# SURVEY AND EVALUATION OF ACTIVE FAULTS ON DAM CONSTRUCTION IN JAPAN

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## SUMMARY

The relative displacement of ground on a fault line in time of earthquake is difficult to handle in the design process. Therefore, the Ministry of Construction, Japan, designs dams after preliminary checking that there are no active faults near the dam site. To avoid active faults, various investigations are systematically performed. First, the literature is researched for a radius up to 50 km from the dam site to have knowledge of the regional characteristics of active faults and to identify any active faults near the site. Next, photographs are interpreted for a radius up to 10 km to investigate the distribution and properties of active faults and to confirm whether active faults described in the literature are present or not. Identified active faults are classified based on the quality and quantity of their tectonic fault topography, and the results of the literature research and photograph interpretation are compared. If the literature research or photograph interpretation finds any active fault within 3 km of the dam site, then geological surveys for the fault are carried out.

## 1. INTRODUCTION

Dams must be completely safe and stable because of their immense impact in case of collapse. Therefore, during the design and construction of dams, detailed geological surveys are conducted on the stability of the slopes around reservoirs, as well as the mechanical properties and imperviousness of the basement rocks. Of all the natural disasters, earthquakes and volcanic eruptions are inevitable in Japan since the Japanese Archipelago lies on boundary between plates, and many earthquakes in inland areas are caused by active faults. The impacts of active faults upon dams are classified roughly by two types, earthquake motion and ground displacement on the fault line. Although earthquake-resistant design against motion is performed, the problem of ground displacement cannot be addressed by the design process, so areas near active faults that could threaten dams are avoided when choosing dam sites at present. Accordingly, various quantitative and qualitative investigations on active faults are conducted as well as those on the mechanical properties and imperviousness of basement rocks and the slope stability around reservoirs.

## 2. OBJECTIVES OF ACTIVE FAULT INVESTIGATIONS FOR DAM CONSTRUCTION

The objectives of active fault investigations conducted prior to dam construction, focusing on ground displacement, include the following:

a) To confirm whether or not lineaments and faults, both of which are considered to be active faults, are indeed active faults.
b) To locate active faults with sufficient precision such that they can be avoided when building structures.
c) To identify the activity history of active faults to predict future earthquake occurrence.

Active fault investigations for dam construction must cover all of the above, and so include literature research,

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geomorphological surveys, geological surveys and investigation of potential activity.

## 3. LITERATURE RESEARCH

### 3.1 Investigations of active faults

#### *3.1.1 Purpose of investigations*

The purpose of literature research on active faults is i) to get information of the properties (distribution, direction, degree of activities, direction of displacement, etc.) of active faults over a wide area near a dam site for use as a reference in successive investigations, and ii) to confirm the existence of active faults near a dam site by researching the literature on past investigations.

#### *3.1.2 Area of investigations*

The area that needs to be investigated is around 50 km in radius from the dam site for purpose i) (in which case the properties of active faults distributed over a wide area can be identified, as well as around 10 km in radius from the dam site for purpose ii).

#### *3.1.3 Contents of investigations*

The book titled "Active Faults in Japan -Sheet Maps and Inventories" [Research Group for Active Faults in Japan,1991] is a helpful reference, which lists the distribution and properties of active faults throughout Japan. This reference is sufficient for purpose i). For purpose ii), research should be conducted on the references listed in Research Group for Active Faults in Japan (1991), as well as on new references not yet listed.

#### *3.1.4 Compilation of investigation results*

Electronic copies of location maps and descriptions in Research Group for Active Faults in Japan (1991) are sufficient for purpose i). When compiling investigation results for purpose ii), the locations of active faults stated in the literature (hereafter referred to as reference fault(s)) should be marked on a topographical map on a scale of around 1:25,000, and the properties should be listed in a table. The locations of faults relative to the dam site should also be determined (the shortest distance between the dam site and the reference faults, and whether or not the reference faults are headed toward the dam site).

### 3.2 Investigations of the geological structure and constituent geology

#### *3.2.1 Purpose of investigations*

When researching the literature, the geological structure and constituent geology around the dam site should be investigated, in addition to direct information on active faults. This is for use in geological examinations of the origin of reference faults and lineaments accompanying a tectonic fault topography identified by geomorphological survey, such as how the locations of the reference faults and lineaments are related to the locations of dead faults and geological boundaries (particularly the boundary between geologies with different resistance to erosion).

