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EARTHQUAKE RESPONSE CHARACTERISTICS OF ROCK-FILL DAM WITH ASYMMETRICAL SECTION IN DAM AXIS DIRECTION

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SUMMARY

Recently, the rock-fill dams having an asymmetrical form in dam axis section has been constructed due to the restriction from geographical condition. In this research, we tried to make clear the earthquake response characteristics of a dam having such irregular section form based on data observed during the 2000 Tottori earthquake (M 7.3), and the simulation analysis was carried out using the 2-dimensional finite element method. It was confirmed that the dam reached to nonlinear response domain during main shock. As a result of simulation analysis, the displacement of up-down stream direction on dam crest has a mode, which makes a joint on the location where the dam thickness changes suddenly at the left bank side. From the parametric study using a Ricker wave, it was clarified that the incident angle of input wave dose not influence the vibration mode, and the dam of an asymmetrical section form indicates the same vibration mode as the dam of a symmetrical form section in the main section of the dam.

INTRODUCTION

The most of researches on an behavior of a rock-fill dam during earthquake is performed about the section of up-down stream direction of a dam until now, and there are few by which the response of the dam axis section was considered. When considering safety of a dam during the earthquake, generally the slide safety of up-down stream slope is the most important. Since the usual dam has almost symmetrical form with the dam axis section, it is hard to think that vibration of up-stream direction has unique characteristics in a dam axis section.

However, it is thought that the verification about the behavior of the dam axis section is still inadequate, if a dam has irregular form in dam axis section. Therefore, in this research, we investigated the vibration characteristics of Doyou dam (Chugoku Electric Power Co., Inc.), which has a characteristic cross-sectional form in dam axis direction, during the Tottori earthquake. The simulation analysis was performed about the bisection side of up-down stream direction section and dam axis direction section by using the 2-dimensional time history response analysis and equivalent linear analysis of finite element method, and the parametric survey using the Ricker wave as input motion was also carried out in order to examine the response characteristics of up-down stream direction on the crest.

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OUTLINE OF DAM

The Doyou dam, which locates at the northwest part of Okayama prefecture, is the rock-fill dam of a center core type. The altitude of dam crest is E.L.778.7m, height of dam is 86.7m and dam crest length is 480.0m. It is constructed in 1986 years. The sectional view of a dam is shown in Fig.1. In the up-down stream section (the maximum section), a slope of up streamside is 1:2.6 and down streamside is 1:2.2. The dam is composed of core zone, filter zone, and rock zone. The base rock of dam is mainly Mesozoic tuff (Shono, 1984). Although the up-down stream direction section is similar to a general dam, the dam axis direction section has an asymmetrical form, that is, it has a bank of long and slender shape in the left-bank side.

The seismographs are installed at four points, dam crest center (near the maximum section), core zone, inspection gallery and rim tunnel inside. The seismograph is the movable coil type accelerometer (Katsujiima Co., Ltd). The data observed with each seismograph is recorded by FM magnetic tape recorders in the observation institution of left-bank side on dam.

