Design of base isolated buildings built right above a fault

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SUMMARY
There is not the report of the example that designed the building over the fault, and this article becomes the report of the first example in Japan. We carry out the fault investigation and analyze the position and the scale and the direction of the gap and the size of an assumed gap and a past activity history. As a result of analysis, the fault is proved to be outcropping small strike-slip fault. Based on these analyses, we predicted the strong motion of earthquake based on asperity model. Furthermore, in consideration for firing-step of the fault which analytic simulation is difficult, we reflected it for the structural design of the building. The building is planned as two base isolated buildings which avoided the fault line, and a glass roof is constructed between two, and atrium space is created. It is hoped that this article becomes the guidelines on similar project.

Keywords: Active fault, Base-isolated buildings, Method of structural design, Strike-slip fault, Fling step

1. INTRODUCTION

It is estimated that more than 200 active faults, including those whose existence is low in certainty, lie under the land of Japan [1)].

Since the occurrence of the Southern Hyogo Prefecture Earthquake in 1995, the inland major active faults highly likely to induce a giant earthquake have drawn attention. Surveys and researches have been carried out in concurrence with it under the initiative of the Ministry of Education, Culture, Sports, Science and Technology, and materials and data have been disclosed to the public [2)]. However, even such published data does not include data about the accurate locations of these active faults. Before constructing skyscrapers and large-scale, important structures adopting base isolation, in particular, in locations close to these active faults, we analyze these published materials and data and discuss and determine with clients what action to take against the active faults. On the other hand, fault surveys are seldom conducted in ground surveys at the time of the planning of buildings [3)]. In consequence, there is a possibility that buildings will be constructed right above a fault before someone notices it, and many buildings are also said to have been constructed right above a fault.

One of the reasons active fault surveys are not performed when planning buildings is that little administrative guidance is provided on buildings in connection with active faults. Under this circumstance, there are few reports on aseismic design against active faults, and building design engineers, in fact, have little knowledge about how to perform fault surveys and how to analyze and reflect the results of fault surveys in design. The compilation of design guidelines against nearby active fault is an urgent issue for Japan lying over many active faults.

Since the building described in this paper was planned to be constructed close to a major active fault that was, as a result of a survey performed by the Ministry of Education, Culture, Sports, Science and Technology, expected to cause a giant earthquake, we conducted active fault surveys. Because of the strong possibility of an outcrop of the active fault, we performed trenching and consequently confirmed two streaks of faults just underneath the site. The building was thus planned as a two-wing, base-isolated building avoiding these faults, with a roof arched across the wings, which creates atrium space right above the faults and helps the building stand right above the faults. An outline of the building, the appearance of the building, the positional relationship between the layout of the building and the faults, a plan view of the building, and a cross section of the building are shown in Table 1 and Figures 1, 2, 3, and 4, respectively. Situated not only close to the faults but also in a region that must develop countermeasures against subduction-zone giant earthquakes of high incidence, the building adopts a base isolation structure, making it possible to protect human lives and research achievements.

Table 1. Outline of the building

Application	: Office and laboratory	Number of stories	: 3 above ground		
Building area	: 6,298 m^2	Total floor area	:14,896 m^2	Eaves height	: SGL + 19 meters
Type of structure	: RC structure (S structure in part)	Foundation work	: Direct foundation (raft foundation)	Structure	: Base isolation structure

