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SAFETY ASSESSMENT OF A CONCRETE GRAVITY DAM BASED ON SEISMOGRAPHIC RECORDS IN THE CHUETSU EARTHQUAKES

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Foreword

A dam shall maintain its water storage function even in case of a severe earthquake, so acceleration and displacement of a dam body caused by an earthquake are observed in order to assess the safety of a dam at any time.

The Chuetsu earthquakes began on October 23, 2004. The main earthquake shock is estimated at the magnitude of 6.8. A seismographic station near the seismic center recorded the maximum value of 1,500 gal and 130 kine. After the main earthquake shock, there were several strong aftershocks. Hereinafter, the main earthquake and aftershocks of the Chuetsu earthquakes are referred to as "the earthquakes." The earthquakes caused major damage to many embankments and concrete structures.

There are some J-POWER's dams around the seismic source as shown in Figure-1, however, none of them suffered damage from the earthquakes. Among them, the Tagokura Dam lies 20 to 30 km from the source of the major earthquake shocks. Dimensions of the dam are as shown in Table-1. Earthquakes have been observed since the dam was completed in 1959. The seismometer set up on the crest recorded the maximum acceleration of 600 gal at the aftershock of 10:40 on October 27 as shown in Table-2.

Table-1 Dimensions of Tagokura Dam

Reservoir	River	Tadami
	Effective storage capacity	370 million m^3
	HWL	EL.510 m
	LWL	EL.458 m
	Available drawdown	52 m
Dam	Type	Concrete gravity
	Height	145 m
	Crest length	462 m
	Dam volume	1.962 million m^3
	Crest width	9 m
	Crest EL.	515 m
	Upstream slope	>EL.420m vertical <EL.420m 1:0.2
	Downstream slope	1:0.82
	Foundation	rhyolite and tuff
Power-house	Effective head	105 m
	Max. discharge	420 m^3/sec
	Output	380 MW

In relation to the dam response during the earthquakes, the three-dimensional (3-D) dynamic analysis is made for actual earthquake behavior of dams during earthquakes to evaluate the values of dynamic shear modulus and the damping factor of dams and foundations, and those stability and durability against severe earthquakes are assessed. Such 3-D dynamic analysis for the actual earthquake behavior of existing dams can be made by combining between the earthquake observation at the dam site and the accurate 3-D analysis method.

Table-2 Major Earthquakes Characteristics and Responses Observed at Tagokura Dam during Chuetsu Earthquakes (2004)

Acceleration gal

	Number		1	2	3	4	5	6	7	8	9	10
Earthquake	Date		10/23	10/23	10/23	10/23	10/23	10/23	10/23	10/23	10/23	10/23
	Time		17:56:00	17:59:36	18:03:13	18:07:31	18:11:57	18:34:06	18:36:51	18:57:26	19:36:46	19:45:37
	Depth	km	13.1	15.7	9.4	14.9	11.5	14.2	7.4	7.5	11.0	12.3
	Distance	km	37.4	30.3	27.4	37.7	41.1	31.7	31.4	39.4	42.5	36.6
	Focal distance	km	39.6	34.4	28.9	40.6	42.7	34.8	32.3	40.1	43.9	38.6
	Magnitude		6.8	5.3	6.3	5.7	6.0	6.5	5.1	5.3	5.3	5.7
	JMA Intensity		7	5-upper	5-upper	5-upper	6-upper	6-upper	5-lower	5-upper	5-lower	6-Lower
Max. response acceleration	Dam crest EL515m	Stream	454.9	72.0	336.1	45.5	108.6	457.9	171.0	126.0	47.6	120.0
		Damaxis	183.8	22.1	107.3	21.7	30.0	145.8	39.7	26.2	6.6	42.4
		Vertical	219.6	24.0	144.0	20.0	71.7	172.6	73.0	37.2	13.2	49.[illegible]
	Foundation gallery EL399m	Stream	89.7	12.9	35.1	11.3	18.4	66.5	16.3	13.6	4.3	11.9
		Damaxis	102.5	10.2	32.0	9.4	23.0	45.9	15.3	6.9	2.1	13.[illegible]
		Vertical	79.1	9.0	32.2	8.1	20.3	74.8	15.6	8.5	3.9	12.0

