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Behavior of Geologic Bodies Under Paleostress Field and Groundwater Environment at the Foundation of the Nanakita Dam, Northeast Japan

By

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With 5 Tables, 9 Text-figures and 1 Plate

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ABSTRACT

Miocene tuffaceous rocks are developed at the foundation and adjacent ground of the Nanakita Dam in Miyagi Prefecture. During the detailed surveys for the construction of the dam, a large number of open cracks and clay veins were found in tuff breccia and sandy tuff, respectively. In addition, formation of open cracks was observed in the sandy tuff at the time of Miyagi-ken-oki Earthquake on June 12, 1978. Since these open cracks and clay veins will surely cause serious problems for the dam foundation, detailed investigations have been carried out on the formation processes of these geological phenomena, and appropriate foundation treatments have been performed during the construction based on the results obtained.

Shear fractures in the tuff breccia and extension fractures in the sandy tuff were concluded to be formed under the paleostress field at the period of late Tertiary. The direction of the principal compressive stress axis of the paleostress field was estimated horizontal and N77°E which well coincides with the direction of E-W compressive stress field of the late Miocene to Pliocene ages. The latter is commonly recognized in the southern part of the Tohoku District. It is concluded that the difference between the shear fractures and extension fractures is attributable mainly to the differences in the confining pressure and the mechanical strength of the respective rocks caused by the overlain sediments. Shear fractures in the tuff breccia became gradually open cracks by weathering process, mainly due to the groundwater agents. Extension fractures in the sandy tuff, on the other hand, became clay veins by deposition of clay materials suspended in ground water. This difference probably originates from the difference of resistivity against weathering.

As the result of proper foundation treatments, the dam has been confirmed as a safe structure with no problems for the past four years.

CONTENTS

I. INTRODUCTION

Miocene tuff breccia characterized by the development of numerous open cracks is developed in the investigated area, i.e., occupying more than 60 percent of the foundation area of the Nanakita Dam in Miyagi Prefecture. The tuff breccia is overlain by the alternation of tuffaceous sandstone and mudstone, thin tuff bed, tuff breccia, tuffaceous sandstone and sandy tuff from the lower to the upper layers. A number of clay veins were observed in the sandy tuff. In addition, numerous fractures were characteristically formed in the sandy tuff by the Miyagi-ken-oki Earthquake (5 JMA scale) on June 12, 1978.

These open cracks, clay veins and fractures formed by the earthquake have caused quite serious problems for the construction of the dam. Therefore, it was indispensable to improving the geological conditions for constructing a dam. On encountering these alarming geological phenomena, countermeasures were established in accordance with respective defects, and the dam foundation was stabilized through appropriate engineering work.

Except for the fractures formed by the earthquake, the open cracks and the clay veins were produced by definite geologic process. Shear fractures in tuff breccia and extension fractures in sandy tuff were formed under the same paleostress field. Later, both fractures were subjected to groundwater agent, and as the result, the open cracks in the former and the clay veins in the latter were formed respectively.

Hirayama et al. (1965) reviewed the analysis method of stress fields, citing many actual examples. Among various methods, small fault, dike and joint methods are important in practice. Concerning the small fault method, the following researches should be mentioned: researches by Gzovskii (1954), Kakimi et al. (1966), Kodama (1968), Kinugasa et al. (1969), Mitsui (1971a, b), and Yokota (1974a, b), and the studies of Nakamura et al. (1975), Takeuchi (1977, 1978, 1981), Kobayashi et al. (1978) on the dike method. Furthermore, regarding a method combining the joint method and others, there are the works of Kitamura (1962), Hoshino (1965), Mitsui (1971a), Hirano (1969), Yokota (1974a, b), and Kimura (1980). The method for the estimation of paleostress fields used in the present study does not correspond directly to any of the above methods, however, eclectic one of the three methods. The paleostress field in the area of the Nanakita Dam site was examined based on the geometrical analyses of both shear fractures and extension fractures, using the method established in the present study.

Nanakita Dam is located at a place approximately 17 km northwest of the center of Sendai City and is a rockfill dam of 74 m in height and $2.682\times10^6\ m^3$ in volume having the purposes of flood control, irrigation, and city water supply. Construction work was finally completed in 1984.

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II. TOPOGRAPHY AND GEOLOGY IN SURROUNDINGS OF THE NANAKITA DAM

The Nanakita River on which Nanakita Dam has been constructed rises from a volcanic mountains with height of 800 to 1,000 m such as Izumigadake, Kurohana, and Kokura, and runs down through elevated tablelands or river terraces with 300 to 400 m altitude. In the vicinity of Nenoshiroishi in the city of Izumi, the river grows gathering tributaries passing through elevation tables with about 100 m height, and meanders in the east-southeast direction and goes down to the Sendai alluvial plain with the altitude of less than 50 m, and passes the northeast part of Sendai City flowing into the Pacific Ocean. The location of Nanakita Dam is shown in Fig. 1.

The geology of the area is composed of Tsunaki, Yumoto and Shirasawa Formations of Miocene age from the lower to the upper. The Tsunaki formation is in fault contact with the Yumoto Formation and the fault runs in the NE-SW direction roughly through the middle part of Nanakita Reservoir. That is, the Tsunaki Formation distributes on the west side of the fault and the Yumoto Formation overlain by Shirasawa Formation on the east side. All of these sediments are overlain by mudflow, marsh, terrace and landslide deposits of Quaternary age.

The geological map and its profile revealed by the present research carried out in relation to the construction work of the dam are shown in Figs. 2 and 3, respectively. The Yumoto Formation is overlain by the Shirasawa Formation. The Yumoto Formation is composed of sandstone, tuffaceous sandstone, tuff, tuff breccia, dark gray tuffaceous sandstone, tuffaceous sandstone and mudstone alternations, tuff, and a thin bed of tuff breccia from the lower to the upper. These are superposed conformably with each other, and extend all over the investigated area except for some partial thin layers. All of these sediments except the first two, were observed at the foundation surface of the dam during construction excavation. As shown in Fig. 2, tuff is distributed in the vicinity of the downstream end of the dam foundation and tuff breccia widely from the middle portion of the dam foundation into the left and right banks. The upper members of the rocks are distributed at the parts of the left and right bank slopes.

The Shirasawa Formation is composed of alternation of tuffaceous sandstone and mudstone, tuff, and sandy tuff from the lower to the upper. These are also superposed conformably and show good continuity. These

