INVESTIGATIONS OF ACTIVE FAULTS FOR DAM CONSTRUCTION
- THE PRESENT STATE AT THE MINISTRY OF CONSTRUCTION -

by

Yasuhiko Wakizaka[1)]

ABSTRACT

The displacement of ground by an earthquake due to an active fault is difficult to handle in the design process. Therefore, the Ministry of Construction constructs dams after first 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 understand 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.

KEY WORDS: active fault, dam construction, geological survey, photo-interpretation

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 by types of earthquake motion and ground displacement. 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 equivalent to 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 length of motion of an active fault by one earthquake and hence estimate the magnitude of earthquake that the fault could cause

d) To identify the activity history of active faults

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1) Geology Division, Environment Department, Public Works Research Institute, Ministry of Construction, Tsukuba-shi, Ibaraki-ken, 305-0804, Japan

to predict future earthquake occurrence.

Active fault investigations for dam construction must cover all of the above, and so include literature research, geomorphological surveys, and geological surveys. Fig. 1 shows the flow chart of investigations.

3. LITERATURE RESEARCH

(1) Investigations of active faults

a) Purpose of investigations

The purpose of literature research on active faults is i) to understand 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.

b) 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 shown in Fig. 2), as well as around 10 km in radius from the dam site for purpose ii) (the width of an active fault system perpendicular to the line of the fault is almost always less than 10 km as shown in Fig. 3).

c) Contents of investigations

The book titled "Active Faults in Japan -Sheet Maps and Inventories[1]" 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 "Active Faults in Japan -Sheet Maps and Inventories[1]", as well as on new references not yet listed.

d) Compilation of investigation results

Electronic copies of location maps and descriptions in the literature[1] 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 prop

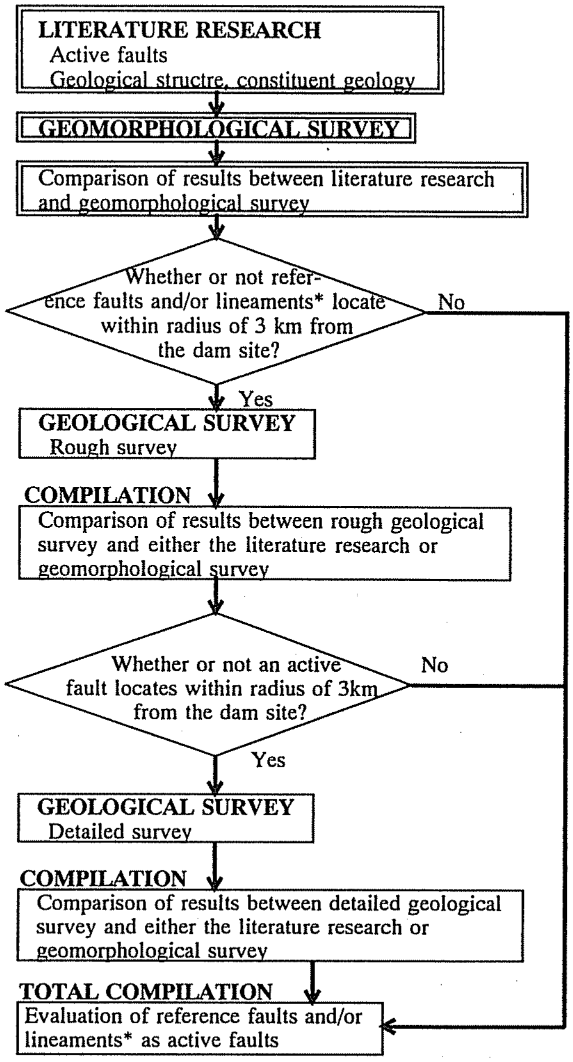

Fig. 1 Flow chart of active fault investigations. Lineaments* means lineaments which are accompanied by a tectonic fault topography.

erties 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).