Figure 1. Appearance of the building

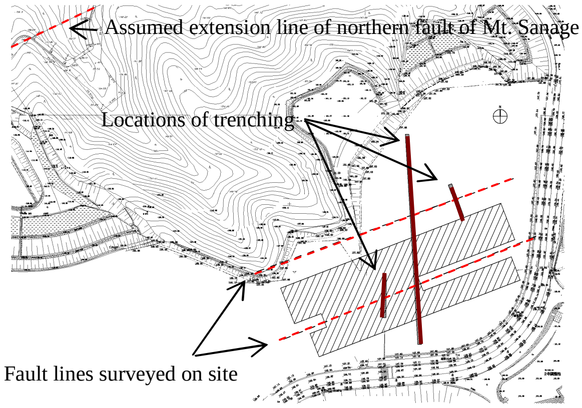

Figure 2. Layout of the building

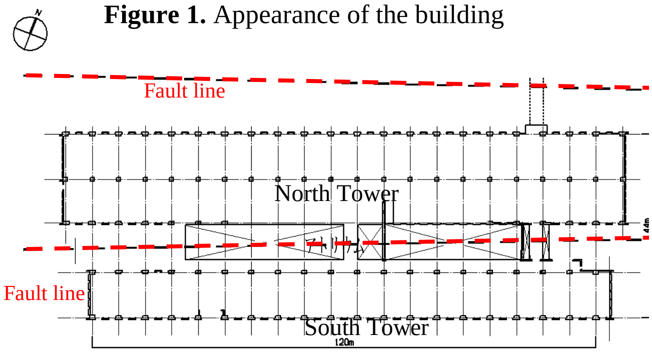

Figure 3. Layout of the building

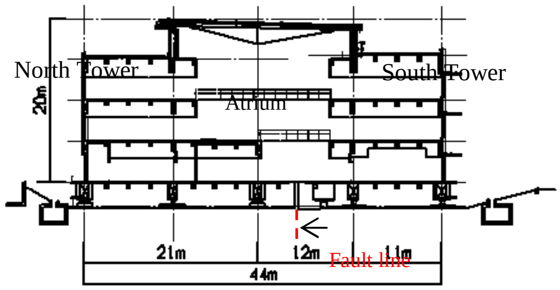

Figure 4. Cross section of the building

Section 2 summarizes the fault survey we conducted and estimated fault behavior. We estimated the distance and direction of fault slip in an earthquake based on the results of the fault survey.

Section 3 describes an outline of the structural plan of the building against the faults. The structural design of the building also takes fling step into account in addition to earthquake-induced vibrations although few cases have been reported with regard to architectural design-related considerations for fault slip, or fling step, that gives rise to permanent displacement [4)].

This paper is a report on the first case in Japan of the building combining structural design against the active faults running under its site and constructed right above them. The active fault survey, analysis procedures, and approaches to considerations for structural plans and structural design are deemed to be helpful reference in similar construction projects in the future and expected to set the course of guidelines concerning structural design against faults.

2. FAULT SURVEY FOR THE CONSTRUCTION OF THE BUILDING

The site of the building is situated close to the northern fault of Mt. Sanage, which is an active fault highly likely to cause an inland earthquake. It is certain that this is an active fault. Figure 5 shows the location of the northern fault of Mt. Sanage, and Table 2 summarizes the results of the evaluation of the fault conducted by the Ministry of Education, Culture, Sports, Science and Technology. The southwestern end of the northern fault of Mt. Sanage probably runs through the northern side of the site and extends toward the west. In fact, a report stated that the existence of the fault was confirmed in the process of the construction work of the railway bridge piers set up in the western part of the site.

We adopted trenching as a method for surveying the active fault on the site. Trenching was conducted to observe the cross section of the fault by digging a linear ditch about 2 meters deep from the surface of the ground. The site is situated on the edge of the depositional plain home to the city of Nagoya, and a seismic bedrock is deemed to be close to the surface of the ground [5]. This fact led us to the conclusion that there was a great likelihood of an outcrop of the fault and it could, therefore, be surveyed through relatively simple trenching. It would be necessary to conduct a larger-scale survey if the active fault was covered with a thick sedimentary layer. Figure 2 shows the location where the trenching was conducted.

In the trenching, two fault lines were confirmed within the site (Figure 2). Figure 6 shows a photo of a portion in the cross section of the trenched stratum proven to be the fault. The photo in Figure 6 depicts some characteristics from which the existence of the fault was confirmed.

Table 2. Characteristics of the northern fault extending from Mt. Ena to Mt. Sanage (cited from material released on October 16, 2001, by the Headquarters for Earthquake Research Promotion, Ministry of Education, Culture, Sports, Science and Technology)

Overview	The overall length of the fault is 51 kilometers extending from the northeast to the southwest. The western half of the fault is the northern fault of Mt. Sanage, and the eastern half is the fault of Mt. Ena.
Past activity	The average rate of slip was 0.2 to 0.4 meter per 1,000 years. It is estimated that the most recent active period of the fault traces back to about 7,600 to 5,400 years from today. Its average interval of activity is presumed to be between about 7,200 and 14,000 years.
Future activity	The magnitude of the earthquake to be caused by the fault is expected to be about 7.7 if the western and eastern halves become active as a single zone. In this case, the northern fault of Mt. Sanage will slide about 2 to 3 meters to the right. Among Japan's major active faults, this fault is rather high in the probability that it will trigger a big earthquake in the next 30 years.

