams are as follows:

(1) Upstream Face: Slide movements, Erosion – breaching, Cracks, Sinkholes, Settlement, Displacement, Slope protection, Debris, Unusual conditions.

(2) Crest: Surface cracking, Settlement, Lateral movement (alignment), Camber.

(3) Parapets, Kerbs, Railings: Deformation, Lateral Movement (alignment), Cracking.

(4) Downstream Face: Erosion – breaching, Cracks, Sinkholes, Slide movements, Settlement, Displacement, Unusual conditions.

(5) Downstream of the dam: Boils, Springs, Sinkholes.

(6) Abutments: Cracks, open joints, Erosion, Sinkholes, Slide movements, Unusual conditions.

(7) Drainage/Inspection Adits: Lighting, ventilation, Total drain flow, Individual drain flows, Cracks, Seepage, Joint offsets, openings, spalling, Rockfalls.

(8) Seepage, Toe Drains, Galleries, Adits, Relief Drains: Locations, Estimated flow(s), Change in flow, Clearness, Colour, Fines.

(9) Methods of flow measurements, Condition of measuring devices, Records, Performance Instruments; Piezometers, Surface settlement points, Internal movement devices, Inclinometers, Reservoir level gage, Seismic instruments.

(10) Special Items

4 Checklist for post-earthquake safety inspection of concrete dams

The members of an inspection team must be aware of the modes of failure of concrete dams.

In concrete dams the major impact is cracking.

For example, horizontal or near horizontal cracking has occurred along construction joints at high elevations such as at Koyna gravity dam in India, Sefid Rud buttress dam in Iran and Hsinfengkiang buttress dam in China.

The main items to be looked at during the inspection of concrete dams are as follows:

(1) Upstream Face: Cracks, Joints, offsets, openings, spalling.

(2) Crest: Alignment of walls, edges, Cracks, Joint openings, offsets, spalling, Parapet wall condition, Lighting.

(3) Downstream Face: Cracks, Joint offsets, openings, spalling, Seepage.

(4) Downstream Toe: Seepage, Scour, undercutting, Cracks, other distress.

(5) Downstream of dam: Boils, Springs,Sinkholes.

(6) Galleries: Lighting, ventilation, Total drain flow, Individual drain flows, Cracks, Seepage,Joint offsets, openings, spalling.

(7) Performance Instruments: Piezometers, Surface monuments, Pendulums, Reservoir level gauge, Seismographs.

(8) Special Items

5 Additional check lists

Special check lists are provided in the ICOLD Bulletin 62 for the inspection of abutments, spillways, outlet works, reservoir, and access roads. Access to remote dam sites in mountaineous regions may be a problem, which has been underestimated in the past. For example, it was not possible to inspect all the dams affected by the 2008 Wenchuan earthquake due to the fact that numerous roads were blocked by landslides and rock falls and the imminent danger of additional mass movements being triggered by aftershocks and heavy rainfall.

The time required for an inspection depends on the size of the dam and the type of damage observed. It is very fast to inspect an undamaged dam whereas the detailed inspection and analysis of a damaged dam may take considerable time.

6 Response action after earthquake

In well-instrumented regions like Japan, California etc. a shake map (Fig. 6) can be produced within an hour or less after an earthquake. This information can be made available to the dam safety authorities and the dam owners. Based on this information decisions can be taken on dam inspections.

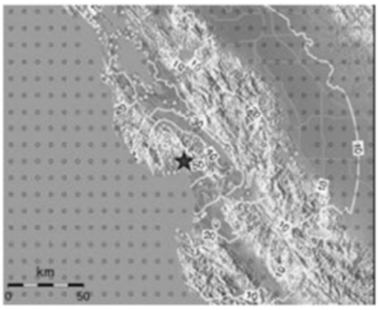

Fig. 6 Shake map produced by the US Geological Survey after the 1989 Loma Prieta earthquake in California (Magnitude 6.9; contour lines of peak ground acceleration as percentage of g)

In Japan, the dam operator would normally be required to inspect dams within 8 hours if the peak ground acceleration (PGA) is greater than 25 cm/s^2 or exceeds a value of 4 on the JMA Intensity Scale, which is equivalent to a MMI of 6. A primary (initial) and secondary inspection are carried out with the primary results reported to the Supervisory Office within 3 hours and the secondary results within 24 hours. In the case of the PGA being less than 80 cm/s^2, the JMA intensity is less than or equal to 4 and if no damage is detected in the primary inspection, no secondary inspection is required.