#### *3.2.2 Area of investigations*

To be compatible with the literature researches of active faults, investigations of the geological structure and constituent geology should cover an area of radius of around 50 km from the dam site for a broad review of the relationship between faults and geological features, and a radius of around 10 km when the relationship is examined in detail.

#### *3.2.3 Contents of investigations*

When conducting investigations, existing geological maps on a scale of 1:200,000 to 1:50,000 shall be used.

#### *3.2.4 Compilation of investigation results*

Electronic copies of existing geological maps are sufficient. For detailed analysis, however, the data obtained should be marked on a topographical map on a scale of around 1:25,000 if required.

## 4. GEOMORPHOLOGICAL SURVEY

### 4.1 Methodology

#### *4.1.1 Purpose of survey*

The purpose of a geomorphological survey is to identify active faults near the dam site and to confirm the existence and properties of the reference faults, notwithstanding the data of past investigations

#### *4.1.2 Area of survey*

A geomorphological survey should cover an area of radius of around 10 km from the dam site. However, if a lineament accompanying a tectonic fault topography heading toward the dam site is discovered further than 10 km from the dam site, or if such a lineament is discovered near the boundary of this area, the survey area should be expanded in the direction of such lineaments.

#### *4.1.3 Contents of survey*

When conducting a geomorphological survey, items such as the location, length, direction of displacement, and constituent topographies of active faults are investigated.

The geomorphological method is principally for discovering tectonic fault topographies, which were formed by active faults, by interpreting aerial photographs and topographical maps. Actual active faults consist of several tectonic fault topographies (which may include single or multiple types of topography). When conducting the interpretation, aerial photographs on a scale of 1:40,000 to 1:10,000 are used. Interpretation of aerial photographs should begin with small- rather than large-scale aerial photographs on a scale of 1:40,000, to make it easier to understand the continuity of active faults. Large-scale aerial photographs are used when there is a lineament accompanying a tectonic fault topography in the direction toward the dam site or near the dam site, or when the existence and displacement of reference faults cannot be determined from small-scale aerial photographs. When interpreting a lineament accompanying a tectonic fault topography heading toward the dam site, the area between the lineament and the site should be included in the scope of investigation.

The interpretation is generally conducted as follows [Yamasaki, 1996].

i) Extract lineaments, then, ii) select lineaments accompanying a tectonic fault topography from all the lineaments.

The lineaments identified by these procedures can then be classified with certainty. When conducting such a classification, Research Group for Active Faults in Japan (1991), Kuwahara (1987), and Japan Society of Civil Engineers (1985) are used as references, of which the Ministry of Construction uses Kuwahara (1987). It must be noted that lineaments with and without a tectonic fault topography should be clearly kept separate, by focusing on tectonic fault topographies and considering the geomorphological origin of extracted lineaments and whether these lineaments would have been formed by an ordinary geomorphic agent. Interpretation of large-scale photographs is often a useful way of examining the geomorphological origin of lineaments. In the case of a dip-slip fault, on the other hand, a summit level map needs to be drawn up for identifying the systematic differences of topographical elevation.

If found, base topographies of fault displacement should also be interpreted, such as geomorphic surfaces (terrace surfaces, depositional surfaces of pyroclastic flow, alluvial fan surfaces, talus surfaces, alluvial surfaces, etc.) and geomorphic lines (former shorelines, terrace scarps, stream channels, ridge lines, etc.). If a lineament is assumed to be running through, geomorphic surfaces should particularly be compared carefully.

#### *4.1.4 Compilation of survey results*

When aerial photographs of 1:40,000 are used, the results of interpretations should be illustrated on a topographical map on a scale of around 1:25,000. The length of lineaments, certainty, the constituent topography of lineaments, articulation of lineaments, and tectonic fault topographies should be arranged in order in tables. The topographies that constitute lineaments should be shown on the topographical map, and changing the types and colors of lines depending on the certainty. When large-scale aerial photographs are used, the data obtained by interpretation should be illustrated on a topographical map on a scale of around 1:10,000 per lineament accompanying a tectonic fault topography. A lineament that is either near the dam site or heading toward the dam site, the dam site should also be marked on the map for clarifying the relation between the dam and the lineament. The base topographies of fault displacements should also be illustrated on the map, if found.