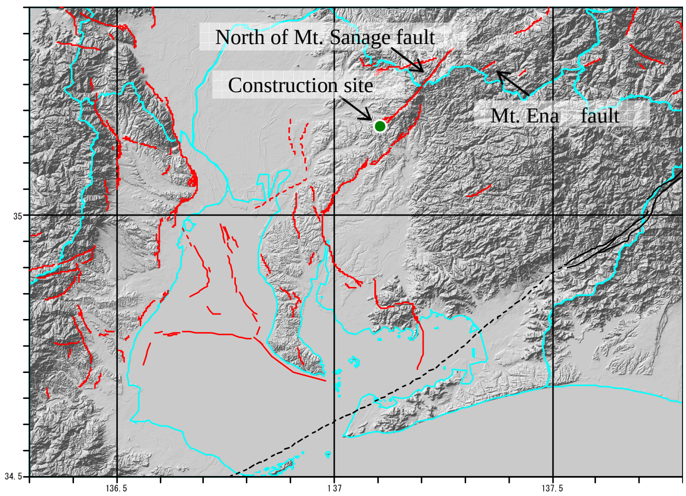

Figure 5. Distribution of active faults surrounding the construction site

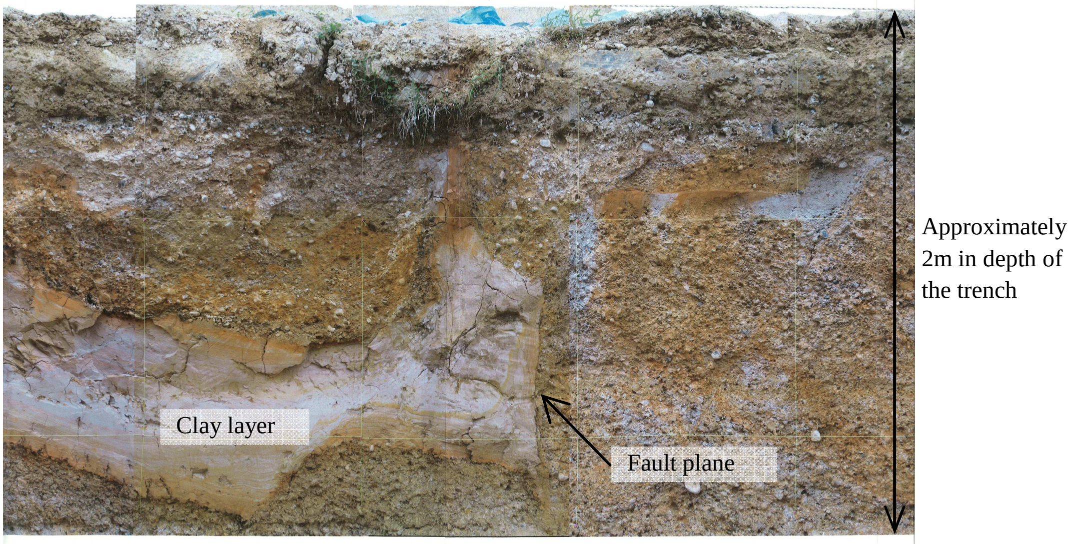

Figure 6. Orthogonal cross section of the active fault confirmed in the cross section of the trenched fault

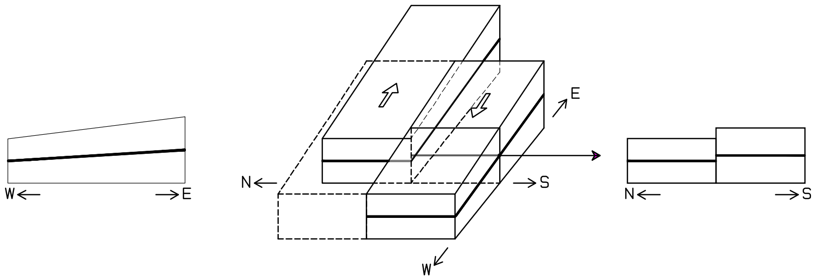

Figure 7. Explanatory diagram of a sloping fault that becomes discontinuous by horizontal placement attributable to a strike-slip fault

One of the characteristics is the floriform structure that is identifiable in the cross section of the fault orthogonal to the fault line. You can see V-shaped fault lines stacking in layers in the ground close to the surface of the ground. The fault plane under the V-shaped layers of the fault lines is a regular, vertical plane. A cross section of this shape is typical of a strike-slip fault.