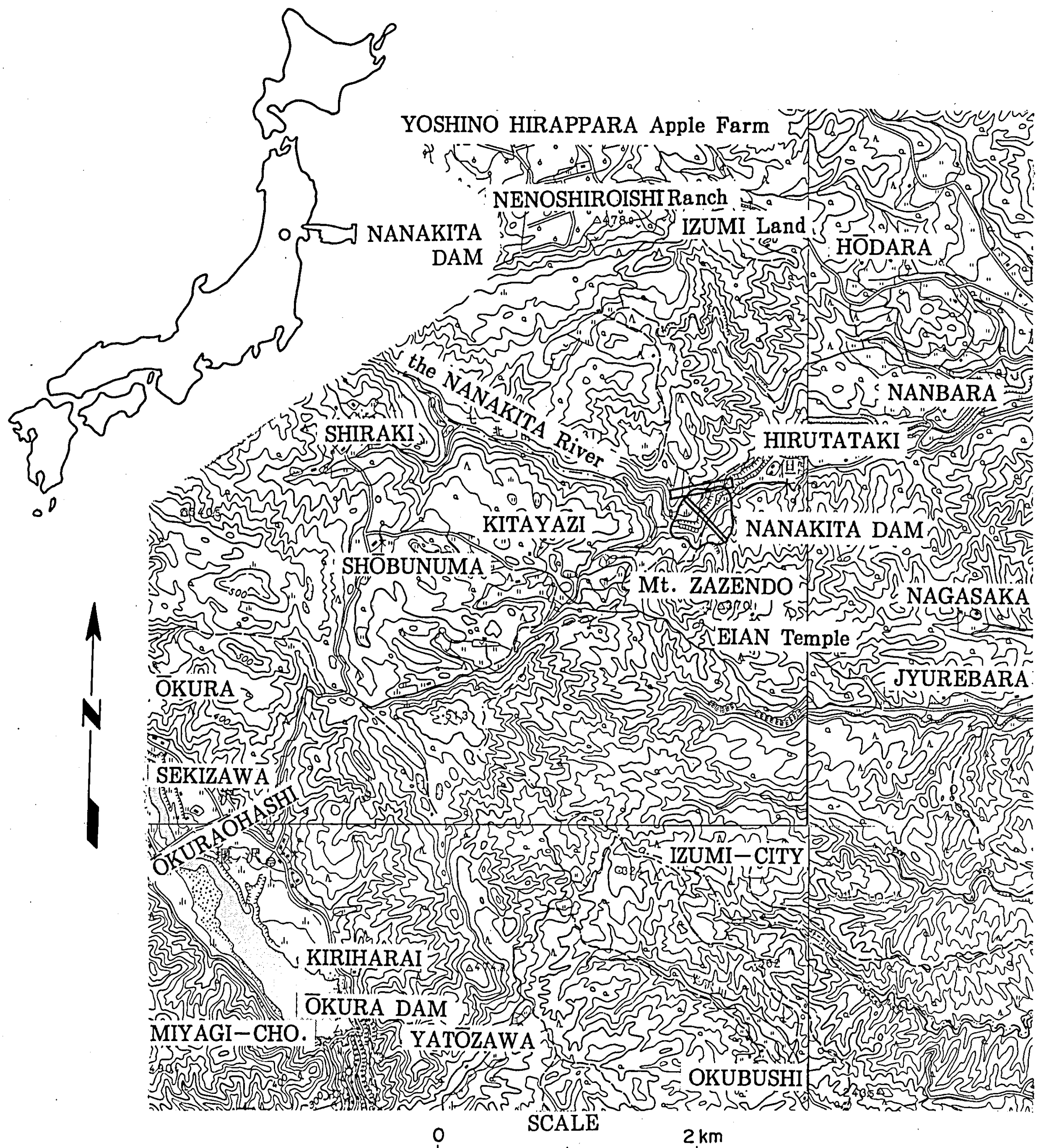

FIG. 1. Location map of the Nanakita Dam.

rocks of the Shirasawa Formation were all exposed at the surface of the dam foundation, and distributed approximately horizontally from the upstream side to the downstream side at the upper part of the right bank slope of the dam foundation.

These two formations at the dam foundation and its vicinity trend NE-SW and dip at low angle of around 10° from the left to right abutments of the dam. The rocks distributed over the widest areas at the surface of the dam foundation are tuff breccia in the Yumoto Formation and sandy tuff in the Shirasawa Formation.

III. OPEN CRACKS

Development of open cracks in the investigated area is limited to the tuff breccia of the Yumoto Formation and some part of the overlain tuffaceous sandstone-mudstone alternation and tuff. The tuff breccia contains rubbles of mudstone, tuff, tuffaceous sandstone, and sandstone of various size up to 20 m in diameter. Such tuff breccia characterized by large rubbles is termed "pyroclastic rubble flow" by Shibata (1962).

Open cracks have been found at 23 places in the tuff breccia during excavation of the dam foundation. At several places, development of swarms of the cracks were observed, so that the total number of the cracks reach a considerable number (see Fig. 4). The maximum width of the open cracks was more than 1 m, and the smallest one was several centimeters. Some were as much as 20 m in length. Although the mode of occurrence of the cracks varies considerably with each other, it can be

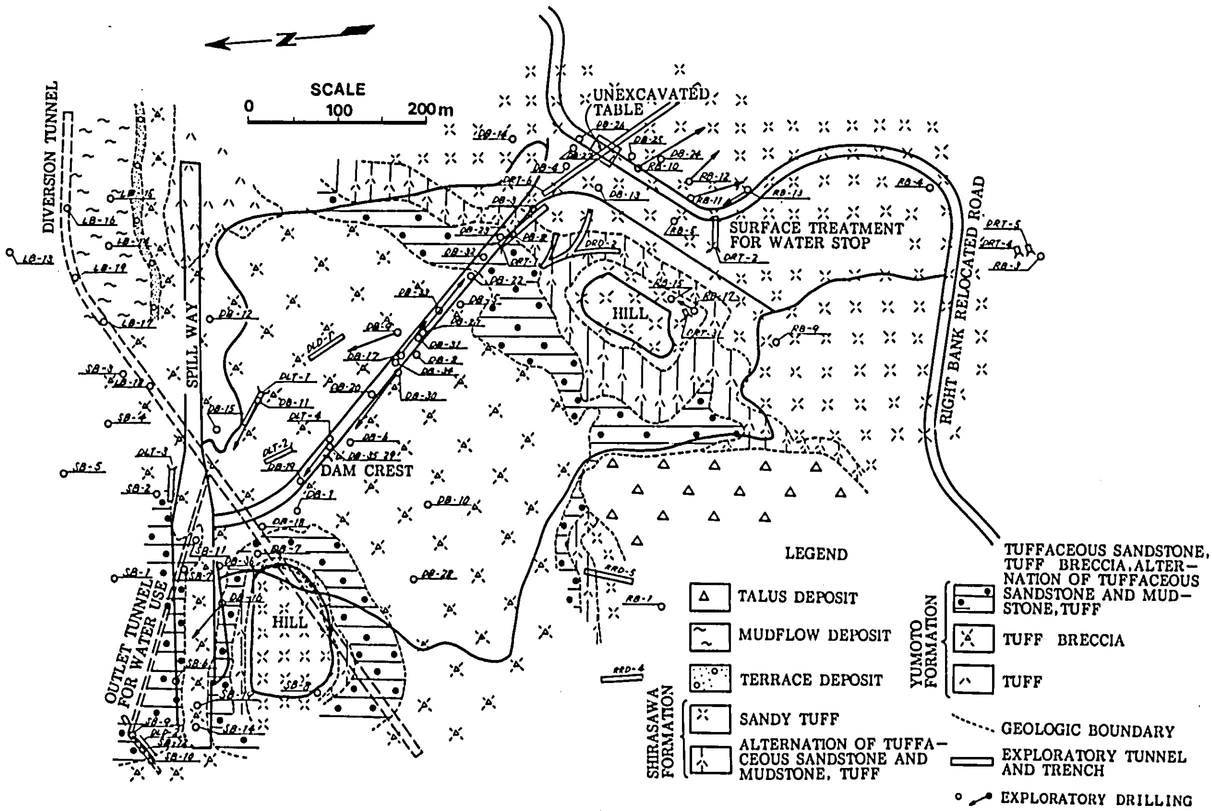

FIG. 2. Geological map of the Dam foundation.