The results of geomorphological survey are compared with those of literature research (see ***7.1.1***). Then, any reference fault and/or lineament with tectonic fault topography do not exist within 10 km radius from the dam site, no further surveys and investigations are required, and construction of the dam is allowable.

## 5. GEOLOGICAL SURVEY

### 5.1 Methodology and purpose

There are two categories of geological survey of active faults: i) a rough geological survey for investigating both lineaments accompanying a tectonic fault topography, and reference faults; and ii) a detailed geological survey for investigating both lineaments accompanying a tectonic fault topography and reference faults near the basement of a dam body.

The purpose of the rough geological survey is to geologically confirm the existence of lineaments accompanying a tectonic fault topography and reference faults, and to identify whether or not they are active faults. The purpose of the detailed geological survey is to confirm the existence and precise locations of lineaments accompanying a tectonic fault topography and reference faults, and to geologically identify the potential fault activity. Investigations of potential fault activity will be discussed in the next chapter.

### 5.2 Rough geological survey

#### *5.2.1 Area of survey*

As with the geomorphological survey, the objects of a rough geological survey is both lineaments accompanying a tectonic fault topography and reference faults within an area of radius of about 3 km from the dam site. If a lineament accompanying a tectonic fault topography and a reference fault are in two different locations but are considered to be identical, then both locations should be investigated.

***5.2.2 Contents of survey***

A rough geological survey includes surface exploration, which is basically the same as the conventional one. When deciding the route of surface exploration, however, the focus is on linear faults. Since, the location of a lineament that is identified by the geomorphological method does not necessarily coincide with the location of a geological fault (fault shear zone), so, the area of exploration needs to be expanded by a certain width on both sides of the lineament, and the route should cross the lineament perpendicularly.

Items to be checked and recorded are the geology of outcrops, the state of weathering and hydrothermal alteration, the features of faults if found (i.e., the existence of shear zones and fault gouges, the degree of shearing, the width per degree of shearing, the width of fault gouges, the structure of fault gouges, the dip and strike of fault surfaces, the existence of striations of fault surfaces, the dip and strike of striations, the amount of displacement, the direction of displacement, the geology of hanging walls and footwalls, the existence of cover beds, and the displacement of the cover bed), and the relation between fault outcrops and lineaments. Matsuda and Okada (1977) proposed applying the rock mass classification, which is generally employed for dams, for classifying the degree of shearing of fault shear zones. Since cataclasite, mylonite, pseudotachylite, and some other fault rocks have recently been considered as shear zones that were formed deep underground [Sibson, 1977], for example), it is important to identify these also.

When conducting a surface exploration, topographies that could indicate displacement such as tectonic fault topographies (particularly low fault-scarps that are difficult to pick out on aerial photographs) and terrace surfaces, should be observed, in addition to geological items.

***5.2.3 Compilation of survey results***

When conducting observations, the observation items stated above must be sketched and photographed, and the data written down on tabular cards for each outcrop. The observation data are then compiled into a route map, and tabulated for each fault. When compiling the results, it is important to clarify whether or not faults that coincide with the reference faults and the lineaments accompanying a tectonic fault topography were confirmed, and if so, whether they are active faults. In the stage of a rough geological survey, the fault is judged as active or inactive based on its relation with a Quaternary cover bed and its topography. Failure to confirm the existence of faults due to unfavorable outcrop conditions in the area around the target lineaments and reference faults should not be confused confirmation of no faults under favorable outcrop conditions.

The results of rough geological survey are compared with those of literature research and geomorphological survey (see ***7.1.2***). As the result of the comparison, no active fault exists near the basement of the dam body, further surveys and investigations are not required, and construction of dam is allowable.

## 5.3 Detailed geological survey

***5.3.1 Target and area of survey***

A detailed geological survey should cover the area surrounding lineaments accompanying a tectonic fault topography and reference faults found near the basement of a dam body. As with the rough geological survey, if a lineament accompanying a tectonic fault topography and a reference fault are in two different locations but are considered to be identical, then both locations should be investigated.