In faults that slip in the vertical direction, such as normal faults and reverse faults, the cross sections of the strata fold in complicated patterns; on the other hand, in strike-slip faults, which move in only the horizontal direction, the strata are in regular form and show regular traces of slips on the fault plane. However, the fault plane close to the surface of the ground spreads in irregular form showing V-shaped fault lines. These V-shaped lines stacking in layers are proof that strike slips repeatedly occurred in the past. We were able to estimate the scale of the fault from the irregular state of the strata close to the V-shaped fault lines, and found that the fault concerned was relatively small in scale.

The second characteristic from which we can identify the fault is the difference of stratum composition between the right and left fault lines confirmed. As shown in Figure 6, the clay layer on the left side of the photo is interrupted at a fault line. Since a strike-slip fault slips in almost the horizontal direction, the inconsistency of stratum composition seems curious, but the fact is that the stratum is inclined. A conceptual diagram of a cross section when sloping ground slips in the horizontal direction is shown in Figure 7. No clay layer is observed on the right side of the photo because the surface of the ground was leveled by cutting, but the results of a past boring survey confirmed the existence of a clay layer above the current surface of the ground. In addition, given the inclination of the stratum, the ratio of stratum slips in the horizontal and vertical directions can be estimated. As a result of an analysis, it turned out that the fault moves in almost the horizontal direction, which is identical to the characteristic obtained from the survey of the northern fault of Mt. Sanage shown in Table 2.

The direction of slips can also be gathered from the distribution pattern of gravel contained in the slip plane of a fault. In a fault plane, slender pieces of gravel slightly bigger than sand in size are sometimes found in the direction of slips. The same pattern was observed in a section of the surveyed fault, and a trace of a horizontal slip was discovered in the fault plane.

Whether a fault is an active fault or not can be determined by identifying the recent age of its activity. An active fault is defined as a fault that showed movement or seismic activity during the last some 2 million years, and the recent age of activity of the subject fault can be consequently determined. As a method for determining the age of activity, an analysis of pollen contained in a sample collected from the site is used. We used this approach to survey the fault concerned, but could not identify the age of its activity and definitely determine whether it was an active fault because the sample did not contained any pollen.

We predicted the future behavior of the fault based on the results of the trenching described above, as well as the results of past fault surveys. Since the subject fault is small in scale, there is a strong possibility that it is a spray fault, not the main fault of the northern fault of Mt. Sanage. Even if it is the main fault, its strike slip is about 2 meters. Considering the fact that two streaks of faults were discovered in the construction site, the strike slip of a single streak is estimated at about 1 meter. Contrary to this, the vertical slip was presumed to be only about 1/10 of the strike slip, or about 10 cm. In addition, judging from past postseismic records on similar strike-slip faults, we reached the conclusion that the load bearing capacity required of the ground could be ensured if it was separated 1 to 2 meters away from the fault line.

Table 3 summarizes the results of the abovementioned trenching and an evaluation of the fault estimated from the results of the trenching.

Table3. Summary of trenching results of the fault

		Remarks
Method of fault survey	Trenching	Applicable because the fault outcropped.
Presence or absence of fault	Two streaks of faults existed within the site.	
Survey of condition of fault plane	Strike-slip fault	Characteristics of the fault plane orthogonal to the fault line • V-shaped fault line in the surface layer • Vertical fault plane under the V-shaped fault line • Distribution of slender pieces of gravel
	Repeated activity	V-shaped fault lines stacking in layers
	Possibility of active fault	The age of activity could not be identified from pollen.
Evaluation of fault	Right-lateral strike-slip fault	Confirmed from the condition of the stratum close to the fault.
	Scale of slip	Horizontal direction: 0 to 1 meter Vertical direction: 0 to 0.1 meter
Required separation	Separation between fault line and building	A separation of 1 to 2 meters is required.

3. OVERVIEW OF STRUCTURAL DESIGN AGAINST THE FAULT

3.1. Actions taken in the past against the fault within the site

We can find examples of measures and approaches to the construction of buildings close to faults, such as the prohibition of construction in areas within a specific distance from any fault in the site and an increase in the design load of buildings. In 1972, the State of California was the first to prohibit the construction of buildings in areas within about 50 feet (about 15 meters) from both ends of fault lines.