(2) Investigations of the geological structure and constituent geology

a) Purpose of investigations

When researching the literature, the geological structure and constituent geology around the dam

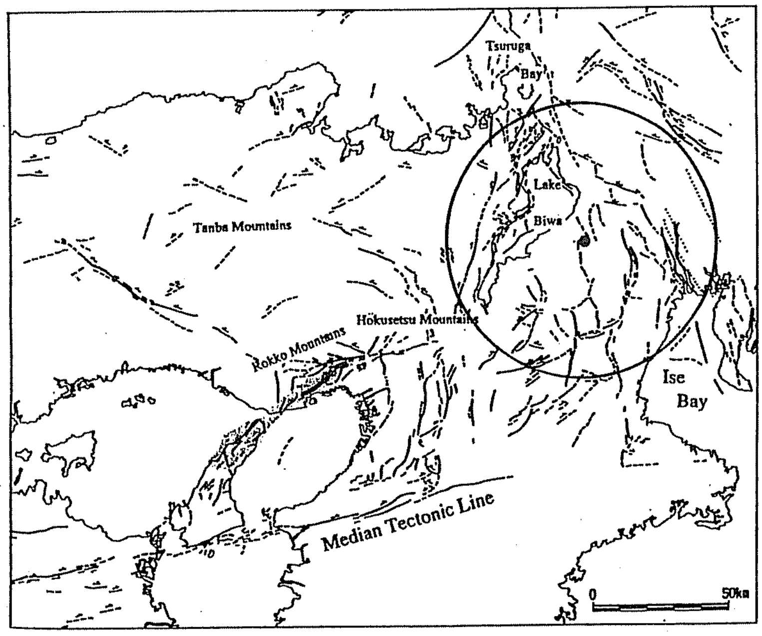

Fig. 2 Area (the circle in this figure) needed to identify the wide-area properties of active faults.

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).

b) 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.

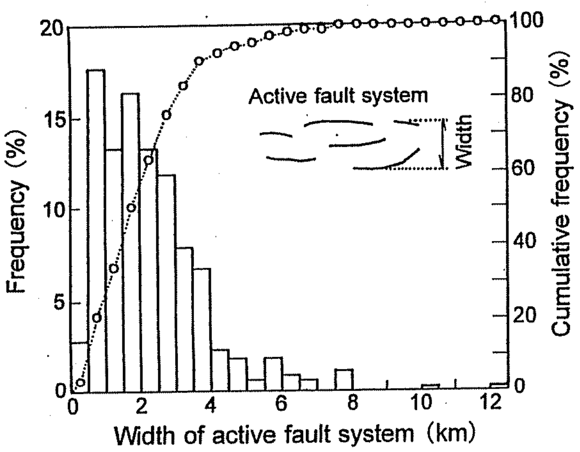

Fig. 3 Frequency distribution of width of fault system.

c) Contents of investigations

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

d) 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

(1) Methodology

a) 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

b) 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.

c) 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.[2]

i) Extract lineaments, then

ii) Select lineaments accompanying a tectonic fault topography from all the lineaments.

There is another method[1] as follows:

i) Extract lineaments, then

ii) Identify active faults based on discrepancies between base topographies of displacement (continuous geomorphic surfaces or geomorphic lines that were formed in the same age).

The lineaments identified by these procedures can then be classified with certainty. When conducting such a classification, the publications "Active Faults in Japan -Sheet Maps and Inventories[1]", Kuwahara[3], and Japan Society of Civil Engineers[4] are used as references, of which the Ministry of Construction uses Kuwahara[3]. 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.

d) 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 (Fig. 4), 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