Acceleration gal

	Number		11	12	13	14	15	16	17	18	19
Earthquake	Date		10/23	10/24	10/25	10/25	10/27	11/4	11/8	11/10	12/28
	Time		19:48:[illegible]	14:21:35	0:28:08	6:04:59	10:40:50	8:57:30	11:15:55	3:43:09	18:30:37
	Depth	km	14.1	11.6	10.1	15.2	11.6	18	0	4.6	8.1
	Distance	km	40.104	41.462	38.697	30.288	22.707	35.6	24.695	26.262	27.094
	Focal distance	km	42.6806	43.0273	40.1772	33.6889	25.4984	39.8028	24.695	26.6447	28.2201
	Magnitude		4.4	6	5.3	5.8	6.1	5.2	5.9	5.3	5
	JMA Intensity		5-lower	5-upper	5-lower	5-upper	6-lower	5-upper	5-upper	5-lower	5-lower
Max. response acceleration	Dam crest EL515m	Stream	120	12.65	93.69	277.47	600.21	162.76	140.24	61.64	37.93
		Damaxis	42.37	27.43	19.68	81.34	185.97	67.47	38.24	21.67	19.68
		Vertical	49.11	41.56	27.83	104.1	285.77	81.6	43.27	19.83	19.45
	Foundation gallery EL399m	Stream	10.7	2.102	8.628	38.11	72.01	17.09	17.41	9.72	7.259
		Damaxis	9.69	0.927	4.389	61.49	116.07	14.49	16.67	9.84	6.307
		Vertical	9.67	1.284	6.349	38.34	82.04	16.79	16.74	7.162	8.49

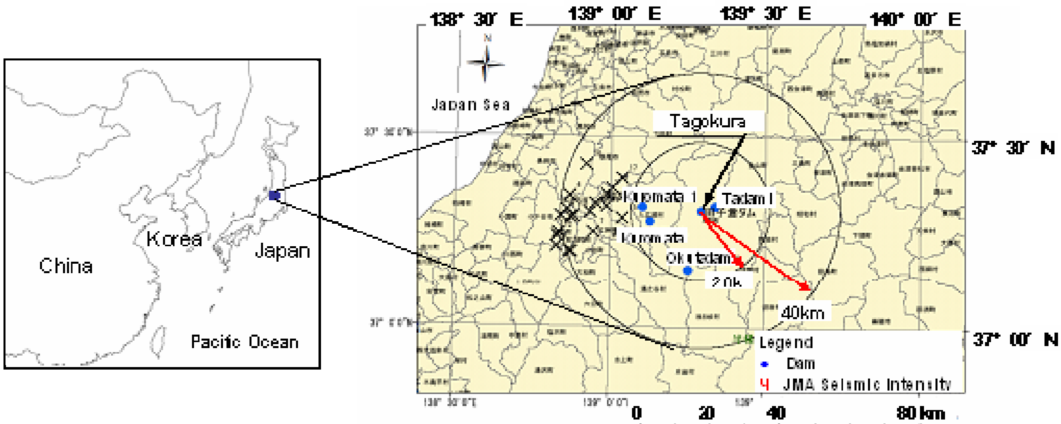
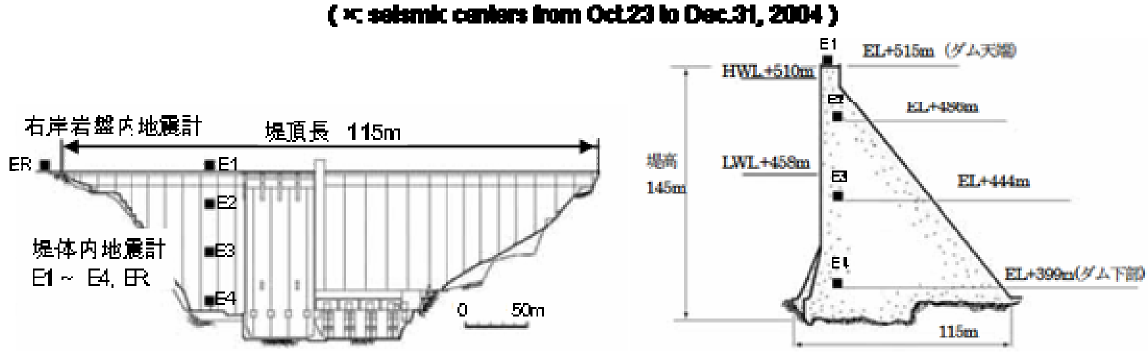


Figure-1 Location of Tagokura Dam and Seismic Centers of Chuetsu Earthquakes
(×: seismic centers from Oct.23 to Dec.31, 2004)



a) Downstream front　　　　b) Transverse section

Figure-2　　Typical Section of Tagokura Dam and Location of Seismometers(■ mark)

This report states a dynamic response of a concrete gravity dam under a severe earthquake and assesses dam safety by observed responses of the dam and dynamic analytical results.