Some municipalities of Japan also provide guidance concerning the construction of buildings close to faults. Following the Southern Hyogo Prefecture Earthquake in 1995, the city of Nishinomiya enacted an ordinance in the same year, which obligates all constructors to conduct surveys in connection with the development of medium- and high-rise buildings close to active faults and, if necessary, requests them to take aseismic measures. The city of Yokosuka compiled a brochure detailing the results of surveys of the active faults existing in the entire area in 2000, imposes an obligation on constructors to survey active faults in large-scale development projects, and offers guidance on limiting the construction of buildings above active faults. Some cases of buildings constructed above active faults have already been reported. In 2008, Fukuoka Prefecture enforced an ordinance making it mandatory to reinforce the aseismicity of medium- and high-rise buildings constructed close to the Kego Fault running under the central part of the city, and advises the owners of these buildings to increase their seismic loads for design. Such administrative guidance, however, is not legally binding, and there is a possibility that buildings will be constructed in disregard for this guidance. These efforts that have been made to date are administrative guidance of prohibiting the construction of buildings very close to relatively large-scale active faults and increasing the strength of existing buildings in these areas. On the other hand, the fault described herein is small in scale, and its location is pinpointed. Judging from these facts and the expected fault displacement, the subject fault is one above which buildings may be constructed if proper architectural schemes are adopted. There is no guidance in the construction of buildings above such faults.

3.2. Structural design policy against the fault

This section describes structural design considerations for the analytical results of the fault survey and an approach to achieving them. It is a known fact that pulse-like earthquake waves of relatively long cycle sometimes appear due to directivity when the rupture of the fault advances toward a point of observation in connection with tremors of fault-induced earthquakes. This pulse-like waveform was also observed in the 1995 Southern Hyogo Prefecture Earthquake, and literature pointed out that the waveform was a contributing factor to the aggravation of damage to the buildings 6). We determined to use a scenario type strong ground motion prediction method 7), with which the effect of directivity can be accurately evaluated, to create seismic ground motions to be used for analysis in the phase of design. Although the fault existing in the site is small in scale, it is there is no denying that it forms part of the northern fault of Mt. Sanage. We, therefore, created seismic ground motions on the assumption that they would be induced by the northern fault of Mt. Sanage and the fault of Mt. Ena extending to the northeast in synchronization with each other, which was intended to set an assumption with the highest level of safety, and the rupture of both of the northern fault of Mt. Sanage and the fault of Mt. Ena would advance toward the site concerned. As fault parameters, the results of an evaluation performed by the Headquarters for Earthquake Research Promotion were used.

In connection with fault slip, pulse waveforms induced by fling step have been observed in locations, for example, right above faults 6) as were observed in the Chichi Earthquake, which struck Taiwan in 1999. Thus far, there has been no case of design against such single-direction permanent displacement. Today's strong ground motion prediction schemes are capable of analytically producing simulated waves of relatively long pulse attributable to directivity, but it is difficult for them to create analytically create simulated waves up to pulse waveforms by fling step. For this reason, we determined to adopt seismic ground motions using a scenario type strong ground motion prediction method as tremors resulting from seismic ground motions and to allow for large base isolation clearance against fault slip and provide the building with extra strength in anticipation of a case of a collision over the clearance.

3.3. Structural design criteria

As seismic ground motions to be expected in structural design, we defined a medium- or small-scale earthquake level (level 1), a giant earthquake level (level 2) and, in addition, new earthquake levels in excess of level 2, levels 3 A and 3B. Level 3A represents input 1.5 times higher than level 2, which is assumed in Japan, with the degree of importance of the building taken into account. Level 3B is an earthquake level given that the fault lying under the site is an active fault.

The set target performance of the building is very high with the intention of achieving an equivalent level of performance to the target performance set at level 2 even at level 3A and of protecting human lives at level 3B imposing severer conditions. Table 4 shows the target performance of the building, and Table 5 describes the structural design criteria set on the target performance. Table 6 lists the seismic ground motions used for the design.