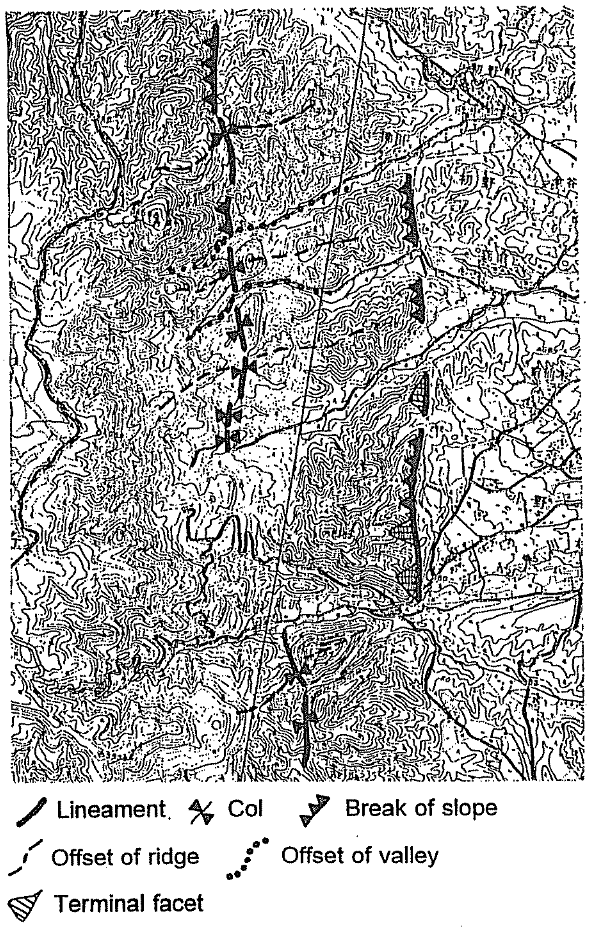

Fig. 4 Example of indicating the tectonic fault topographies along lineaments.

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.

2) Problems of geomorphological surveys and their countermeasures

One problem with the geomorphological survey, or aerial photograph interpretation, is individual differences in recognizing active faults and judgment of certainty of lineaments[5]. Such differences are particularly noticeable when interpreting relatively low activity and low certainty faults in mountainous regions with no key topography for interpretation. These problems hinder the preliminary investigations for dam construction, especially since dams are usually built in mountainous regions.

Judgment differences among individuals arise because the criteria of certainty are not necessarily quantitative. It is considered that certainty can be judged more objectively by indicating the interpretation results along with the topography of faults as described above (Fig. 4).

Subjectivity in interpretations can be minimized by combining the extracted lineaments and surface landform classification that is commonly conducted. The Geology Division, PWRI, Ministry of Construction, is currently developing this method. With this method, lineaments that consist of cols in mountainous regions are extracted; the surface landform of the same area is classified; and then active faults are detected by comparing the both results[6]. Judgment objectivity can be improved by conducting interpretations based on these two different criteria. Nevertheless, since this method is still under development, it has not yet been confirmed as suitable for general-purpose use. The best method at present for reducing interpretation variations is for at least two persons to interpret aerial photographs of the same area separately, and then draw a conclusion by comparing the respective results.

5. GEOLOGICAL SURVEY

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.

2) Rough geological survey

a) 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.

b) 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, as will be described later, 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[7] 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[8], for example), it is important to identify these also.

When conducting a surface exploration, topographies that could cause 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.

c) 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.

3) Detailed geological survey

a) 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. When it is apparent that the lineaments accompanying a tectonic fault topography and the reference faults are not active ones based on the rough geological survey, no detailed geological survey is required.

b) 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.

c) Trenching and adit investigations

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[9], and Okada and Matsuyama[10]. 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[11].

Adit investigations are similar to trenching.

d) Drilling

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.

e) Investigations using long Geo-slicer method

Recently, a fault investigation method other than trenching has been developed, called the long Geo-slicer method[12]. 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.

f) Geophysical exploration

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.[13], 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.

4) Problems of geological survey and their countermeasures

a) Problems of surface exploration

Since geological surveys for investigating active faults are mostly conducted based on geomorphological survey results, except for earthquake faults, the precision of the results must be considered when selecting the locations for the geological survey. Often, the location of a lineament that is estimated geomorphologically is several tens of meters away from the actual fault. This may partly be due to the precision of photograph interpretation; but such discrepancies are geomorphologically significant, since there is a relation between the difference in elevation of geomorphic surfaces on both sides of a fault and the discrepancy of estimated and actual faults[14], as shown in Fig. 5. If the difference in elevation of geomorphic surfaces on both sides of a fault indicates a cumulative fault displacement, faults with a greater difference in elevation will be assumed to have been active for longer, provided their degree of activity is similar. Accordingly, Fig. 5 can be interpreted to mean that the distance between the estimated lineaments and actual faults increases with fault age. It is considered that the discrepancy in locations between lineaments and actual faults becomes greater with fault age, because older fault-scarps have had more chance of being recessed due to erosion or buried under talus deposits. Thus, when conducting a surface exploration, the discrepancy of locations between lineaments identified geomorphologically and actual faults should be considered.