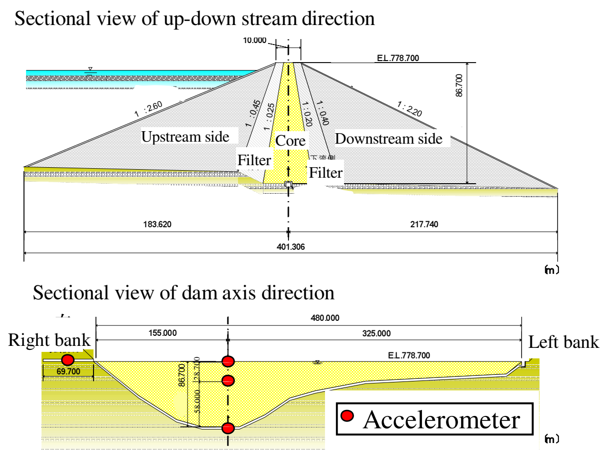

Fig.1 Sectional view

EARTHQUAKE OBSERVATION DATA AND ANALYSIS

The 2000 Tottori earthquake

The 2000 Tottori earthquake (focal depth of about 10km) happened in the south about 20 km of Yonago city of Tottori prefecture at 6 August, 2000. It generated the strong ground shaking of seismic intensity 5 in the Okayama northern part and the Kagawa eastern part. As for damage, although the number of the injured was 130 or more persons and brought about 5000 or more destruction of building, casualties have not come out. The dislocation of the fault was direction of northwestern-southeast and to be 87 degree in inclinations. The epicenter, estimated fault and a dam site is shown in Fig.2. The distance from epicenter of main shock to the dam is about 18km and the shortest distance from dam to estimate fault is about 12km.

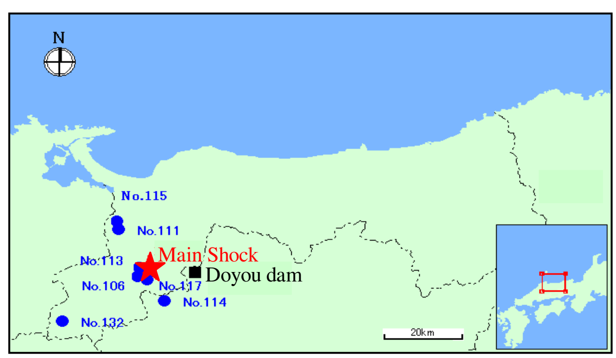

Fig.2 Epicenters and dam site

Analysis

Distribution of Maximum Acceleration Amplification Factor

The maximum acceleration amplification factors between inspection gallery and dam crest were examined using 32 aftershock acceleration records. The result is shown in upper figures of Fig.3. The figures shows that the maximum acceleration at inspection gallery amplifies on dam crest about 7 times for up-down stream and dam axis directions, respectively and about 4 times for vertical direction. This result is harmony-like as compared with the rate of amplification of the other rock-fill dams. On the case of adding the rate of the maximum acceleration amplification of the main shock is shown in lower figures of Fig.3. From the figures, the main shock separates greatly from the amplification line of aftershocks for the up-down stream direction. This is considered because the response characteristic of a dam arrived at the nonlinear domain in the main shock. However, it is suggested that responses in the dam axis direction and the vertical direction is not influenced of nonlinear like that in up-down stream direction.