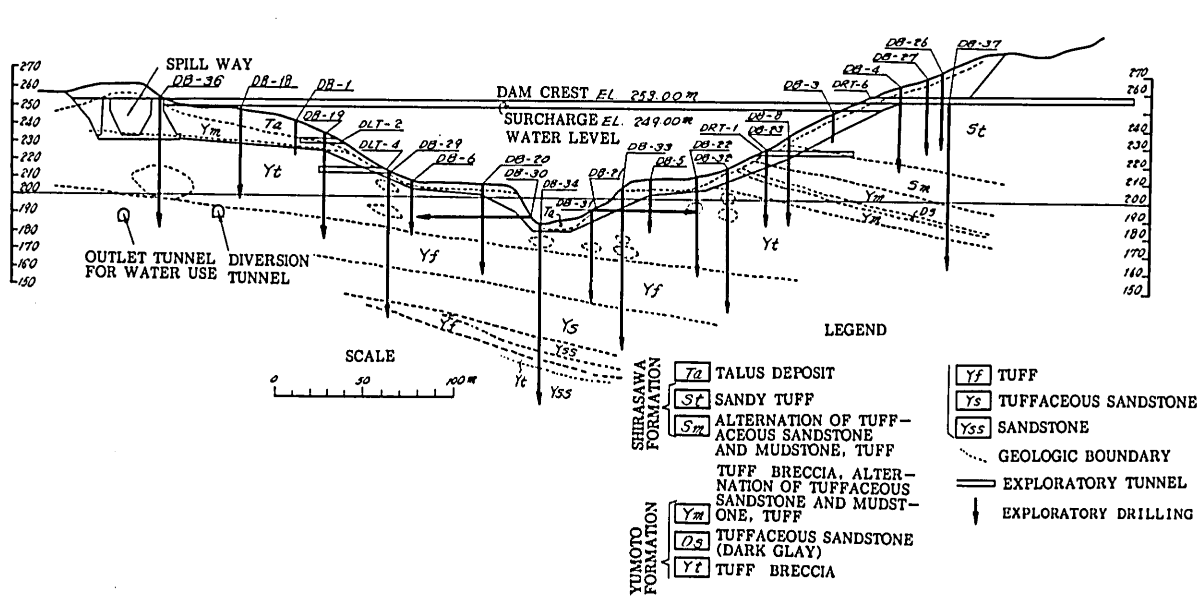

FIG. 3. Geological section along the Dam axis. The dotted circles in Yt member show the huge pebbles of tuff or mudstone.

divided into the following six types.

a) Type A Open Cracks

(1) The cracks were all slender, the walls on both sides had irregular and crooked surfaces with different orientation, i.e. no parallelism has been confirmed between both sides and reconstruction of the original form is almost impossible.

(2) All of the open cracks become tight more and more to the ends and finally disappears.

(3) At the ends of the open cracks, clay materials derived from the wall rock were found in the places preserving the original texture.

In view of the above facts, it might be concluded that type A having these features were formed by washing out the original materials along fractures.

b) Other Open Cracks

Type B open cracks were found immediately above the Type A in the alternations of tuffaceous sandstone and mudstone and the tuff which overlie the tuff breccia. These open cracks were not appeared as smooth straight lines, but were of extremely irregular shapes, as if rock masses had been piled up without any order and the

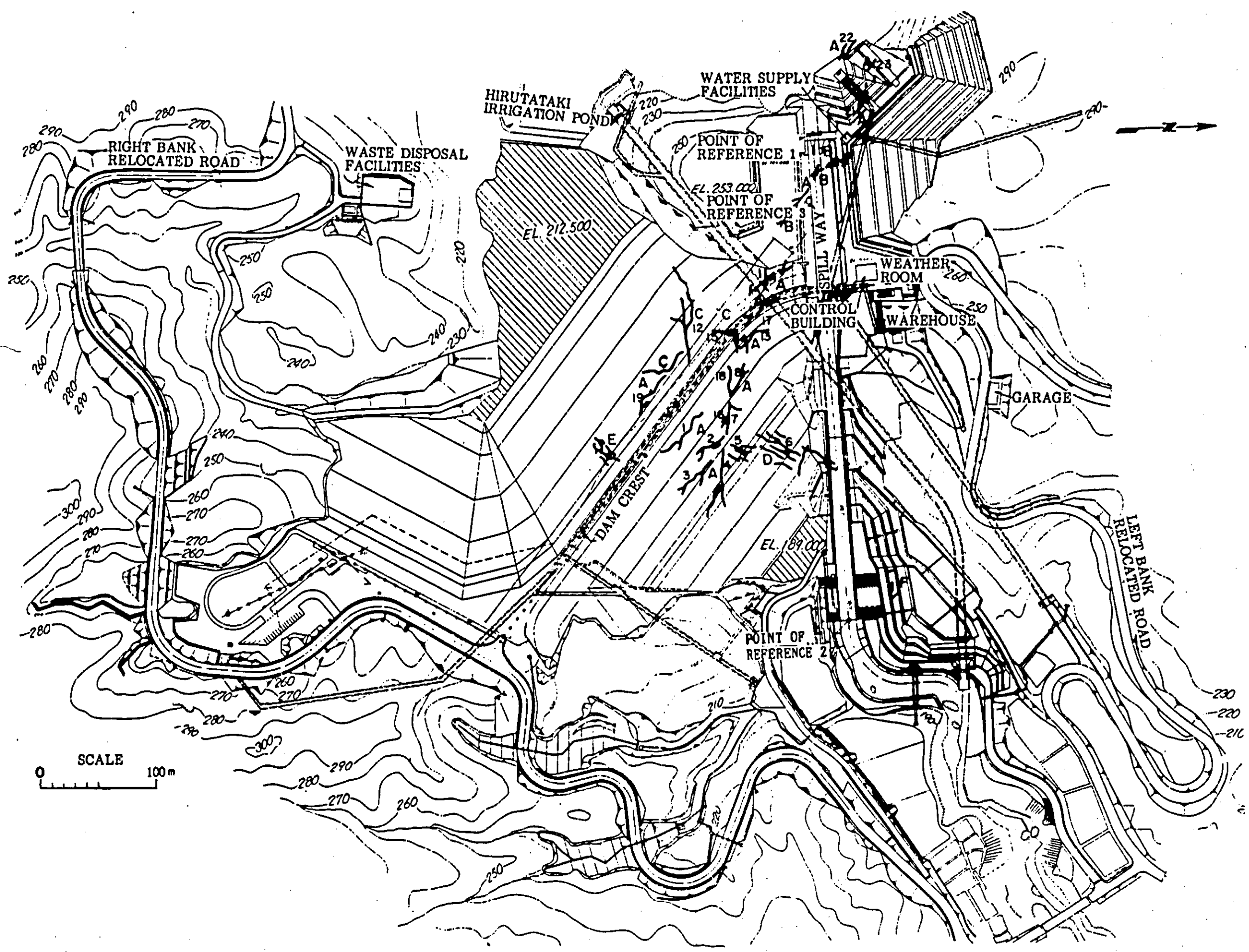

FIG. 4. Principal open cracks developed in the Dam foundation.
A–F: Type of open cracks.
1–23: Number of open cracks.

boundaries between the rock masses had remained as open cracks. None of materials such as weathered country rocks were observed anywhere in the open cracks. Consequently, it is concluded that the Type B were formed as the result of propagation of Type A to the overlying sediments by earthquake.

Type C open cracks were distributed in the zones in which Types A and B developed and in tuff breccia adjacent to the zones. Both sides of walls of the cracks were parallel with each other and restoration of the previous conditions was possible. Soft weathered material of wall rock was not held anywhere in these open cracks. Therefore, it is considered that the Type C were formed by the bedrock shifting toward open cracks of Type A due to earthquake.

Type D open cracks were found in the tuff breccia with frequency of 20 to 30 per about 1, 000 m^2. Although the walls of these open cracks were not even,

TABLE. 1. OPEN CRACKS FOUND IN THE TUFF BRECCIA.