Characteristics of the Tagokura Dam

Geology

The foundation of the dam consists of sound rhyolite and tuff ranges in the other part. Elastic wave investigation records state that the dam foundation has elastic velocity of 3.0 to 4.2 km/sec and elastic modulus of 19,500 to 38,200 MPa before foundation treatment, and 4.2 to 4.5 km/sec and 34,700 to 43,800 MPa after treatment.

Measurement

Displacement of the dam has been measured by plumb lines, and pore pressure and quantity of water leakage of the dam foundation and seismic acceleration have also been measured.

Seismometers are installed to measure acceleration perpendicular and parallel to the dam axis, and in a vertical direction at the location as shown in Figure-2.

Seepage water from drain holes and transverse joints is collected in an inspection gallery and measured as quantity of water leakage of the dam by a triangle weir. Weirs are installed at two locations to measure quantity of water leakage of the part higher than EL.399 m and lower than it.

Figure-3 shows the reservoir water level in the past five years. The reservoir water level when the earthquakes occurred was a few meters lower than HWL.

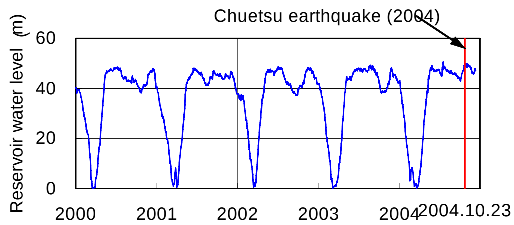


Figure-3 Reservoir Water Level of Recent 5 Years

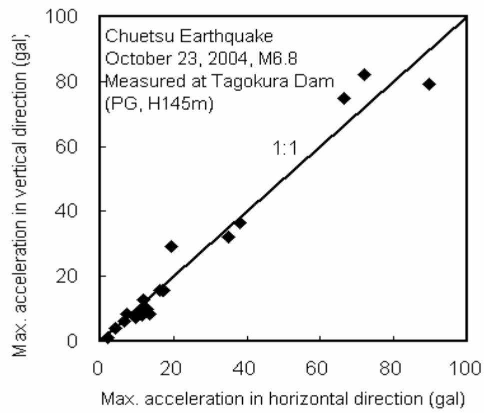


Figure-4 Seismometer Record (EL399m) at E4 Location

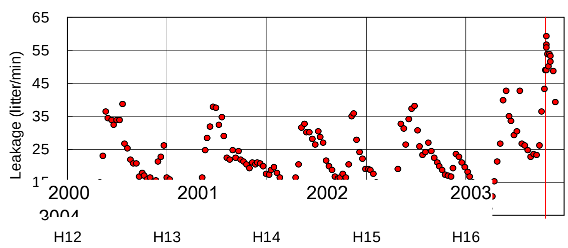


Figure-5 Quantity of Water Leakage of Tagokura Dam

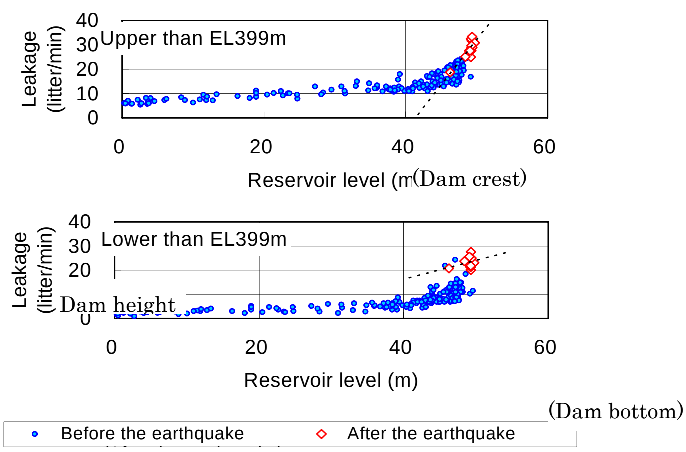


Figure-6 Water Leakage Record

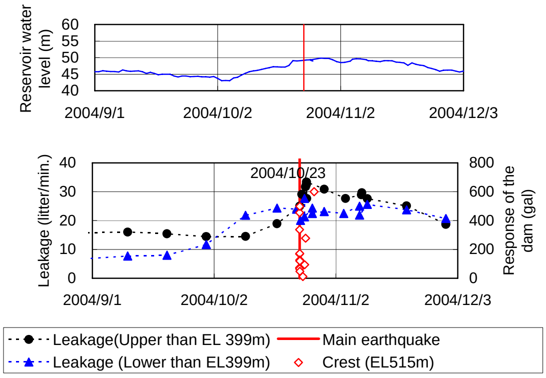
Measured Records of the Earthquakes

Acceleration

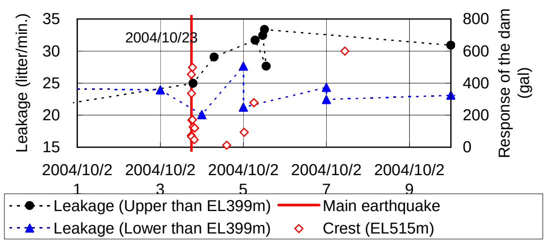
Figure-4 compares seismic acceleration perpendicular to the dam axis and in a vertical direction observed at the dam base, which shows that acceleration is almost the same in both the directions. The dam recorded the maximum response acceleration of 600 gal at the crest, E1, at the aftershock of a magnitude 6.1 at 10:40, October 27, 2004, and 73 gal at the lowest location, E4. This aftershock was not the highest class among the aftershocks of the earthquakes, however, it caused relatively large response acceleration in the dam because it occurred nearest the dam.

Water leakage