The greatest problem with surface exploration is that fault outcrops seldom exist even when active faults definitely are present. The existence of a fault can be confirmed when a fault outcrop with features identical to geomor- phological features exists near a lineament (to judge the fault as active, there must be proof that it has displaced a Quaternary bed several times). However, the existence of a fault can be neither confirmed nor denied if no fault outcrop is dicovered. With surface exploration, the existence of an active fault can be denied only when no fault is recognized in continuous outcrops (cut slopes of roads and tunnels) within an area established by considering the discrepancy between a geomorpholo- gical location and an actual location. When there are generally few outcrops and no fault outcrops, then the investigation results should be compiled into columns, as with stratigraphy. This technique is used to measure the distances from the location where a lineament is assumed to pass through, to the respective outcrops; sort the outcrops by distance; and quantify them in figures and documents.

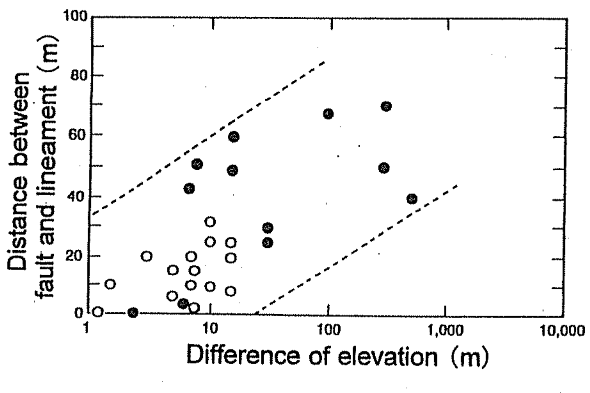

Fig. 5 Relationship between difference in elevation of geomorphic surfaces on both side of a lineament and distance between a lineament and a fault[14].

b) Problems with trenching, adit investigations, and drilling

As with surface exploration, the biggest problem with trenching, adit investigations, and drilling is that the location of a lineament does not necessarily coincide with that of an actual fault. Accordingly, before conducting these investigations, the precise location of a fault must be identified by conducting preliminary investigations such as preparatory drilling and geophysical explorations.

One problem with trenching is the difficulty of recognizing traces of past earthquakes remaining in Quaternary beds. There are usually more than one recognition criterion on trenched walls, so accurate classification of strata and comparison of the strata on both sides of a fault must be conducted to ensure that such traces are found.

When dealing with a reverse fault, it is necessary to start trenching over a wide area, and gradually narrow it down toward the target, due to discrepancies of locations between the reverse fault and the lineament. On the other hand, although it is comparatively easy to select a trenching area for a lateral fault. However, it is difficult to estimate the net displacement because there are not many criteria for estimating the displacement of lateral offset. These problems with trenching are common to adit investigations.

A problem with drilling is that the existence of a fault cannot be determined even based on a core sample that is taken by penetrating a fault, because a shear zone is unlikely to be formed in young strata such as alluvium and diluvium. When the basement rock of alluvium and diluvium is shallow, drilling should be conducted by penetrating the fault in the basement rock. When the basement rock is deep underground, faults are detected based on the discrepancy of the sequence in the samples taken by drilling on both sides of the fault. Nevertheless, since the sequence is often disturbed due to buried valleys in alluvium and diluvium, trenching may be more suitable for investigating active faults in alluvial and diluvial areas because it can take samples of wide and continuous sections. If trenching is not feasible due to problems of securing land, investigations should be conducted by a combination of drilling and the seismic reflection method, as well as based on the long Geo-slicer method.

c) Problems with geophysical explorations

A problem with the seismic reflection method is that good results cannot be obtained unless a discontinuity, which acts as a reflection surface for earthquake waves. Electric prospecting, electromagnetic prospecting, and gravity prospecting can be used to resolve this problem, none of these methods has been proven reliable because they have rarely been used for active fault investigations. Shinagawa[15] recently conducted fault investigations in the Suwa basin using a type of electromagnetic prospecting method called the CSAMT method that can detect resistivity underground, and found a fault inside basement rock buried under alluvium. This method may be promising for prospecting for faults inside basement rocks.

To identify an active fault, the accumulation of fault displacements must be studied. Except for the seismic reflection method, the accumulation of fault displacements cannot be confirmed by geophysical exploration methods. Thus, geophysical exploration methods, except for the seismic reflection method, should be called fault investigation methods, rather than active fault investigation methods.

6. INVESTIGATION OF POTENTIAL ACTIVITY

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.