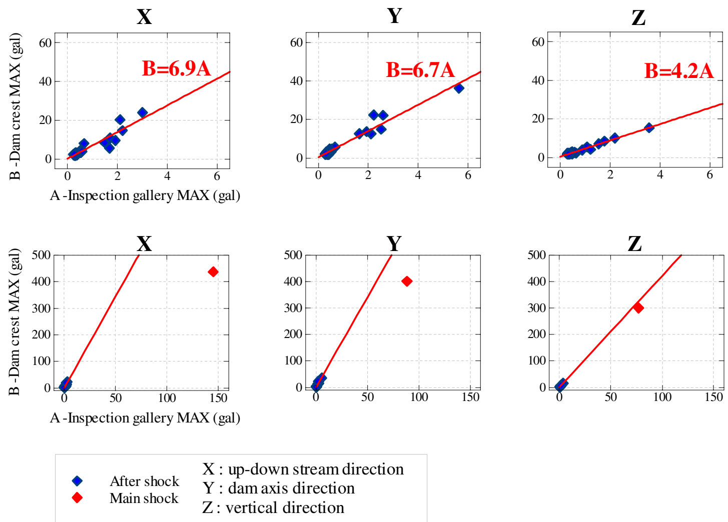

Fig.3 Distribution of maximum acceleration amplification factor

Spectrum analysis
We performed the spectral analysis of the velocity waveforms integrated the acceleration records. In the up-down stream direction and the dam axis direction, a spectral peak is among 2.2-2.5Hz, and a clear peak was not seen of the vertical direction. The transfer function between inspection gallery and dam crest is shown in Fig.4. The transfer function for aftershocks, its average and the transfer function for main shock are shown in the figure. Although the peak of transfer function of aftershock is 2.5Hz for up-down stream direction and 2.7Hz for dam axis direction, the peaks of the main shock are 1.8Hz and 2.2Hz, respectively, which moves to low frequency side. Much difference is not seen in the vertical direction. The nonlinear influence by the main shock has appeared most in the up-down stream direction, and this is the same as the tendency by amplification factor of maximum acceleration described previously.

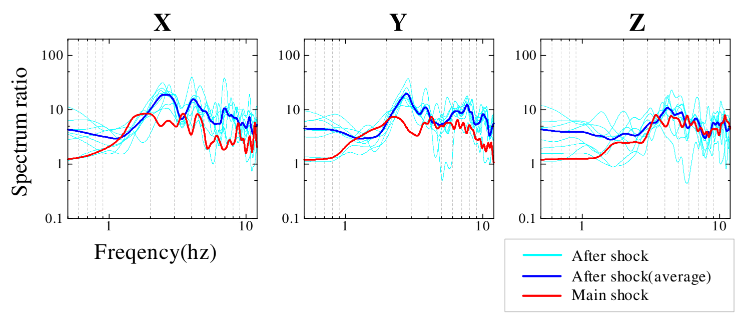

Fig.4 Transfer function between dam bottom and crest

PHYSICAL PROPERTIES OF DAM

In advance of simulation analysis, it is necessary to examine the distribution of physical-properties value of a dam in the section of up-down stream- and the dam axis-section. We divided the dam as shown in a figure 5, and examind the physical-properties value for analysis as following.

Core zone

The PS loggings ware carried out in the core zone in 1985, 1995 (Chuden Technical Consultant Co. Ltd, 1995). Based on these results, the preliminary physical-properties value of the core was determined. However, in the core zone, it was confirmed from past researches that there is a tendency which elastic wave velocity increases by secular change of a dam, therefore, the physical-properties value was reexamined in the actual simulation analysis,

Rock zone

Since any investigation has not been conducted, the physical-properties value of the rock zone couldn't be assumed directly. Sawada, et al. (1977) carried out the velocity measurement for the rock-fill dam of typical electric power facility and proposed the general physical-properties value distribution model. Moreover, Okamoto (2002) examined regression about the survey data in much more dams, and obtained the result that a Sawada's model is appropriate on the average about S wave velocity distribution. Therefore, S wave velocity and Poisson's ratio along the depth from a surface of a rock zone are decided according to a physical-properties model as shown in Table-1. In addition, we assumed the value of 1.90 - 2.15 g/cm^3 for the density of materials and the general value for the material-damping constant (Kondo, 1992).

Filter zone

As for the filter zone, since there was also no measurement data, the mean value of a core and a rock zone was mainly assumed.

Base rock

The investigation record did not exist about the velocity structure of the base rock of a dam. For this reason, based on PS logging data about borehole in Yubara observation site of the KiK-net Strong Earthquake Motion Network (OKYH09) currently installed near the dam, S and P wave velocity were set up. The density and the damping constant of rock zone were assumed the value of similar base rock.