Figure-5 shows a change in quantity of water leakage of the dam. Quantity of water leakage of the dam has the same seasonal cycle as the fluctuation of the reservoir water level as shown in Figure-3, which means that the quantity of water leakage originates in seepage water through the foundation of the dam. Figure-5 shows that the quantity of water leakage decreases significantly in the latter half of each year though a change in the reservoir water level is low, and it is considered to be related with deformation of the dam body caused by a change in temperature of the downstream surface. Figure-5 also shows that the quantity of water leakage increases temporarily just after the main earthquake shock and it returns quickly to the usual quantity.



a) Reservoir water level and quantity of water leakage



b) Enlargement of a)

Figure-7 Quantity of Water Leakage of Tagokura Dam

Figure-6 shows relations between the reservoir water level and quantity of water leakage. The figure shows that a change in quantity of water leakage of the part higher than EL.399 m is divided into two at about EL.500 m, about 50 m from LWL, as a boundary; a part where quantity of water leakage increases gradually and rapidly.

Figure-7 shows changes in quantity of water leakage before and after the earthquakes and response acceleration of the dam. Figure-7 shows that quantity of water leakage increases significantly just after the main earthquake shock but returns gradually to the usual quantity within one and half months. The quantity of water leakage also increases a little at aftershocks.

Those tendencies show that quantity of water leakage changed with the earthquakes.

Displacement

Displacement of the dam is evaluated with relative displacement from a reference point fixed on an inspection gallery of EL.390 m. Displacement of the dam has been measured at EL.399 m, 429 m, 444 m, 486 m and 516.2 m, the crest of the parapet at the dam crest.

Figure-8 shows changes in displacement of the dam and the figure shows that the displacement has a seasonal cycle. The reservoir water level goes down from HWL to LWL and returns to HWL in winter, and is near HWL in the other seasons as shown in Figure-3. From these conditions, it is estimated that an increase of displacement to the downstream direction in the latter half of the year is not caused by the change in the reservoir water level but by a change in temperature of the downstream side of the dam body corresponding to a change in air temperature.

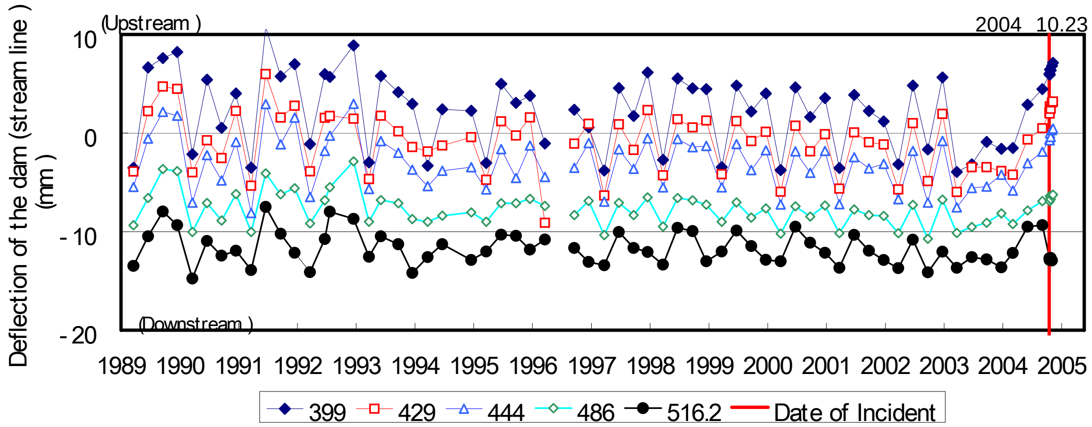


Figure-8 Displacement of Tagokura Dam

Figure-9 shows the reservoir water level and displacement of the dam just after the earthquakes. There are few data after the earthquakes, observed on October 24, 25, November 1 and 8, however, the figure shows that the displacement increases to the downstream direction after the earthquakes. However, inspection was carried out in the dam after the earthquakes and no cracks were found on the surface.