Type of crack	Number	Genesis	Location
A	1•2•3•4•5 a part of 6•a part of 10•a part of 11•13•14•17 •18•19•21•22•23	Weathered soft bedrock material along fracture has been washed away by ground water, the fracture having been formed by crustal stress at the time of late Tertiary.	Zone from intake to spillway, and further, cutting diagonally across dam axis toward dounstream area and connecting with center of dam foundation 50m downstream from dam axis.
B	9•a part of 10	Falling down of rock mass into Type A open crack due to earthquake and propagation of loosening along Type A open crack in tuff breccia to overlying stratum.	Horizontal portion and on slopes of both sides in the upper stream of spillway.
C	A part of 11•12 A part of 13•15•16	Movement of bedrock toward Type A open crack due to earthquake.	Vicinity of Type A open crack.
D	Greater part of 6	Deflection of bedrock toward river due to earthquake.	Left bank terrace table between 80m and 150m from dam axis in the lover stream.
E	No number	Movement and settlement of bedrock due to earthquake after washing away of soft weathered material by ground water along fracture.	Old river bed in range of 30 to 70m in the upper stream of dam axis.
F	No number	Creep of bedrock due to earthquake.	Leftbank slope at spillway stilling basin.

both sides were almost parallel with each other and it was possible to reconstruct the original tight condition. Soft weathered material of the wall rock was not sandwiched anywhere in the cracks. Therefore, it can be said that Type D open cracks were formed when the bedrock with potential cracks was deflected toward the open space of the river due to earthquake.

Type E open cracks were found in tuff breccia at the river bed in the bottommost part of the dam foundation. Numerous open cracks were intertwined showing an irregular web pattern with parts of the open cracks which was filled with weathered material of the wall rock and sand-gravel. Consequently, it seems that the Type E were formed by settling rock masses due to earthquake toward gaps. Weathered materials of bedrock filling the cracks were washed away by groundwater agency.

Type F open cracks were found in tuff breccia all over the left bank slope in the vicinity of the spillway stilling basin. These open cracks were in the form of rock masses surrounded by open cracks with parts containing soil deposits that had fallen in. Consequently, it seems that the Type F were formed by creep of bedrock induced by earthquakes.

As described in the foregoing, the open cracks other than Type A had their origins in Type A or potential cracks and were formed due to earthquake, and were caused differently from Type A. The main open cracks in the district are shown in Fig. 4 and Table 1.

IV. CLAY VEINS

Clay veins of various size are commonly observed in the sandy tuff of Shirasawa Formation. The sandy tuff is massive and is composed of volcanic glass, quartz, feldspar, pumice, and clay minerals. The rock is uniform soft with value of unconfined compressive strength of 7 kg/cm^2. The bedding planes measured by carbonaceous bands are roughly N45° to 60°E with dipping of about 10°SE.

About 160 clay veins were recognized at the right bank slope of the dam foundation. These veins were confirmed at outcrops, in adits and on trench excavations. The veins were either concentrated at spacings of about 2 m or with intervals of 20 m or more. As is shown in Fig. 5, orientation of the clay veins is concentrated in the direction of strike N77°E and dip 79°NW. Accordingly, they are roughly perpendicular to the bedding plane of the sandy tuff. The length of the clay veins ranges from several meters to 20 m and the thicknesses are mostly in the range from 1.1 to 5.0 mm as shown in Table 2. In general, those less than 3 mm in thickness consisted of brown clay material, whereas larger ones contained fragments of country rock. Some typical occurrences of these clay veins are shown in Plate e.

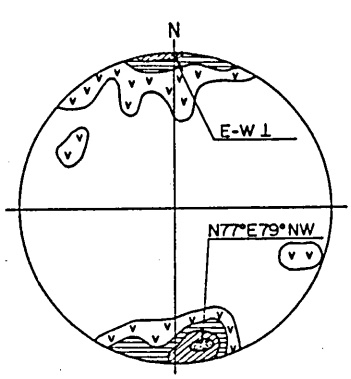

FIG. 5. Distribution frequency of clay vein.

TABLE. 2. THICKNESS FREQUENCY OF CLAY VEIN.

Thickness(mm)	Number	Ratio(%)
Below1.1	26	16
1.1~5.0	47	30
5.1~10.0	30	11
10.1~50.0	45	28
50.1~100.0	8	5
over100.0	3	2
Total	159	100

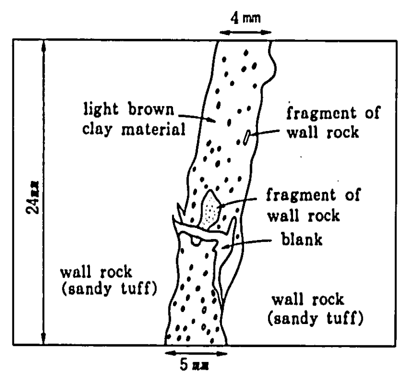

FIG. 6. Schematic illustration of clay vein (No. DRT-6, Exploratory Tunnel). Note that small fragments of quartz or plagioclase are included in the vein. Clear boundary between the clay vein and the wall rock is characteristic.

Fig. 6 shows microscopical occurrences of numerous fragments of quartz and feldspar in light brown fine grained clay material. These mineral fragments are mostly angular, but in some places somewhat rounded fragments are also recognized. Under the polarizing microscope, flow texture is observable in the clay material as shown in Plate d. Signs suggesting shear stress are not recognized at the boundaries between clay vein and wall rock and as well as the clay veins. Characteristics of the clay veins together with the results of X-ray diffraction and electron microscopy are given in Table 3.

Microfossil analyses were made on the bluish gray silt collected at the vicinity of the hamlet of Kitayazi (see Fig. 1) and clay material of veins. The results are given in

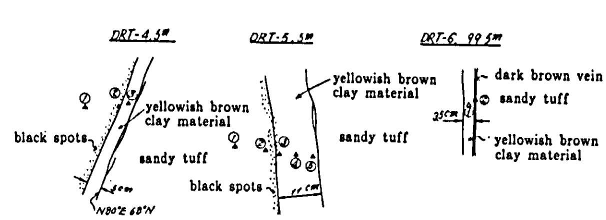

FIG. 7. Schematic illustration showing sampling localities of various clay veins.

TABLE. 3. MINERAL COMPOSITION OF CLAY VEIN AND WALL ROCK.

Specimen No.		No Elutriated	Elutriated	Remarks
DRT-4	1	quartz plagioclase allophane(?)	allophane(?)	Existence of allophane is assumed from the X-ray powder diffraction pattern, although no distinct peaks exist as seen in X-ray diffraction. Under electron microscope, nothing typical seen and close to imogolite.
	2	quartz ※smectite allophane	smectite	
	3	quartz smectite metahalloysite	smectite metahalloysite allophane(?)	Argillization most prominent of all specimens. More smectite than metahalloysite.
	open-ing	quartz smectite	smectite	
DRT-5	1	quartz plagioclase smectite(?)	allophane(?) smectite(?)	
	2	quartz plagioclase allophane(?)	allophane(?) smectite(?) kaolinite(?)	Determination difficult due to small quantity of clay mineral.
	3	※smectite ※kaolinite(?)	smectite metahalloysite allophane(?)	
	4	quartz ※smectite allophane(?)	smectite	
	5	quartz smectite	smectite metahalloysite allophane(?)	
DRT-6	1	quartz ※smectite	smectite metahalloysite halloysite	
	2	quartz plagioclase	allophane(?)	Halloysite with poor crystalline state is observed under the electron microscope. Material suspected to be smectite is existed in part.

Notes : 1. Material marked "allophane(?)" began to present pink color 0.5 to 1 hr. after dropping of phenolphthalein and became bright pink several hrs. to 12 hrs. later.
2. Asterisks(※) indicate the material of low degree of crystallization. Stratification in the C-axis direction is no good.
3. Smectite swells from 16 Å to between 17.5 and 18 Å upon ethylene glycol treatment.
4. All marked "allophane(?)" are not typical and thought to be intermediate between allophane and imogolite.

TABLE. 4. LIST OF DIATOMS.