Table 4. Target performance of the building

	Level 1	Level 2	Level 3A	Level 3B
Assumed seismic ground motion	Medium- or small-scale earthquake	Giant earthquake	Seismic ground motion 1.5 times higher than level 2	Tremors and slip attributable to earthquake induced by the fault just under the site are taken into account.
Target performance of building	No damage	Although the structure is slightly damaged, it does not require repairs to maintain strength.	Although the structure shows a slight decrease in strength in part, it does not require immediate repairs.	Although the structure is damaged in part, it does not significantly decrease in strength and can protect human lives.

Table 5. Structural design criteria on target performance

	Level 1	Level 2	Level 3A	Level 3B
Amount of fault slip	Not taken into account			Horizontal direction: 0 to 1 meter Vertical direction: 0 to 0.1 meter
Upper structure	Equal to or lower than allowable stress for temporary loading			Equal to or lower than horizontal bearing capacity
	Maximum story deformation angle: 1/3,000 rad or less	Maximum story deformation angle: 1/1,500 rad or less	Maximum story deformation angle: 1/1,000 rad or less	Maximum story deformation angle: 1/200 rad or less
Isolating devices	Shear strain shall be within 250%, and deformation shall be within 60 cm.		Shear strain shall be 313% or less, and deformation shall be 75 cm or less.	Direction of fault slip Shear strain shall be 417% or less, and deformation shall be 100 cm or less. (The clearance in the slip direction shall be 100 cm.) Orthogonal direction to direction of fault slip Shear strain shall be 313% or less, and deformation shall be 75 cm or less. (The clearance in the orthogonal direction to the slip direction shall be 80 cm.)
	Compressive: 20 N/mm^2 or less Tensile: 1 N/mm^2 or less			Equal to or lower than compressed limit strength
Foundation structure	Equal to or lower than allowable stress for temporary loading			Equal to or lower than horizontal bearing capacity

Table 6. List of input seismic ground motions for design (Each value indicates the maximum velocity (cm/s).)

	Level 1	Level 2	Level 3A	Level 3B
Simulated motion (Hachinohe)1968EW	12	60	90	—
Simulated motion(Tohoku University)1978NS	15	74	110	—
Simulated motion (Kobe)1995NS	15	74	111	—
Mt. Ena – north of Mt. Sanage fault NS※	—	—	—	120

※Simulated seismic ground motion created by scenario type strong ground motion prediction method

3.4. Overview of structural design

The building concerned is designed as a two-wing, base-isolated building avoiding the two fault lines identified within the site. However, it needs to be used as a single building. To meet this requirement, a roof arches across the two wings, which creates atrium space, and a bridge is constructed on each floor between the wings, making them available as a single building. One end of each of the roof and the bridges stretching across and the other end are designed to be fixed by pins and supported by rollers, respectively. The rollers are required to move a long distance because they connect the two base-isolated structures, and are permitted to move up to 160 centimeters on one side.

The building adopts base isolation design that is very effective in reducing earthquake input into the building and achieves a long-cycle base-isolated structure [8)]. To help realize this design, bearing supports are used together with laminated rubber isolator generally used as vibration isolating members for sections responsible for bearing vertical supporting force (Figure 8). Consequently, the building fulfills the target structural performance against the assumed high seismic ground motion levels.

The structural performance of the building was evaluated by verifying through a time history response analysis that it was within the structural design criteria. Figure 9 shows the results of the analysis to level 3B seismic ground motions. The figure shows only the results of the northern wing against tremors in the direction of the fault as representative data, but a similar trend was observed with each wing in each direction. In addition, all response values were within the set structural design criteria. However, as already described in Section 3.2, even seismic ground motions handled as level 3B for analysis were assumed to be only earthquake tremors. For this reason, we adopted design anticipating a large displacement of the building in consequence of the action of the slip of the active fault, in addition to the analysis results shown in Figure 9.

As a measure against slip, the two measures described below are adopted to ensure base isolation design and extra strength of the upper structure. One is 100-centimeter base isolation clearance provided by adding a slip-direction allowance 20 centimeters longer than the orthogonal direction. The purpose of adopting devices as large as 1,200 millimeters in diameter as laminated rubber isolators is to maintain vertical supporting force even in case of a deformation of 100 centimeters, which is equal to the base isolation clearance.