2) Methodology

There are two methods for identifying the history of activities of an active fault: One is based on whether or not the stratum is cutted by a fault, while the other is to date the intrafault materials themselves.

a) 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).

b) 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; and iii) a method for obtaining indirectly the date of fault activity relative to the absolute date to be obtained[16].

Method i) includes a method to observe the surface conditions of quartz grains contained in intrafault materials[17),18),19], which uses the change of surface conditions of quartz grains formed by breakage due to fault activity. The surfaces of quartz grains are eroded by the chemical action of groundwater. With this method, the absolute date is not obtained directly but is estimated indirectly by comparing the surface conditions of target quartz grains with those of quartz grains of known date.

Method ii) includes electron spin resonance (ESR), thermoluminescence (TL), K-Ar, and fission track.

Method iii) focuses on mineral veins inside a fault, with which the date of fault activity is estimated based on whether or not mineral veins are cutted by a fault and whether or not a fault is cutted by mineral veins. Methods used for dating mineral veins are fission track, ESR, and TL.

3) Problems with investigating potential activity of faults

A problem common to the above-mentioned methods for investigating the potential activity of faults is that the results are not certain unless sufficient conditions.

The method based on cover beds is difficult to use the method in mountainous areas, because Quaternary cover beds often do not exist.

When dating intrafault materials, note that intrafault materials were not necessarily formed by fault movement at one time when using either method i) or ii). Also, when using method ii) the date of the target minerals must have been reset to zero due to fault movements. Fukuchi[20] points out some problems with ESR dating, such as i) ESR signal resetting by fault actions, ii) evaluation of annual dose, and iii) influence of hydrothermal solution on the total radiation dose. In regard to ESR signal resetting, he mentions that signals are completely reset at a depth about 620 to 670 m and a width of 2 to 3 mm from the fault surface based on a model due to frictional heat, and that signals are not reset completely at a depth of about 70 to 80 m underground or shallower based on the results of a ring shear test. On the other hand, Lin[21] conducted both ESR and TL dating of fault gouges sampled by varying the distance from the fault surface, and showed that ESR signals are more easily reset the shorter the distance to the fault surface is, since the intrafault materials are closer to the fault surface, the younger they are.

The problem with the method of observing the conditions of quartz grain surfaces is that the method may not be applicable nationwide due to variations of the physiochemical properties of groundwater.

7. COMPREHENSIVE COMPILATION OF INVESTIGATION RESULTS

1) Compilation

The existence of dangerous active faults for dam construction shall be clarified by compiling all investigation results.

a) 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.

b) 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.

c) 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.

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[22] as an old reference). Recently, the concept of "past" differs depending on researchers; the Japan Association for Quaternary Research[23] considers the past as 730,000 years ago, while Matsuda[24] 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[25] 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 Würm 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.

Fig. 6 shows the recurrence intervals of earthquakes in order of degree of fault activity, which were recently obtained by trenching. Despite some dispersions, there is a correlation between the degree of activity and the recurrence interval, with the recurrence interval becoming longer as the degree of fault activity decreases. If more such data can be gathered, it would facilitate judging whether a fault is likely to become active again, based on whether the date of last activity is sufficiently older than the recurrence interval

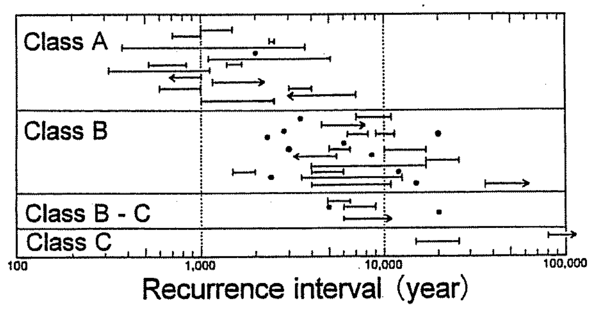

Fig.6 Recurrence intervals of active faults by degree of activity.

determined from the degree of activity of the fault.