7 Strong motion instruments

The conventional monitoring instruments installed in large dams are well suited for the monitoring of the long-term behaviour of a dam. Accordingly, the frequency of most readings is one measurement per week or month. However, actions like earthquakes cannot be recorded satisfactorily by these instruments.

The strong motion accelerometers available on the market today are able to record both small amplitude vibrations and motions caused by strong earthquakes or even explosions. Moreover, during the last decade the cost of digital sensors and recorders has dropped and at the same time the performance of these instruments and the data analysis features built into these systems have improved dramatically.

Dam monitoring forms a key element in the overall safety concept of a dam, which comprises the following:

(1) Structural safety (capability of a dam to resist water load, earthquake forces and other types of forces

and actions);

(2) Dam safety monitoring (evaluation of dam behaviour and safety based on visual and instrumentally recorded data);

(3) Safe operation (safe operation of reservoir on the basis of reliable rule curves, well-trained staff, and dam maintenance); and

(4) Emergency management (timely warning of the population in the case of an accident and preparation of evacuation plans, etc.).

Records of strong motion instruments could be used to contribute to all four of the above safety elements of a large dam project. They can be used to issue an alarm, if critical acceleration or spectrum intensity values etc. are exceeded. Therefore, strong motion instruments installed within the dam are important components of an alarm and rapid response system and allow the timely warning of the population living in the downstream valley (water alarm).

Today, strong motion instruments and a rapid alarm system should belong to the standard instruments for the safety monitoring of large dams. As the prediction of the time, location and magnitude of strong earthquakes, which may affect the safety of a dam, will not be possible in the foreseeable future, the aspect of rapid warning of the population living downstream of a dam is an important issue.

Moreover, the data collected from strong motion instruments can be used to check and to improve the seismic design criteria of the dam, and to perform a back analysis of dams.

Three instruments would be the minimum for a large dam as it has to be assumed based on past experience that one instrument may not be working properly at the time of a strong earthquake due to maintenance problems.

Any new dam with a large damage potential should have at least a few strong motion instruments and the monitoring systems of the existing dams should eventually be upgraded as well (Fig. 7).

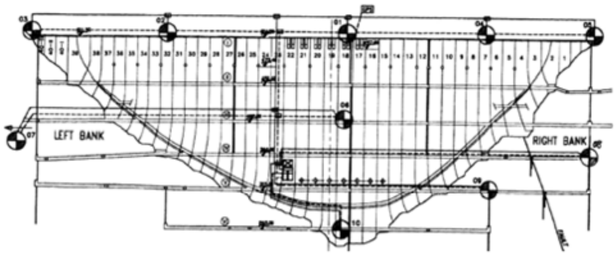

Fig. 7 Layout of strong motion instruments in the 272 m high Enguri arch dam in Georgia

8 Conclusions

The main conclusions are as follows:

(1) Inspection of dams after an earthquake is required in the context of the integral safety concept for large storage dams. This inspection has to be carried out immediately after an earthquake so corrective measures can be taken to reduce any risk to the people living downstream of the dam.

(2) Check lists have been prepared by ICOLD, which can be used for the effective safety inspection of dams.

(3) Networks of seismic instruments and strong motion instruments installed in large dams will provide useful information on the dams to be inspected after an earthquake and the severity of ground shaking at selected dam sites. Therefore, strong motion instrumentation of large dams is recommended.

(4) After strong earthquakes a large number of dams have to be inspected within a short period of time. A consistent safety assesment is only possible by experienced teams using proper check lists.

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