Species Name	Clay Vein	Bluish Glay Silt
Achnanthes lanceolate (Breb.) Grunow	1	1
Achnanthes microcephala Kuetzing	1	—
Amphora ovalis var. affinis (Kuetz.) V.Heurck	—	1
Cymbella minuta Hiles ex Kabh	3	1
Diploneis ovalis (Hilse) Cleve	—	1
Eunotia exigua (Breb.) Grunow	9	1
Eunotia pectinalis var. minor (Kuetz.) Rabenhorst	—	1
Eunotia praerutpa Ehrenberg	1	—
Eunotia veneris (Kuetz.) De Toni	—	1
Fragilaria brevistriata Grunow	2	3
Fragilaria construens var. venter (Ehr.) Grunow	—	1
Fragilaria elliptica Schumann	2	12
Fragilaria lapponica Grunow	3	4
Fragilaria leptostauron var. dubia Grunow	—	2
Fragilaria pinnata Ehrenberg	3	6
Fragilaria pinnata var. lancettula (Schum.) Hustedt	—	3
Fragilaria virescens Ralfs	1	—
Gomphonema angustatum var. producta Grunow	2	1
Gomphonema lingulatum Hustedt	1	—
Hantzschia amphioxys (Ehr.) Grunow	—	1
Melosira cf. distans (Ehr.) Kuetzing	23	52
Melosira gulanylate (Ehr.) Ralfs	27	16
Melosira gulanylate var. angustissima Muller	—	6
Melosira italica (Ehr.) Kuetzing	3	5
Meridion circulae Agardh	1	—
Navicula clementis Grunow	—	2
Navicula cocconeif ormis Gregory	1	—
Navicula contenta Grunow	5	—
Navicula contenta fo. biceps (Arnott) Hustedt	5	—
Navicula contenta fo. parallela (B.Petersen) Hustedt	2	—
Navicula pseudoscutiformis Hustedt	—	2
Neidium iridis (Ehr.) Cleve	—	1
Pinnularia subcapitata Gregory	2	—
Rhoicosphenia curvata (Kuetz.) Grunow	—	1
Rhopalodia gibberula (Ehr.) O.Muller	1	—
Synedra parasitica (W.Smith) Hustedt	1	—
Synedra rumpens Kuetzing	1	—
Tabellaria flocculosa (Roth) Kuetzing	—	1
Marine Water Species	0	0
Marine to Brackish Water Species	0	0
Brackish Water Species	0	0
Fresh Water Species	101	126
Total Number of Diatoms	101	126

Tables 4 and 5. As is shown in Table 4, diatom fossils indicate lacustrine sedimentary environment. On the other hand, pollen fossils (Table 5) did not exist in the clay veins at all, but only in the bluish gray silt. Color of clay veins are brown as the result of advanced weathering,

TABLE. 5. LIST OF POLLENS.

Name	Clay Vein	Bluish Glay Silt
Abies	—	20
Tsuga	—	15
Picea	—	11
Larix—Pseudotsuga	—	14
Pinus subgen. Haploxylon	—	10
Pinus (Unknown)	—	6
Salix	—	1
Juglans	—	1
Betula	—	1
Alnus	—	19
Quercus subgen. Lepidobalanus	—	1
Rosaceae	—	1
Polygonum sect. Reynoutria	—	1
Thalictrum	—	2
Umbelliferae	—	1
Artemisia	—	3
Carduoideae	—	1
Unknown	—	1
Lycopodium	—	9
Osmunda	—	1
other Pteridophyta	—	14
Arboreal pollen	0	100
Nonarboreal pollen	0	8
Unknown	0	1
Fern spores	0	24
TOTAL	0	133

and by this process pollen fossils might had been destroyed.

Thus, it may be concluded that the clay veins have been formed by filling with fine grained clay material of weathered rock transported from the bottom of a lake through the existed fissures. Suspended micro-organisms in the lake water together with fragments of sandy tuff and rock forming minerals were also derived from the same lake.

V. FRACTURES IN SANDY TUFF CAUSED BY EARTHQUAKE

The locations where fractures produced by the Miyagi-ken-oki earthquake were as follows.

(1) The whole area of the right bank from the upper part of the slope to the peak.

(2) The vicinity of the right bank relocated road shoulder.

(3) The surface of the unexcavated table.

(4) The interior of a test adit (DRT-6).

(5) A single fracture of maximum width of 5 cm running approximately 60 m in the upstream direction on the surface of relocated road at the right bank, on the upstream side of the unexcavated table(see Plate b).

Of these, the fractures of (1), (2), and (3) were accompanied with height difference between their two sides. At the tops of slopes, the tops had sagged down toward the road, and at the mountainside bulging had occurred. All of the fractures were extremely crooked. Based on these features, it can be concluded that the fractures of (1), (2), and (3) were due to creep movement of surface layers of slopes caused by the earthquake. The fractures of (4) and (5), however, were different from those due to creep movement. This fracture (5) was filled with neat cement grout. Later, the downward continuity was investigated by a large number of diagonal boreholes drilled from the surface of the road toward the filled fracture. The result clarified that the fracture was roughly vertical going down 14 to 15 m from the surface.

There were several geological exploration adits in the sandy tuff, and so far as the investigations in these adits were concerned, there were several open cracks less than 1 mm in width that had not become clay veins. Five years had elapsed at the exploratory adits after excavation until the Miyagi-ken-oki Earthquake, but the condition of the open cracks had remained unchanged from the time of excavation of the adits, and they had not been closed. Consequently, at least in a 5-year time span there was no autogenous healing action of the fractures. Since springing of water from these small open cracks was not seen even when it rained, the cracks might not continue to the ground surface. Consequently, these small open cracks were thought not to be earthquake-induced fracture, but fractures that had been produced at the same time as the formation of clay veins. Accordingly, it may be considered that there had not been autogenous healing action for closure of the fractures in the sandy tuff even during a long period of time. Therefore, only several small fractures with width of less than 1 mm and those produced by the Miyagi-ken-oki Earthquake were penetrating deep into the sandy tuff body. In addition, no fractures had been produced in the past earthquakes.

VI. BEHAVIOR OF GEOLOGIC BODIES UNDER PALEOSTRESS FIELD

A. ORIGINAL FRACTURES OF TYPE A AND CLAY VEIN

It has been stated previously that open cracks other than Type A had been formed by earthquake relating to Type A or potential very small fractures, and not due to crustal stresses. However, the fractures that are the origins of Type A are not simple cracks but has fairly complex structures. They are not formed by simple rupturing but have been produced by crustal stresses.

Based on the characteristic mode of occurrence and the zonal distribution in the N72°W direction of type A open cracks as well as on the slightly curved smooth lines of the fractures, it may be concluded that the original fractures of Type A were formed by shear stress under a high confining pressure of a considerable load. Stress which causes fractures in soft rock without lateral movement is tensile stress. But the facts that the clay veins had the prominent trend of N77°E 79°NW, and a large number of clay veins are arranged in parallel in a broad area, cannot be explained by simple tension. Therefore, the original fractures of clay veins have been formed under the paleostress field as extension joints which have grown gradually to the open cracks.

Under the same paleostress field, shear fractures were formed in tuff breccia and extension fractures in sandy tuff. The difference in confining pressures when these two kinds of fractures were formed may correspond to thickness of approximately 30 m of stratum, i.e., the value is well coincide with the sandwiched stratum between the two rocks, as shown in Fig. 3.

The unconfined compressive strength of the tuff breccia is 70 kg/cm^2 as mentioned previously, while that of the sandy tuff is 7 kg/cm^2. Such slight difference in confining pressure and mechanical strength were the main reason why shear fractures were formed on the one hand and extension cracks on the other.