3) Evaluation of length and continuity of an active fault

According to Matsuda[31], there is a relation between the length of an earthquake fault (L) and the magnitude of a corresponding earthquake (M) as follows:

$$\log L\,(\mathrm{km}) = 0.6M - 2.9 \qquad 1)$$

On the other hand, in general an earthquake with a magnitude of 6.5 or smaller does not form an earthquake fault[2]. When $M = 6.5$ is substituted into equation 1), L becomes 10 km. This means that a fault that is shorter than 10 km will not cause an earthquake that forms an earthquake fault. Thus, whether the length of active faults exceeds 10 km is important. Matsuda[32] recently proposed the following two equations for the relation between L and M based on the length of earthquake faults and magnitudes revised based on his recent reinvestigations and new data of earthquake faults:

$$M = 6.32 + 0.693 \log L\,(\mathrm{km}) \quad (8.0 \geqq M \geqq 6.8) \qquad 2)$$

$$M = 6.81 + 0.253 \log L\,(\mathrm{km}) \quad (7.3 \geqq M \geqq 6.8) \qquad 3)$$

These equations can be applied when $M \geqq 6.8$, since the minimum value of earthquake faults in inland areas in Japan was determined to be $L = 5$ km (or $M = 6.7$) based on the data of earthquake faults obtained thereafter. Accordingly, to determine the relation between the magnitudes of earthquakes that form earthquake faults and the length of faults, good quality and quantity of data are required in order to avoid vague discussions.

However, evaluation of the length of active faults involves problems of segmentation and grouping. The problem of segmentation is whether or not an extremely long fault, such as the Median Tectonic Line, acts as one body or in several segments. According to recent research, the Median Tectonic Line acts in several segments, and Okada[33] classifies it into eight segments and one inactive area. On the other hand, a close look at an active fault, particularly an earthquake fault, shows that the ground surface trace of a fault is divided into several segments that go side by side despite their simultaneous activities. Nakata et al.[34] divides the Nojima earthquake fault in the Hyogo-ken Nambu Earthquake of 1995 into five segments.

On the contrary, the problem of grouping is that several faults that are considered to be independent may cause an earthquake by acting as one body. In the case of the Hyogo-ken Nambu Earthquake of 1995, several active faults in the Rokko Fault System (including the Nojima fault) moved at the same time. Matsuda[35] mentions that several faults should be combined into one group, which is called a fault zone, with intervals of up to 5 km, for example.

As mentioned so far, when determining some active faults to be earthquake faults, it is hard to decide how to consider their lengths only by ground surface tracing. The length should therefore be determined based on seismological methods (such as the distribution of microearthquakes), morphological investigations of active faults deep underground, and confirmation of synchronism of the date of activities of the respective faults.

8. COUNTERMEASURES FOR GROUND DISPLACEMENTS BY ACTIVE FAULTS

Since no design method to counter ground displacements has yet been established, faults are avoided when constructing structures that would have a great impact if damaged, such as dams and atomic power plants. Although there are no clear criteria regarding the distance of such structures from a fault, in principle locations immediately above a fault where fault displacements occur must be avoided. The relation between the state of damage of the reservoir dam bodies in Awaji Island due to the Hyogo-ken Nambu Earthquake of 1995 and their distance from the Nojima fault gives a guideline as to the distance between the fault and the structure. According to Hiyoshi[36], all the reservoir dams that suffered huge cracks and leakage were located within 20 m of the Nojima fault. Since it is unlikely that fault displacement was the only cause of such damage to the dam bodies, it should be sufficient not to build structures directly above a fault when considering only the impact of fault displacements. According to the Active Fault Act[37] of the State of California in the US, city and county governments shall not grant permission for developing areas within 500 feet (150 m) from major faults and 200 to 300 feet (60 to 90 m) from clear small faults, unless it is proven by preliminary geological surveys that the ground surface will not be displaced by future fault activity.

The problem here is how to determine faults that are likely to cause fault displacements. To ensure safety, fault shear zones should be considered as possible candidates. Ogata and Honsho[38] confirmed that the width of a fault shear zone is correlated with the length of faults in a granite area in the Chubu mountains, although this fault was not an active one. In addition, Matsuzaki et al.[14] confirmed a similar trend by investigating active faults (Fig. 7). Thus, since the length of a fault is considered to become longer as the width of the fault shear zone increases, structures should be built away from faults when the distribution of fault shear zones cannot be clearly identified.