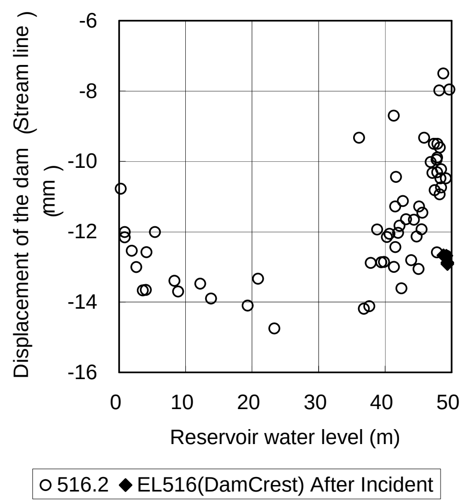


Figure-9 Displacement of Tagokura Dam and Reservoir Water Level
(EL 458m is estimated to be 0 m)

Characteristics of the Dam Response against the Earthquakes

Acceleration response of the dam body increases in proportion to the elevation, especially in about higher 10% of the dam height as shown in Figure-10.

An amplification of acceleration response is defined as shown in the formula (1).

$$A_C = \frac{a_{515}}{a_{399}} \qquad (1)$$

where,

Ac : amplification of response acceleration at EL.515 m, the dam crest

a_{515} : maximum response acceleration at EL.515 m (gal)

a_{399} : maximum response acceleration at EL.399 m, the dam base (gal)

Figure-11 shows that *Ac* for a_{399} of 20 gal or less is significantly large and that the value of *Ac* converges to about seven when a_{399} is 30 gal or more. *Ac* is about five when the maximum a_{515}, 600 gal, was observed. Characteristics of frequency are watched as characteristics of seismic response of the dam body. A distribution of a transfer function at each observation point is calculated using a power spectrum as shown in the formula (2).

$$H_i(f) = \frac{P_{Ei}(f)}{P_{E1}(f)} \qquad (2)$$

,where

$H_i(f)$: transfer function at observation point *Ei*

$P_{Ei}(f)$: power spectrum of seismic response record at observation point *Ei*

$P_{E1}(f)$: power spectrum of seismic response record at standard observation point *E1*, EL.399 m

f : frequency (Hz)

Figure-12 shows transfer functions, $H_i(f)$, in the main part and the last ten seconds of each earthquake movement. A seismic response of the earthquake which occurred on June 2, 1996 at the reservoir water level of EL.496 m was analyzed because the magnitude of this earthquake was relatively large and the reservoir water level when this earthquake occurred was similar to that when the earthquakes occurred.

The analysis shows the following results paying attention to predominant frequency and amplification of the transfer functions.

1) There is no significant difference between the main part period and the last ten seconds;

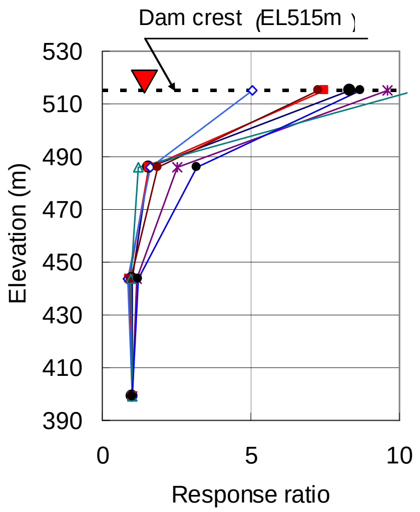


Figure-10 Maximum Response Acceleration

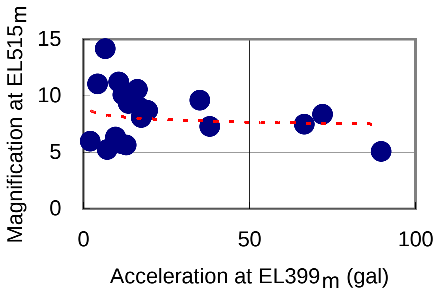


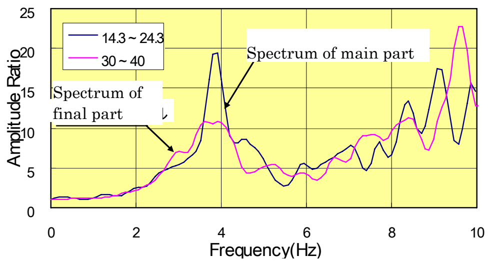
Figure-11 Amplification of Response Acceleration