The other is the design intended to provide the building with extra strength and thereby achieve equal strength to buildings that are not non-base-isolated. This is because the estimates scale of the slip of the active fault has not been elucidated yet and the possibility that the aseismic layer will deform 100 centimeters or over due to the slip of the active fault cannot be denied. This design anticipates that the building will cause displacement in excess of the base isolation clearance, collide with the surrounding retaining wall, and be subjected to impact force. This is the reason why the strength of the building is greatly in excess of the response value. Whether this allowance is proper or not is difficult to evaluate and will have to be evaluated in the future. However, based on the fact that few low-rise RC buildings of aseismic design collapsed when giant earthquakes occurred, we reached the conclusion that the building will not collapse even if it collides with the surrounding retaining wall. The concept of the target structural design described thus far is shown in Figure 10.

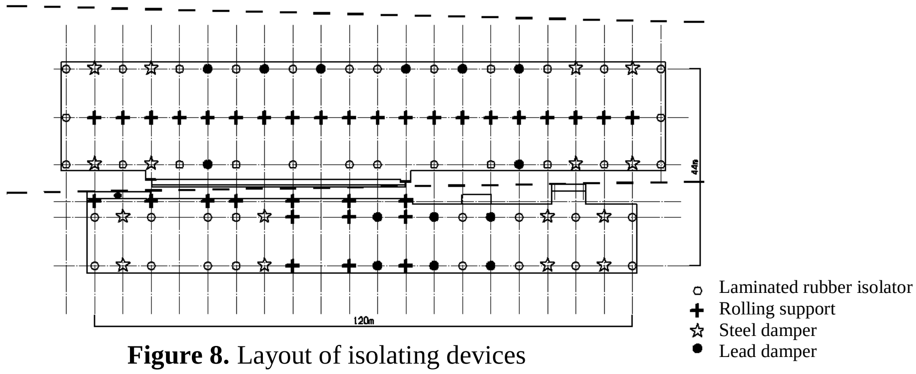

Figure 8. Layout of isolating devices

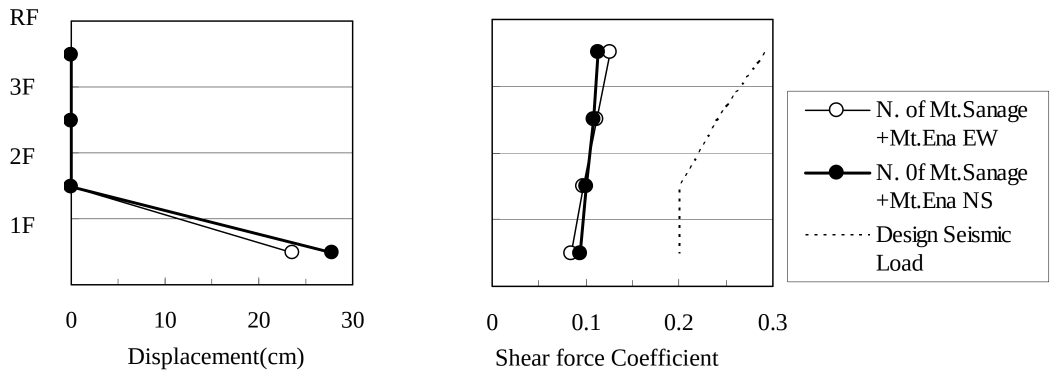

Figure 9. Results of responses analysis of the building to level 3B earthquakes

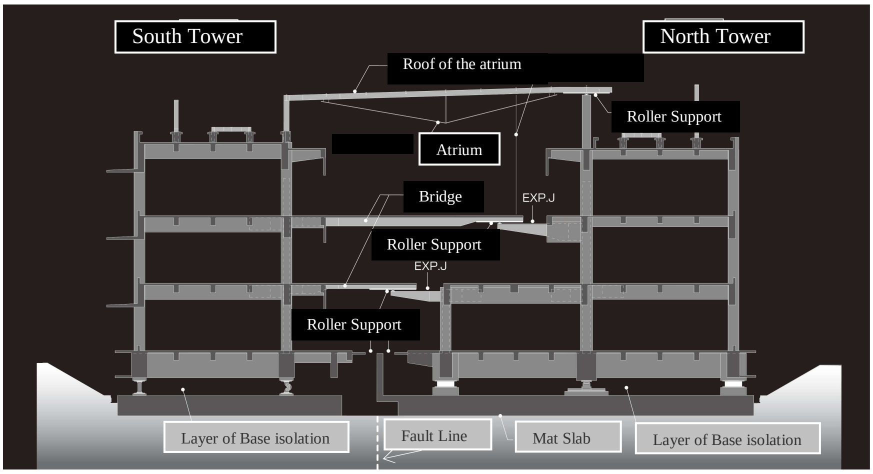

Figure 10. Conceptual diagram of structural design

4. CONCLUSION

The building introduced in this paper is Japan's first structure successfully constructed right above an active fault by estimating the behavior of the active fault just under the site and designing its structure combining measures against it. This paper describes a procedure for conducting