9. CONCLUSIONS

Since the Hyogo-ken Nambu Earthquake of 1995, trenching and various other investigations

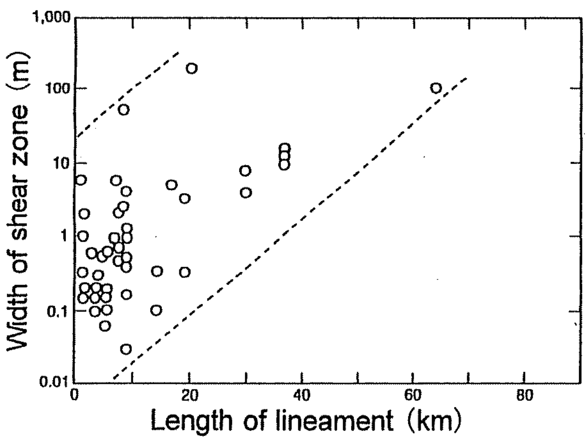

Fig. 7 Relationship between length of lineaments dirived from active faults and width of their shear zones[14].

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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REFERENCES

1) Research Group for Active Faults of Japan: *Active faults in Japan -sheet maps and inventories, Revised ed.* University of Tokyo Press, 437p. 1991. (JwE)

2) Yamasaki, H.: Judgment of certainty and photographic interpretation. In Ikeda, Y., Shimazaki, K. and Yamasaki, H., *What is a active fault?*, University of Tokyo Press, 74-84, 1996. (J)

3) Kuwahara, K.: Procedures of survey on Quaternary fault. *Civil Engineering Journal*, **29**, 293-298. 1987. (J)

4) Japan Society of Civil Engineers, Committee on Nuclear Civil Engineering: Geological survey methods. *Investigation and testing methods of geology and ground, and evaluation methods of seismic stability of ground in an atomic power plant*, Part **2**, 48p. 1985. (J)

5) Matsuda, T., Ota, Y., Okada, A., Shimizu, F. and Togo, M.: Aerial photo-interpretation of active faults -the individual difference and examples. *Bull. Earthquake Research Institute, Univ. Tokyo*, **52**, 461-496, 1977. (JwE)

6) Kuroki, K. and Shinagawa, S.: Method for interpretation of photo-lineament consist of cols and geomorphic lines caused by active fault. *Civil Engineering Journal*, **40**, 7, 62-67, 1998. (J)

7) Matsuda, T. and Okada, A.: Shearing degree of fault shear zones -tentative classification based on field observation. *MTL*, **2**, 117-125, 1977. (J)

8) Sibson, R. H.: Fault rocks and fault mechanics. *Jour. Geological Society of London*, **133**, 191-213, 1977

9) Okada, A.: Studies of active fault by trenching method. In Yonekura, N., Okada, A. and Moriyama, A., Eds. *Tectonic landforms*, 18-44, 1990. (J)