(Crest(EL.515 m)/ Foundation(EL.399 m))

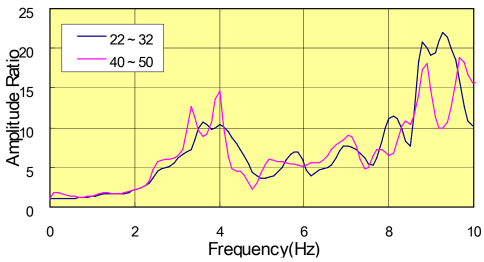
A red dotted line shows approximated value

2) Predominant frequency is within a fixed range including those caused by the past small scale earthquakes; and
3) Amplification of seismic response at the main earthquake shock has larger value but average value at the aftershocks.

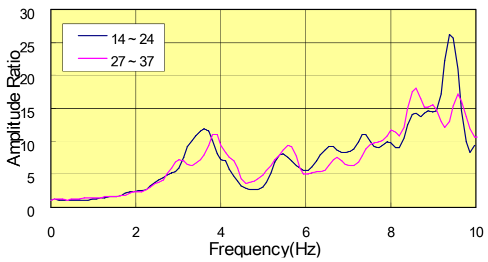
So the dam body has the same seismic response regardless of a scale of seismic acceleration acting at the dam base. However, responses of the past earthquakes have lower peak values and primary part of main earthquakes shocks has large amplification of seismic response, which shall be clarified in the future by analytical studies.



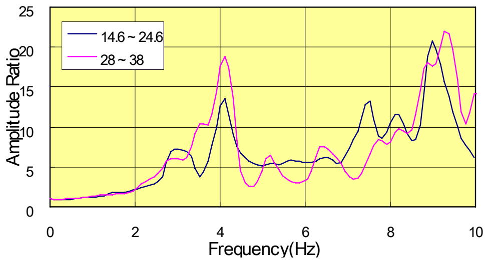
(a) Earthquake of 17:56, Oct. 23, 2004



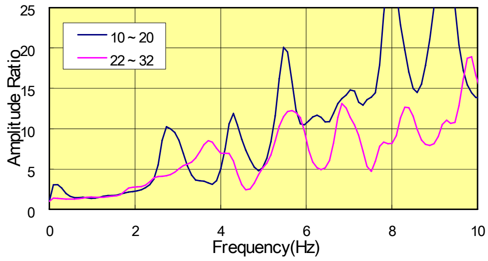
(b) Earthquake of 18:03, Oct. 23, 2004



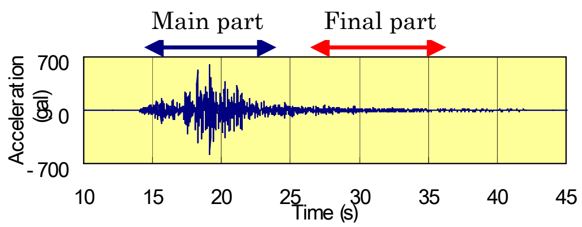
(c) Earthquake of 10:40, Oct. 237, 2004



(d) Earthquake of 11:15, Nov.08, 2004



(e) Earthquake of Feb.21, 1998



(f) Analysis range of response frequency

Figure-12 Transfer Function

3-D Dynamic Analysis of the Tagokura Dam

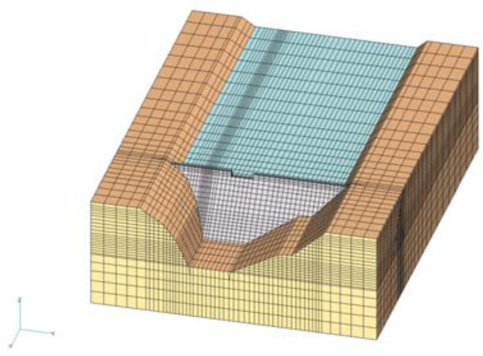
Input data

The dynamic deformation property values of dam and foundation have significant effects on the dynamic stresses and strains calculated by the dynamic analysis, so the values of the dynamic shear modulus and the damping factor should be quantitatively evaluated based on the actual earthquake motions. In other words, an efficiency and validity of the seismic safety evaluation method should be verified based on actual earthquake phenomena in order to realize an accurate and reliable evaluation for seismic safety of existing dams.

The values of the dynamic shear modulus and the damping factor can be identified by reproducing the actual earthquake behaviors of existing dams. The dynamic shear modulus can be evaluated effectively by reproducing the predominant frequencies of transfer function between dam base and dam crest. The damping factor can be evaluated by reproducing the maximum amplitude of motions at the dam crest.