fault surveys and setting target structural design when constructing a building in a location very close to an active fault, and shows an overview of the structural design of the building designed. In addition, the structure of the building is designed in light of not only tremors induced by earthquakes caused by the fault but also the behavior of the building attributable to the slip of the active fault. The flow of the structural design of the building concerned against the active fault is shown in Figure 11.

We believe that the three fortunate events described below made it possible for us to design and construct the building right above the fault. The first is that the fault outcropped. If a fault is covered with a thick sedimentary layer like a depositional plain in an urban area of Japan, trenching is impossible, and a fault survey is difficult to perform. The second is that the fault in the site was small in scale. If the fault just under the site was large in scale, the construction of the building would have certainly been suspended. The third and the last is that the fault was undoubtedly a strike-slip fault. If the fault was one causing large displacement in the vertical direction, such as normal and reverse faults, it would have been very difficult to plan the building over the fault.

It is also desired as a future challenge that the fling step behavior of the ground be able to be evaluated more accurately. We expect the design case introduced herein to be used as guidelines in designing future similar projects.

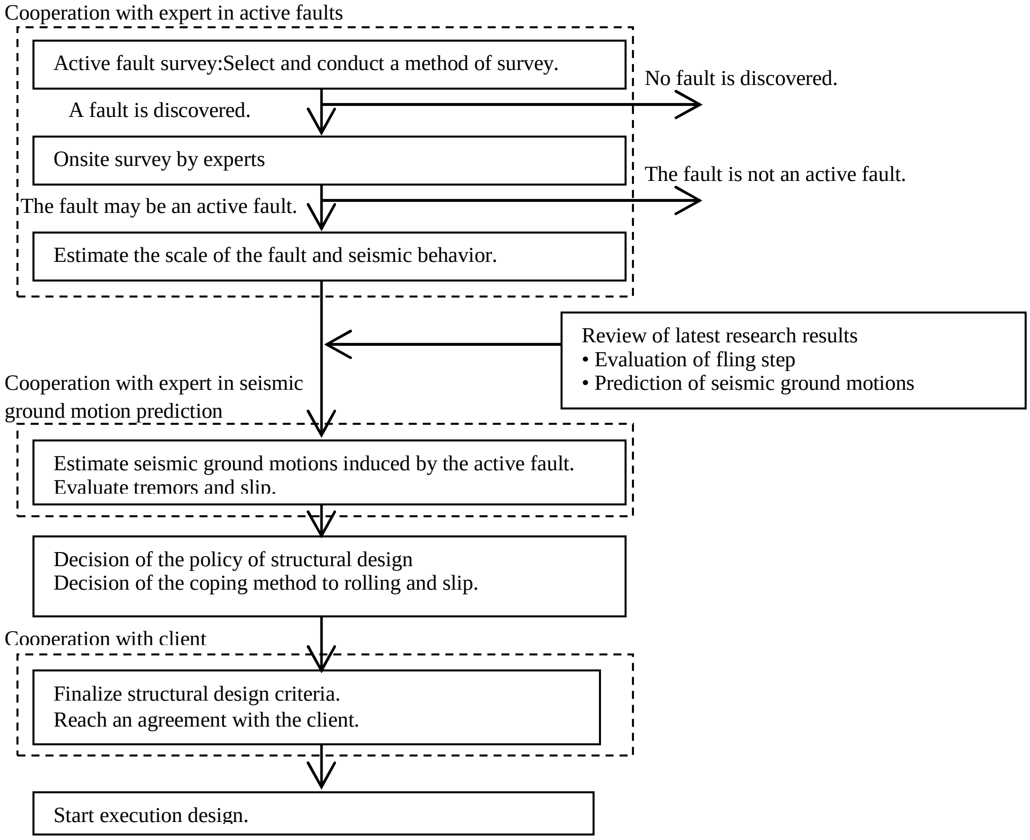

Figure 11. Flow of fault survey in architectural design

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