***5.3.2 Methodology***

As with the rough geological survey, the first step of the detailed geological survey is to conduct a surface exploration, the contents of which are same as those of the rough geological survey. If surface exploration is not feasible because the outcrop conditions are not favorable, investigations should be conducted by other means such as trenching, adit investigations, drilling, investigations using the long Geo-slicer method, and geophysical explorations. The most appropriate method should be selected from the above, depending on the topographical and geological conditions in situ.

Trenching is the most often used of the above methods for active fault investigations, and can achieve the purposes of the geological survey for investigating active faults most effectively. The details of trenching are described in Okada (1990), and Okada and Matsuyama (1992). To determine potential fault activity, trenching is often conducted in locations where a fault is thought to pass through a Quaternary bed. To estimate potential fault activity, it is necessary to interpret fault displacements caused by past earthquakes, as described in Allen (1986). Adit investigations are similar to trenching.

Drilling is conducted in the same manner as ordinary core drilling. The objectives of drilling for investigating active faults include: i) direct identification of faults by coring the faults themselves; and ii) indirect identification of faults by confirming the displacement between the hanging walls and footwalls of active faults. For i), core samples in good conditions should be taken, as with large-diameter drilling and drilling using a surface-active agent, regardless of whether the fault is in either a Quaternary bed or a basement rock. For ii), drilling should be conducted several sites on both the hanging wall and the footwall. When drawing a geological sectional map based on drilling data, the possibility of stratum displacement due to geological phenomena other than fault displacement must be considered.

Recently, a fault investigation method other than trenching has been developed, called the long Geo-slicer method [Haraguchi et al., 1998]. With this method, long iron sheet piles with a flat U-shaped cross section are driven into an unconsolidated bed; iron plate shutters are inserted to face these iron sheet piles; and then the piles and shutters are pulled out to take undisturbed samples of strata of a certain width. If the iron sheet piles are driven along the measurement line, continuous cross sections of strata can be observed. This method is advantageous in regard to the ease of securing land for conducting investigations compared with trenching, and the ease of bringing the strata samples back to the laboratory for detailed observations.

All the methods described so far are for directly observing active faults. However, one problem is the difficulty of deciding where to conduct trenching and drilling because outcrops of active faults are seldom exposed and faults are sometimes covered with alluvium. In such cases, geophysical exploration is effective for identifying faults and approximate locations of the faults. According to Takahashi et al. (1997), the types of geophysical exploration for active fault investigations include the seismic reflection method, sonic prospecting, electric prospecting, electromagnetic prospecting, gravity prospecting, and radioactive prospecting. Of these, the seismic reflection method can locate faults if geological conditions are favorable, and confirm the accumulation of fault displacements based on the amount of displacements in strata that increases with strata age.

#### *5.3.3 Compilation of survey results*

The survey results are compiled as same as the case of rough geological survey, and compared with the results of literature research and geomorphological survey (see ***7.1.3***). Then, no active fault exists near the dam body, construction of dam is allowable.

## 6. INVESTIGATION OF POTENTIAL ACTIVITY

### 6.1 Purpose of investigations

When a fault, which is thought to be active, is found near the basement of a dam body by detailed geological survey, its potential activity must be investigated.

### 6.2 Methodology

#### *6.2.1 Method based on cover beds*

When either a natural or man-made fault outcrop is found and there is fault that has displaced a Quaternary bed, the time of activity can sometimes be identified. There are several strata whose sedimentation ages are known, and there are various displacement due to branching of faults, then the activities (called events) of the respective branched faults can sometimes be dated. In this case, the recurrence intervals of fault activity can be estimated. To specify the ages of strata, the $^{14}C$ age of carbonaceous matter and a distal tephra whose age is already known are often used. These are the most accurate methods at present for specifying the ages of active fault activity, provided sufficient information is available (the number of strata whose ages can be specified and the number of events).

#### *6.2.2 Dating of intrafault materials*

When dating intrafault materials, a Quaternary cover bed does not need to exist, since intrafault materials are investigated directly. Fault activities based on intrafault materials are dated by i) obtaining a relative date; ii) a direct method for obtaining the absolute date of fault activity (dating of interafault materials by ESR and TL); and iii) a method for obtaining indirectly the date of fault activity relative to the absolute date to be obtained [Tanaka, 1989].