Analytical model for the dam

Figure-13 shows the 3-D analytical model for the dam. The model is made as the 3-D coupled dam-foundation-reservoir system. The dam and the foundation are meshed with the finite elements, and the reservoir is meshed with the finite different grids. As for the boundary conditions, the rigid boundary is applied for the bottom boundary, and the viscous boundary for the lateral boundaries. The water depth of the reservoir is set to be the same condition when the earthquakes occurred.



Concrete Gravity Dam
Dam height: 145m, Crest length: 462m
Dam volume: 1950000m^3

Figure-13 3-D Analytical Model for Tagokura Dam

Transformation of motion from the observed point to the input boundary

In order to execute a 3-D reproduction analysis, it is necessary to transform the observed earthquake motions at the dam site into the input motions at the bottom boundary of 3-D analytical model. The input motions at the bottom boundary of the 3-D model for the reproduction analysis can be regenerated based on the earthquake motions recorded at the dam by utilizing the transfer function between the earthquake observation point at the dam and the bottom boundary of the model, as shown in Figure-14. Each component of earthquake motion is converted one by one in the case of de-convolution. And three components of motions are input simultaneously in the 3-D reproduction analysis.

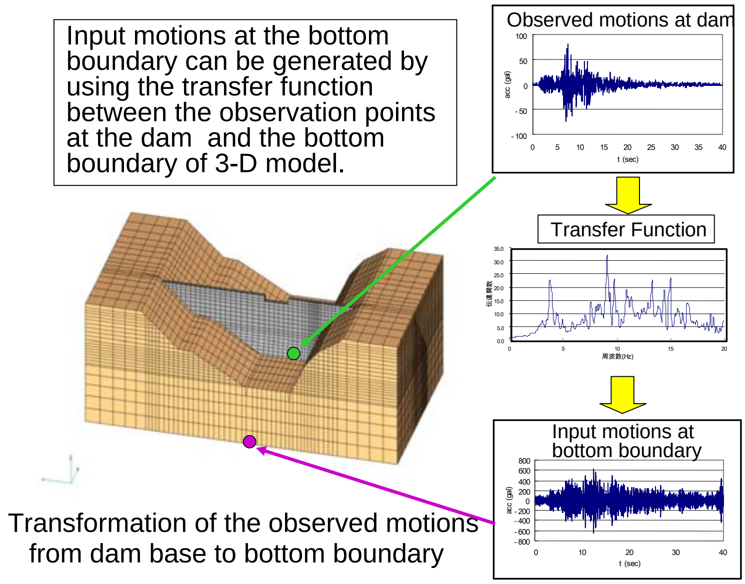


Figure-14 De-convolution of Actual Earthquake Motions Observed at Tagokura Dam

Dynamic property values identified

The dynamic property values of the dam identified by the 3-D dynamic simulation analysis for actual earthquake behavior during the earthquakes are shown in Table-3.

The shear wave velocity and damping factor of the dam are evaluated to be 1,980 m/sec and 5%, respectively. In this case, as the amplitude of earthquake motions is not so large, the actual earthquake behaviors can be reproduced well by the linear analysis. In case of very strong earthquake motions, the nonlinear dynamic analysis taking the non-linearity of dam material will be required.

The damping factor described here means a material damping factor, or a hysteretic damping, because the radiation of wave energy from the boundary of foundation to the free field can be naturally considered in the 3-D dynamic analysis based on the strict theory. If the radiation damping from the foundation to the free field is not considered in the dynamic analysis, some additional damping factor should be taken into account. The values of the shear wave velocity and the damping factor are slightly changed according to the dams analyzed, because of the differences about the shape and size of dams, the level of earthquake motion, the mutual influence between the foundation and the dam, and so forth.

Table-3 Dynamic Property Values for Tagokura Dam

Item	Density	Poisson's ratio	Dynamic shear modulus	Shear wave Velocity	Damping Factor
Dam	2.4 g/cm^3	0.20	9,600 N/mm^2	1,980 m/sec	5.0%
Rock	2.6 g/cm^3	0.25	8,000 N/mm^2	1,740 m/sec	5.0%

Safety of the dam against the earthquakes

Figure-15 shows the distribution of maximum acceleration, and Figure-16 and Figure-17 show the distribution of maximum tensile stress in the upstream-downstream direction and the dam-axis direction, respectively.