B. ANGLE OF INTERNAL FRICTION OF TUFF BRECCIA

The direction of the maximum principal compressive stress caused the extension fractures in the sandy tuff should coincide with the direction of the strike of clay veins. The direction, as shown in Fig. 5, is N77°E. On the other hand, the original fractures of Type A open cracks in the tuff breccia were produced by shear resulting a zonal concentration of open cracks in the direction of N72°W. The relation between the two directions is shown in Fig. 8. Since the direction of strike of the clay veins coincides with the maximum principal compressive stress axis, the angle of internal friction ψ of the tuff breccia will be

$$\psi = 90° - 2\theta = 28°$$

where, θ is the angle between the shear plane and the maximum principal compressive stress axis.

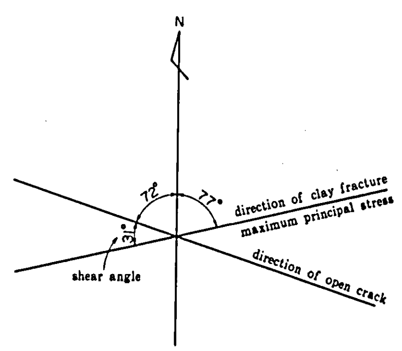

FIG. 8. Orientation relations between open crack and clay fracture.

C. AGE OF PALEOSTRESS FIELD

After the formation of original fractures of the Type A open cracks, the following process should have proceeded.

(1) Uplift movement and erosion of ground surface.

(2) Progress of weathering along fractures.

(3) Washing out of weathered material by ground water.

The entire duration of the Quaternary Period up to the present is probably required for such a process to take place. The fact that the direction of the clay-vein is perpendicular to the bedding plane suggests that these fractures have produced before inclination of the entire dam foundation roughly 10° to the southeast, as shown in Fig. 3.

The strata shoud be horizontal when the clay-vein fractures were produced and the direction of the maximum prinipal stress axis at that time was parallel to the clay-vein fractures, and was horizontal. In the same way, the direction of the minimum principal stress axis at that time would have been perpendicular to the clay-vein fractures, and was also horizontal. The intermediate principal stress axis was in th direction of gravity. If the direction of gravity coincides with the direction of minimum principal stress, the clay-vein fractures may have been prouduced horizontally. Consequently, when the clay-vein fractures formed, considerably thick strate should overlie the sandly tuff to act as a top road (see Fig. 9). Until the present topography has formed, a considerable long period such as whole Quaternary may be required because the thick sediments should be eroded out by weathering. Thus, it is concluded that acting stage of the compressinvė stress formed the original fractures of the open cracks and clay veins is at the late Tertiary.

VII. Behavior of Geologic Bodies Under Groundwater Environment

By erosion agency, the strata overlain the sandy tuff were removed from the surface, and a fresh-water lake was formed on the eroded surface. The diatom fossils found in the clay veins are of identical to the diatom fossils in the silt distributed in the vicinity of the Kitayaji hamlet (see Fig. 1) approximately 70 m higher than the dam site. All of these fossils are fresh-water lacustrine species and no marine species is found. Consequently, the clay materials suspended in ground water were transported from the bottom of the lake existed in the vicinity of the Kitayaji hamlet into the extension fractures in the sandy tuff. Micro-organisms in the lake water were also transported together with clay materials and rock fragments of sandy tuff flowing into fractures. The ground water went down further into the Yumoto formation of about 30 m thickness, i.e., through the alternations of tuffaceous sandstone and mudstone, and the thin layers of tuff, tuff breccia, and tuffaceous sandstone and finally reach the underlying tuff breccia (see Fig. 3). To be noted is that a fracture zone in the tuff breccia have received the erosion agency of the ground water. The fine grained soft material in the fractures was removed by ground water together with the surface water passing through the sandy tuff resulting the fractures changes to open cracks.

In such a manner, ground water has played the most important role for the formation of clay veins in sandy tuff on the one hand and in the tuff breccia open cracks have formed on the other.

VIII. Consideration

A. Original Fractures of Type A Open Cracks

In spite of detailed observations in many exploratory drills, none of the significant evidence for the cause of cave-in was found. The open cracks occurred as a zone with an orientation of N72°W, and no evidence indicating lateral movement as the cause of the fractures in the overlying strata of the tuff breccia was confirmed. Furthermore, any movement under high confining pressure at the time of crack occurrence is not conceivable. Therefore, formation process of the open cracks can not be explained only by simple tension. That is, the fact of a single arrangement of the open cracks can not be reasonably explained by extension. Consequently, the original fractures of Type A open cracks can not be considered to have been formed by simple tension or extension.

Furthermore, it is impossible for any stress that has caused shear fractures only in the intermediate tuff breccia and not in the overlying rocks including the sandy tuff and the underlying rocks including the tuff. Shear stresses have acted on all of the strata in the district, but depending on the differences of the physical properties of the respective rocks the way of fracturing is completely different.

B. Formation Process of Clay Veins

The facts that clay veins show certain preferred orientation and the geologic structure dips toward the right bank with a gentle angle of around 10° suggest that the original fractures of clay veins are not produced by lateral movement such as shrinkage and rock slides. One possibility is that the fractures may have produced by movement of bedrock by earthquakes. However, by the Miyagi-ken-oki Earthquake, fractures were formed only in sandy tuff. That is, formation of the fractures of (4) and (5) with character of almost vertical extending to 14 to 15 m depth, was a very special phenomena.

The reason is probably due to the difference of the environmental condition between past earthquakes and the Miyagi-ken-oki Earthquake. The main differences are 1) the sudden relief of stress due to removal of the great amount of load through excavation for construction of the relocated road, and 2) the characteristic configuration of the ground surface formed as a result. With overlapping of these conditions, initial fractures were opened along clay veins by the earthquake and not to have been restored to their former states because of the plastic deformation. Therefore, the original fractures for the clay veins were not formed by lateral movement of the bedrock caused by earthquake.

Detailed geological reconnaissance of an area of approximately 40 km^2 in the vicinity of the Nanakita Dam site have revealed no features indicating thermal effects in the various rocks so that warping due to intrusion of igneous rocks is not conceivable. Fault system caused by intrusion of igneous rock as pointed out by Withjack (1979) is not found in the investigated area. Evidence of folding is not confirmed even at the boundary of various geologic units as shown in Figs. 3 and 9. Although clay veins are commonly distributed in the surveyed area, it could not be a main reason of the ground cave-ins lie latent underground in such a broad area.

C. Paleostress Field and Behavior of Geologic Bodies

Although it is not easy to differentiate shear fractures and extension fractures (Hirano, 1971), the two were distinguished at the foundation of Nanakita Dam. That is, shear fractures in tuff breccia and extension fractures in sandy tuff have been confirmed as the result under the same compressive stresses. The direction of the maximum principal compressive stress axis is N77°E, and the direction roughly coincides with Takeuchi's (1981) P type