## 7. COMPREHENSIVE COMPILATION OF INVESTIGATION RESULTS

### 7.1 Compilation

#### *7.1.1 Comparison of results between literature research and geomorphological survey*

When assessing the relationship between reference faults and lineaments accompanying a tectonic fault topography found by the geomorphological survey, the following points are considered and the results shown in maps and tables.

i) Whether or not they correspond with each other, i.e., whether a lineament accompanying a tectonic fault topography corresponds to the reference fault, and vice versa.

ii) When they coincide, a) the location, b) length, c) certainty, and d) displacement must be identified.

iii) When they do not coincide, the case of when no lineament accompanying a tectonic fault topography corresponds to the reference fault should be clearly distinguished from the case of when no reference fault corresponds to the lineament accompanying a tectonic fault topography.

#### *7.1.2 Comparison of results between rough geological survey and either the literature research or*

***geomorphological survey***

The results of the geological survey are compared with those of either the literature research or the geomorphological survey, regarding the reference faults and the lineaments accompanying a tectonic fault topography found by the rough geological survey in terms of the following:

i) Whether a geological fault exists that corresponds to the reference fault and the lineament accompanying a tectonic fault topography.

ii) When a corresponding fault exists, a) the location of fault outcrop, b) the basis of the correspondence, and c) whether the fault is active must be clarified.

iii) When no corresponding fault exists, the origin of either the reference fault or the lineament accompanying a tectonic fault topography should be examined based on the results of the rough geological survey, the geological structures, and the geology obtained by the literature research.

iv) When the existence of a geological fault cannot be confirmed by the rough geological survey due to unfavorable outcrop conditions, it should be specified that the geological fault could not be confirmed due to unfavorable outcrop conditions.

#### *7.1.3 Comparison of results between detailed geological survey and either the literature research or geomorphological survey*

The results between the detailed geological survey and either the literature research or geomorphological survey should be compared in the same manner as the rough geological survey.

### 7.2 Evaluation of potential activity of faults

The criteria for judging whether a fault is active are as defined in the descriptions of active faults. In general, active faults are those that "have acted in the recent past, and are likely to act again in the future" (Tada (1927) as an old reference). Recently, the concept of "past" differs depending on researchers; the Japan Association for Quaternary Research (1987) considers the past as 730,000 years ago, while Matsuda (1994) defines it to be hundreds of thousands to 1,000,000 years ago. What is important here is the phrase "faults that are likely to act again in the future." Since this cannot be predicted directly, the possibility of future activity is estimated based on previous repeated activity. Particularly, Yamasaki (1996) emphasizes "activities that have occurred several times (cumulative displacement)," and states that it is wrong to determine a fault to be active if it has displaced a Quaternary bed only once.

Nevertheless, since it is not possible to check the history of fault activity other than partially by trenching for evaluating potential fault activity. A fault that is identified geologically and accompanies a tectonic fault topography, or a lineament accompanying a tectonic fault topography, often has to be judged as active. This is based on the idea that fault displacement remaining within a topography is proof of cumulative fault activity in the recent past, not a single activity. Thus, tectonic fault topographies must be analyzed carefully based on literature research, geomorphological surveys and geological surveys.

A lineament in a mountainous area that exists on both sides of an alluvial surface, such as a waste-filled valley, may sometimes be determined to have been inactive since at least the Wurm glacial stage and thereafter if there is no tectonic fault topography such as a low fault-scarp on the alluvial surface. However, since the formation of a tectonic fault topography on an alluvial surface depends on the slip rate of the fault and the sedimentation rate of the alluvium, fault-scarps do not easily form on an alluvial surface when the degree of activity of the fault is low and the fault slip rate is smaller than the sedimentation rate of the alluvium. In addition, an alluvium surface is often modified artificially into paddy and upland fields. Therefore, active faults need to be analyzed carefully in the above case.

## 8. CONCLUSIONS

Since the Hyogo-ken Nambu Earthquake of 1995, trenching and various other investigations have been conducted on active faults, and the location and history of activity of large-scale active faults and active faults located near major cities have been obtained. However, the state of active faults in mountainous areas where many dams are planned to be construct has not been clarified sufficiently, nor have effective methods been established for investigating and evaluating active faults in mountainous areas where little is known about the base topographies. Accordingly, since existing methods for investigating and analyzing active faults for dam constructions have not been fully established, further research is needed to establish such concepts by improving investigation methods and by accumulating knowledge on active faults.

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