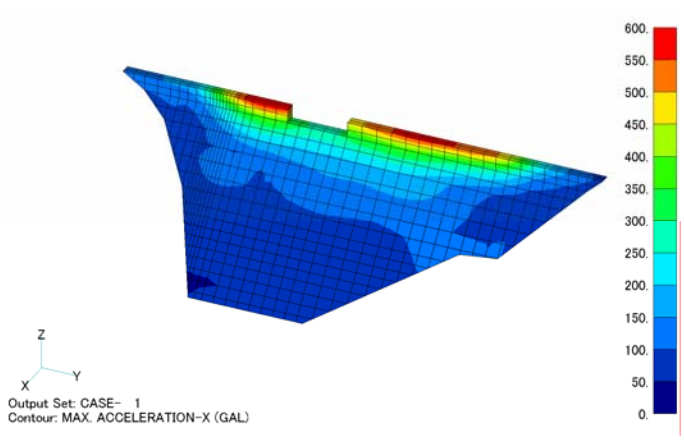


Figure-15 Distribution of Maximum Acceleration in the Upstream-Downstream Direction

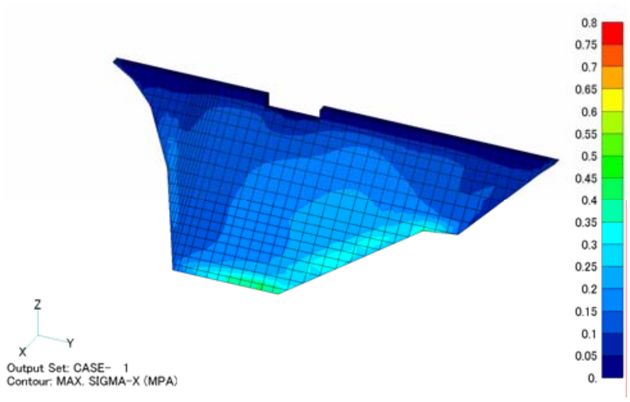


Figure-16 Distribution of Maximum Tensile Stress in the Upstream-Downstream Direction

Maximum tensile stresses are evaluated as shown in Table-4. The maximum value of tensile stress is evaluated to be 0.80 N/mm^2. Generally, the dynamic tensile strength of dam concrete is thought to be 3 to 5 N/mm^2.

So it is considered that the dam was quite safe against the earthquakes.

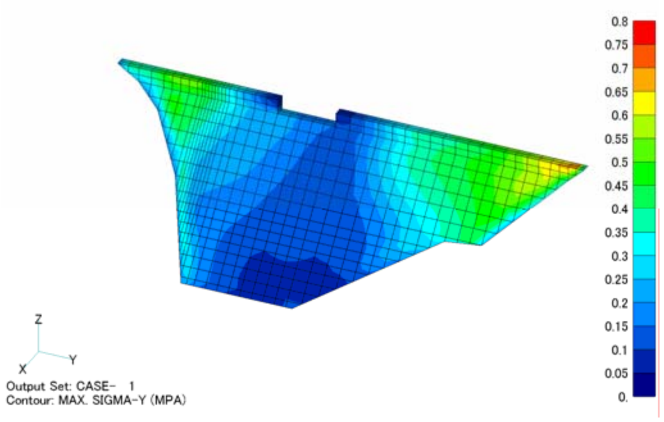


Figure-17 Distribution of Maximum Tensile Stress in the Dam-Axis Direction

Table-4 Maximum Stresses evaluated for Tagokura Dam

Direction	Maximum stress	
	Tensile stress	Compressive stress
Up-down Stream	0.40 N/mm^2	0.46 N/mm^2
Dam-axis	0.71 N/mm^2	0.68 N/mm^2
Vertical	0.80 N/mm^2	0.77 N/mm^2

Conclusion

The Chuetsu earthquakes (2004) gave the maximum seismic response acceleration of 600 gal at the crest of the Tagokura Dam. This report assesses the dam safety through not only the studies on the measured records of the quantity of leakage water, the dam displacement and the seismic response against the earthquakes, but also the 3-D dynamic analysis.

The conclusion of this report is as follows:

1) Quantity of water leakage and displacement of the dam were increased by seismic response acceleration but not remarkably compared with past observation records. Quantity of water leakage returned gradually to the usual quantity. The inspection found no cracks on the surface;
2) Among response characteristics of the dam, a predominant frequency and amplification of a seismic response did not change during the earthquakes, which is similar to response characteristics in the past earthquakes;
3) From the above facts, it is considered that that the earthquakes did not give large deformation to the dam which damaged dam safety; and
4) Based on the analytical results of the 3-D analysis, the dam is considered to be quite safe against the earthquakes, because the maximum tensile stress evaluated was 0.80 N/mm^2.

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