10) Okada, A. and Matsuyama, N.: *Trenching of active faults -investigate history of earthquake faults*. Fault Research Data Center, 28p. 1992. (J)
11)Allen, C. R.: Seismological and paleoseismological techniques of research in active tectonics, In *Studies in geophysics: Active Tectonics*, National Academy Press, 148-154, 1986
12)Haraguchi, T., Nakata, T., Shimazaki, K., Imaizumi, T., Kojima, K. and Ishimaru, K.: A new sampling method of unconsolidated sediments by long Geo-slicer, a pile-type soil sampler. *Jour. Japan Society of Engineering Geology*, **39**, 306-314, 1998. (JwE)
13)Takahashi, T., Mimoto, K. and Hayakawa, T.: Present state of applications of geophysical methods to characterization of active faults. *Jour. Japan Society of Engineering Geology*, **38**, 118-129, 1997. (J)
14)Matsuzaki, T., Kuroki, T., Shinagawa, S. and Wakizaka, Y.: Quantitative relationships beetween the geomorphological and geological features of active faults in East Japan. *Proceedings of the Annual Conference of the Japan Society of Engineering Geology*, 57-60, 1997. (J)
15)Shinagawa, S.: Investigation of buried faults in urban areas using electromagnetic exploration. *Civil Engineering Journal*, **41**, 2, 26-31, 1999. (J)
16)Tanaka, K.: Evaluation of activity of faults based on intrafault materials. *Proceedings of the Symposium*, Japan Society of Engineering Geology, 15-26, 1989. (J)
17)Kanaori, Y., Miyakoshi, K., Kakuta, T. and Satake, Y.: Surface texture of quartz grains from fault gouges. *Abiko Research Laboratory Report* No.**377011**, Central Research Institute of Electric Power Industry, 21p. 1978. (JwE)
18)Kanaori, Y., Miyakoshi, K., Kakuta, T. and Satake, Y.: Dating fault activity by surface textures of quartz grains from fault gouges (part I) -Classification and forming-process of surface textures-. *Jour. Japan Society of Engineering Geology*, **23**, 18-32, 1982. (JwE)
19)Kanaori, Y., Miyakoshi, K., Kakuta, T. and Satake, Y.: Dating fault activity by surface textures of quartz grains from fault gouges (part II) -Fracturing mode and movement age of fault. Jour. *Japan Society of Engineering Geology*, **23**, 65-75, 1982. (JwE)
20)Fukuchi, T.: ESR dating of active faults -Its controversial points and future prospect-. *Active Fault Research*, **7**, 13-21, 1989. (J)
21)Lin, A.: ESR and TL datings of active faults in the Iida area of the southern Ina valley. Active fault Research, 7, 49-62, 1989. (J)
22) Tada, F.: Two kinds of active faults. *Geographical Review of Japan*, **3**, 983-990, 1927. (J)
23) Japan Association for Quaternary Research: *Quaternary Maps of Japan*. University of Tokyo Press, 119p. 1987. (J)
24) Matsuda, T.: Search active faults. In Shimazaki, K. and Matsuda, T., Eds. *Faults and Earthquakes*, University of Tokyo Press, 24-44, 1994. (J)
25) Yamasaki, H.: What is a active fault? In Ikeda, Y., Shimazaki, K. and Yamasaki, H., *What is a active fault?*, University of Tokyo Press, 35-71, 1996. (J)
26) Geological Survey of Japan: Interim report on active fault researches in the 1995 fiscal year. *Geological survey of Japan Interim Report*, **259**, 98p. 1996. (J)
27) Geological Survey of Japan: Interim report on active fault researches in the 1996 fiscal year. *Geological survey of Japan Interim Report*, **303**, 140p. 1997. (J)
28) Geological Survey of Japan: Interim report on active fault and paleoearthquake researches in the 1997 fiscal year. *Geological survey of Japan Interim Report*, **EQ/98/1**, 188p. 1998. (J)
29) Science and Technology Agency: *Proceedings of the meeting on earthquake research in the 1995 and 1996 fiscal years*. Science and Technology Agency, 241p. 1997. (J)
30) Science and Technology Agency: *Proceedings of the 2nd meeting on active fault research*. Science and Technology Agency, 344p. 1998. J)
31) Matsuda, T.: Magnitude and Recurrence interval of earthquakes from a fault. *Zisin, Jour. Seismological Society of Japan*, 2nd Ser. **28**, 269-283, 1975. (JwE)
32) Matsuda, T.: Present state of long-term prediction of earthquakes based on active fault data in Japan -An example for the Itoigawa-Shizuoka Tectonic Line active fault system-. *Zisin, Jour. Seismological Society of Japan*, 2nd Ser. **50**, 23-33. 1998. (JwE)
33) Okada, A.: Proposal of the segmentation on the Median Tectonic Line active fault system. *Mem. Geological Society of Japan*, **40**, 15-30, 1992. (JwE)
34) Nakata, T., Yomogida, K., Odaka, J., Sakamoto, T., Asahi, K. and Chida, N.: Surface fault ruptures associated with the 1995 Hyogoken-Nanbu Earthquake. *Jour. Geography*, **104**, 127-142, 1995. (JwE)
35) Matuda, T.: Seismic zoning map of Japanese Islamds, with maximum magnitude derived from active fault data. *Bull. Earthquake Research Institute, Univ. Tokyo*, **65**, 289-319, 1990. (JwE)
36) Hiyoshi, S.: The relationship between the damage on the reservoirs and the distance from the Nojima Fault in north Awaji Island. *Tsuchi-to- Kiso*, **43**, 11, 59-60, 1995. (J)
37)Hart, E. W.: Fault-rupture hazard zones in California, Aliquist-Priolo special studies zones act of 1972 with index to special studies zone maps (revised), *California Department of Conservation, Division of Mines and Geology Special Publication*, **42**, 31p. 1992.
38)Ogata, S. and Honsho, S.: Fault activity evaluation inthe case of electric power plants. *Jour. Japan Society of Engineering Geology*, **22**, 67-87. (JwE)

(J): in Japanese, (JwE): in Japanese with English abstract.