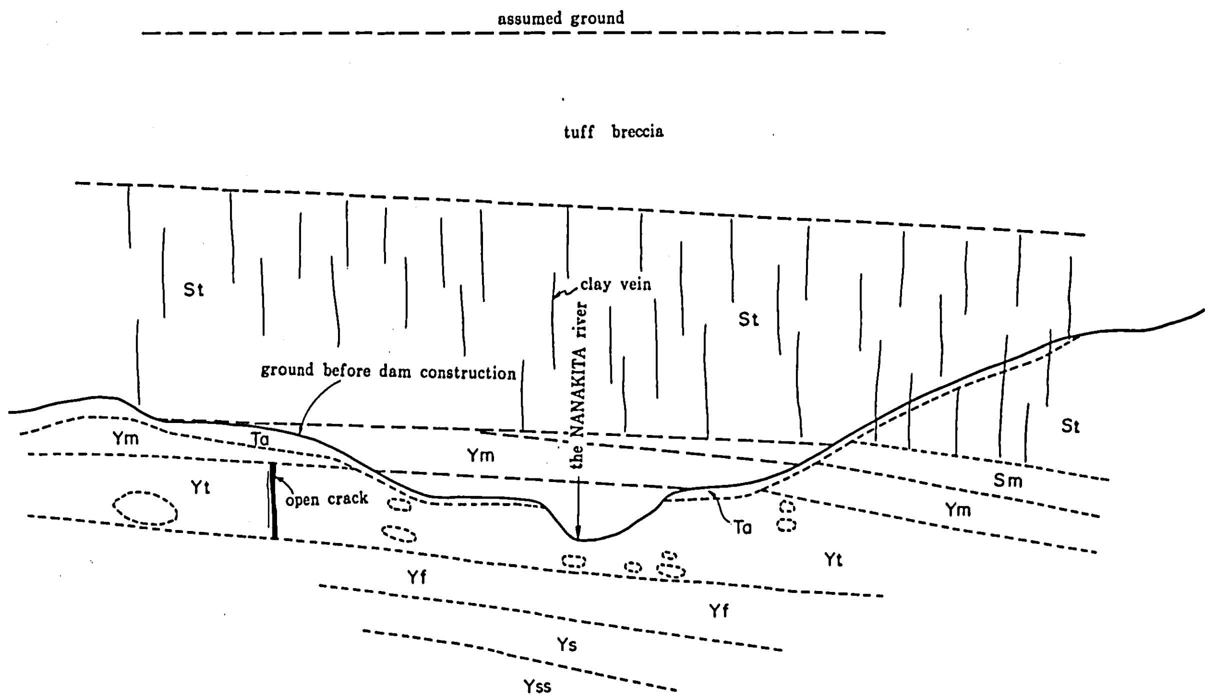

FIG. 9. Assumed paleo-geological cross section along dam axis. Abbreviations are the same as those of Fig. 3.

stress field with E-W compressive axis at the period from the latter half of the late Miocene to the Pliocene.

Even under the same conditions such as temperature and hydrostatic pressure, each lithologic body with different characters is deformed differently. Similarly, the same rock will be deformed differently under different conditions (Kimura, 1973). In addition, one geologic body behaves differently under stresses depending on age, region, and furthermore, depth of burial (Koide et al., 1971). In case of brittle failure, tension fractures appear in the direction of the compressive stress axis under normal pressure or small confining pressure. When confining pressure is increased, shear fractures appear. With increasing confining pressure, the failure angle becomes larger and compressive strength also increases (Murai, 1971; Patterson, 1958). The fact that extension fractures are developed in sandy tuff of which confining pressure is small, and shear fractures in tuff breccia whose confining pressure is large, explains well the above-mentioned theories. As confining pressure increases, rupture angle becomes larger and internal friction angle becomes smaller. Since the internal friction angle of the tuff breccia of 28° was a value at a large confining pressure, it should be larger at the present since there is no longer any confining pressure.

D. CLAY MATERIAL FLOWING INTO FRACTURES

Concerning filling mechanism of the fractures in rock masses, Hayashi (1966) discussed clastic dikes in various parts of Japan, and Mii (1953) and Kutsuzawa et al. (1967) clastic dikes in the Sendai district. The constituent materials of these clastic dikes comes from the strata lower than the clastic dikes. Such clastic dikes described by Mii (1953) and Kutsuzawa et al. (1967) were confirmed during construction of the dam. However, the clay vein was different from the clastic dikes originating in the underlying strata, and there was no underlying stratum of the same materials as those in the clay veins.

The rounded rock fragments intermixed with the clay materials are sandy tuff of the wall rock, and in addition, fragmental quartz and feldspar are also derived from the wall rock of sandy tuff. Allophane is also identical to that contained in the wall rock of sandy tuff. In some parts, lenticular wall rock arranged in parallel with each other is contained in thick clay veins. During formation process of the extension fractures, the walls of the fractures were spalled off resulting the present structure. Veins within veins were also formed.

IX. SUMMARY

A considerable number of open cracks and clay veins as well as fractures formed by the earthquake were found at the foundation of the Nanakita Dam, which caused exceedingly severe problems for the dam construction. The formation processes of these open cracks and clay veins were presented in this paper. Based on the results obtained, proper treatments have been performed during the dam construction (Civil Department Miyagi Prefecture, 1985). The main results are summarized in the following.

(1) Fractures in tuff breccia are shear fracture whereas fractures in sandy tuff are extension fracture. Both fractures have been formed under the same paleostress field.

(2) Analyses of the formation mechanisms of these fractures and subsequent development of open cracks and clay veins suggest that the related paleostress field is that of late Tertiary.

(3) The direction of the principal compressive stress axis of the paleostress field is estimated horizontal and N77°E, which roughly coincides with that of the P type of Takeuchi (1981) with E-W compressive axis of late Miocene to Pliocene age. The internal friction angle

of the tuff breccia determined from the direction of the paleostress field is 28°.

(4) Under the same paleostress field, shear fractures were formed in the tuff breccia while extension fractures in sandy tuff. The difference is mainly ascribed to the difference of confining pressure and mechanical strength of the respective rocks, i.e, high confining pressure and mechanical strength of the tuff breccia.

(5) The fractures formed by the Miyagi-ken-oki Earthquake are ascribed mainly to the sudden relief of stress in relation to the excavation during the dam construction. No fractures have been formed in previous earthquakes.

(6) The shear fractures in tuff breccia were transformed to open cracks as the result of groundwater action, while the extension fractures in sandy tuff became later to clay veins by filling with weathered materials. That is, the sandy tuff situated closer to the surface and played a role of the first filter against lake water. The difference of the two rocks in lithologic character against weathering played also an important role.

The Nanakita Dam has been completed after proper foundation treatments and has demonstrated normal functions during the past four years. Since the completion of the dam, none of the problems such as abnormal leakage or instability have occurred.

References

Civil Department Miyagi Prefecture, Sendai Hokubu Dam Construction Office (1985): Construction recod of Nanakita Dam (in Japanese). 1–626.

GZOVSKII, M. V. (1954): Tectonic stress-field (in Russian). Izvestia Akad. Nauk. SSSR, Ser. Geophys., 5, 390–410.

HAYASHI, T. (1966): Clastic dikes in Japan (1). Jap. Jour. Geol. Geogr., 37, 1–20.

HIRANO, M. (1969): Joint system of the Rokko mountain range, Tectonic of uplifting massif in the Kinki district, Japan (1). Jour. Geosci. Osaka City Univ., 12, 25–44.

——— (1971): Problems related to brittle fracture in plutonic rock with special reference to joints in granitic rocks of the Rokko Mountains (in Japanese). Jour. Geol. Soc. Japan, 77, 257–263.

HIRAYAMA, J., and KAKIMI, T. (1965): An analytical method for determination of tectonic stress-field and its applications (in Japanese). Earth Science, 78, 23–31.

HOSHINO, K. (1965): Fracture system and natural gas occurrence in the Joban Coal-Field. Geol. Surv. Jap. Rep. 210, 1–36.

KAKIMI, T. HIRAYAMA, J. and KAGEYAMA, K. (1966): Tectonic stress-fields deducted from the minor fault system in the northern part of the Miura Peninsula (in Japanese). Jour. Geol. Soc. Japan, 72, 469–489.

KIMURA, G. (1980): Analysis of joint systems and mechanism of folding in the Futamata area, eastern Hokkaido, Japan. Jour. Geol. Soc. Japan, 86, 105–118.

KIMURA, T. (1973): Deformation and geologic structure of rock, on the Stockwerkbau specially (in Japanese). KAGAKU, 43, 738–744.

KINUGASA, Y., KAKIMI, T. and HIRAYAMA, J. (1969): The minor-fault systems on the coastal area of the eastern Boso Peninsula (in Japanese). Bull. Geol. Surv. Japan, 20, 13–38.

KITAMURA, N. (1943): Geological Map of Miyagi Prefecture. Naigai Map Co., Ltd.

——— (1962): Preliminary report on systematic jointing in the Taishu Group developed in Mitsushima-cho, Tsushima island, Japan. Tohoku Univ. Sci. Rep. 2nd Ser. (Geol.), Spec. vol., 303–319.

KOBAYASHI, Y. and NAKAMURA, K. (1978): Restraction of tectonic stress field of Tertiary southwest Japan by means of dikes. Intern. Geodyn. Conf. Tokyo, 86–87.

KOIDE, H. HOSHINO, K. INAMI, K. IWAMURA, S. and MITSUI, S. (1971): Variation of mechanical properties of Tertiary sedimentary rocks in Japan (in Japanese) Jour. Geol. Soc. Japan, 77, 327–334.

KODAMA, K. (1968): An analytical study on the minor faults in the Jogashima Island (in Japanese). Jour. Geol. Soc. Japan, 74, 265–278.

KUTSUZAWA, A. and FUJITA, Y. (1967): Genesis of clastic dikes and planeless faults in the Miocene Deposits of the Sendai district, Studies on Faults at the Boundary of Sedimentary Basins (2) (in Japanese). Jour. Geol. Soc. Japan, 73, 19–34.

MII, H. (1953): Clastic dikes in the Akyu Group in the western hilly region of Sendai. Short Papers, IGPS, 5, 51–66.

MITSUI, S. (1971a): Studies on the mechanism of deformation of sedimentary rocks in the Iwaki area of the Joban Coal-Field, Fukushima Prefecture. Tohoku Univ. Sci. Rep. 2nd Ser. (Geol.), 42, 199–272.

——— (1971b): Rock deformation and geologic structure-Shear fractures in the Iwaki areas of the Joban coal-field (in Japanese). Jour. Geol. Soc. Japan, 77, 265–271.

MURAI, I. (1971): Some problems in structural analyses based upon fracture systems (in Japanese). Jour. Geol. Soc. Japan, 77, 249–254.

NAKAMURA, I. and UI, T. (1975): Problems of restoration of tectonic stress field by the dike group (in Japanese). GDP Connection Paper, 3, 75–82.

PATTERSON, M. S. (1958): Experimental deformation and faulting in Wombeyan marble, Geol. Soc. Am. Bull., 69, 465–476.

SHIBATA, T. (1962): Geology of the Sendai and Nanakita - Sanbongi Area, Miyagi Prefecture. Sci. Rep. Tohoku Univ., 2nd Ser., (Geol.), 34, 239–321.

TAKEUCHI, A. (1979): Stress field and tectonic process during the Neogene and later period in the northern part of Nagano Prefecture, central Japan (in Japanese). Jour. Geol. Soc. Japan, 83, 679–691.

——— (1978): The Pliocene stress field and Tectonism in the Shin-Etsu region, central Japan, Jour. Geosci. Osaka City Univ., 21, 37–52.

——— (1981): Temporal changes of regional stress field and tectonics of sedimentary basin (in Japanese). Jour. Geol. Soc. Japan, 87, 737–751.

YOKOTA, S. (1974a): Analytical studies of the joint systems in the Konan Mountain area (Konan Alps), Shiga Prefecture. Jour. Geol. Soc. Japan, 80, 205–214.

——— (1974b): Surface deformation of a fault block, brittle fracturing and viscous flow in tectonic movements (1). Jour. Geosci. Osaka City Univ., 17, 87–98.

WITHJACK, M. (1979): An analytical model of continental rift fault patterns. Tectonophysics, 53, 59–81.

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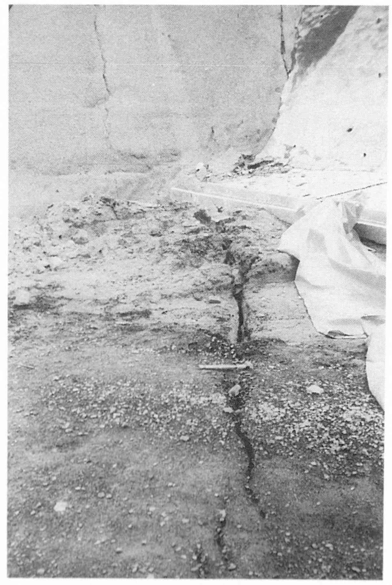
EXPLANATION OF PLATE

a. Vertical open crak with about 20 cm width (upper middle part of the photo) is clearly observed only in the tuff breccia. It should be noted that the boundary between the upper tuff breccia and lower tuff is almost horizontal, and development of vertical cracks in the lower tuff.
b. Fracture formed by the Miyagi-ken-oki earthquake.
c. Type A open crack (No. 13).
d. Microphotograph of clay material. Note that the intersti-tial spaces between quartz and feldspar are filled by clay material and are arranged in certain flow direction.
e. Clay veins in sandy tuff. Note that the numbered vertical fractures have been formed by rainfall action, which washed out the preexisted clay materials, i.e. clay veins.

a



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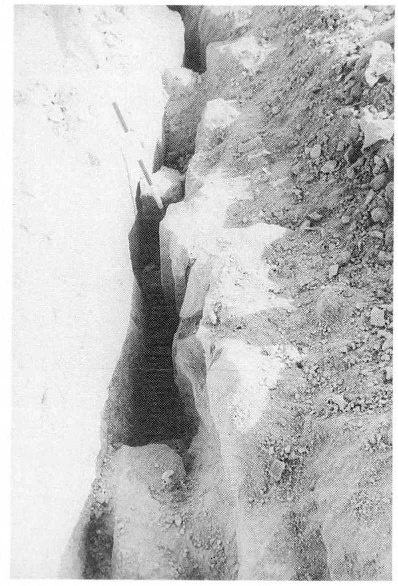

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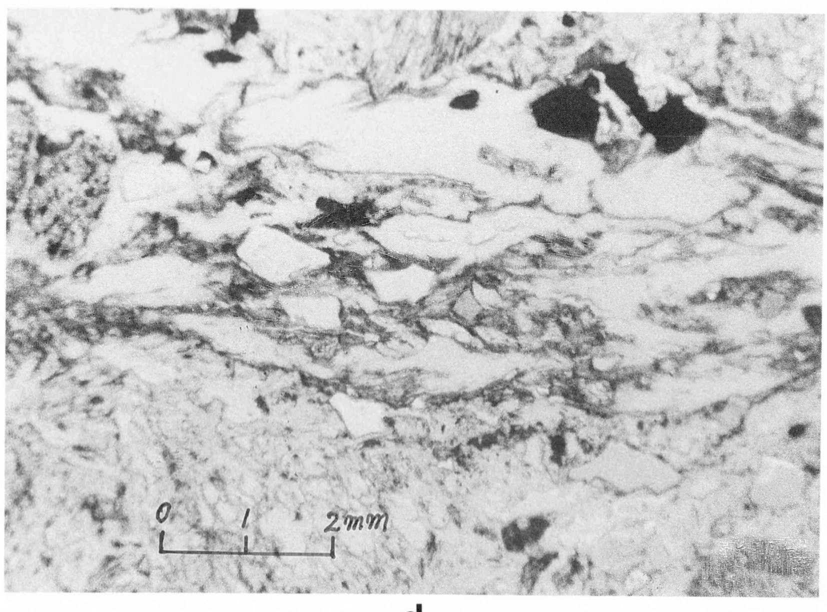

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