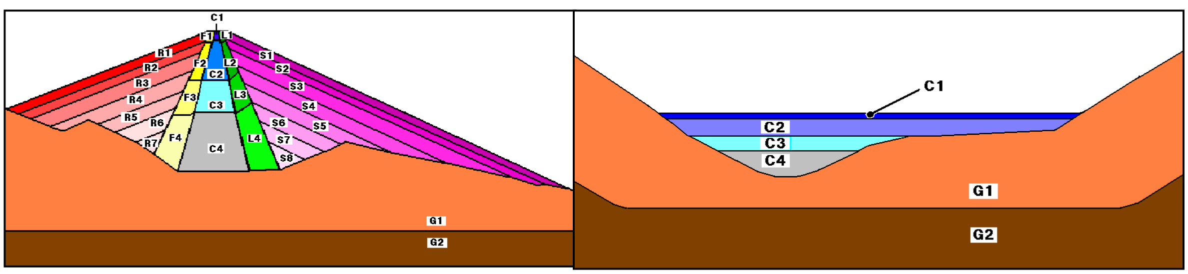

Fig.5 Physical-properties distribution of a dam

Table.1 Physical property model of rock zone

Depth (m)	The physical-properties value of a rock zone			
	down stream side		up stream side	
	Vs	Poisson's ratio	Vs	Poisson's ratio
0 - 5	Vs=240	$\nu=0.375-0.006\times Z^{0.58}$	Vs=240	$\nu=0.49-0.001\times Z^{0.95}$
5 - 30	$Vs=250\times Z^{0.20}$		$Vs=250\times Z^{0.20}$	
30 -	$Vs=250\times Z^{0.315}$			

EARTHQUAKE RESPONSE SIMULATION ANALYSIS

2-dimensional Analysis

In this analysis, by using the finite element method program TDAPⅢ and FDAP, the time history response analysis and equivalent linear analysis were performed. The plane strain and the shell element were used for the model. As for boundary conditions, the side boundary element (viscous boundary) was added to the both side ends of a model, and by using a bottom viscosity element for the lowermost part of a model, a half infinite layer should be expressed. The model was divided so that calculation up to 10Hz might be possible. The restricted conditions were as follows. In the plane strain analysis, all the rotation and Z direction were fixed, and all the rotation and X direction were fixed in the out plane analysis. It was used combining Rayleigh and material attenuation for attenuation, and could be about 6% by the whole model.

Section model

The up-down stream section is shown in Fig.6 as the last model. On the actual dam, since it was considered from the plan of a dam that the base rock has projected at the dam bottom under down stream rock zone, we reflected this in a model and considered the maximum section as the section model of up-down stream direction. Moreover, we made the calculation by considering that the base rock has the uniform foundation horizontally. The size of a model is height of 400m and width of 1800m. The dam axis section model also created as shown in Fig.7 according to the same procedure. The size of a model is height of 500m and width of 2000m.

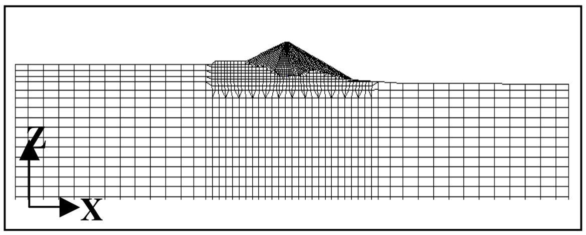

Fig.6 Section model of up-down stream direction

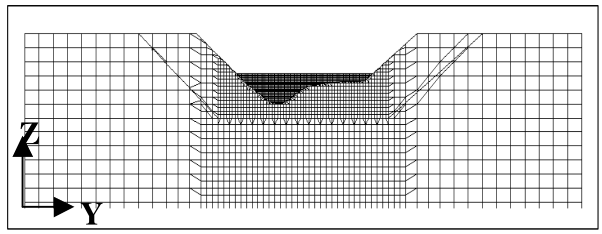

Fig.7 Section model of dam axis direction

SIMULATION ANALYSIS FOR THE 2000 TOTTOR EARTHQUAKE

Simulation analysis of after shock

Reexamination of physical-properties

At first, the eigen values analysis was performed using the physical-properties defined in preliminary stage. Consequently, in the up-down stream section, it was 2.4Hz, and 2.1Hz in the dam axis section. On the other hand, the peak frequency obtained from the analysis of earthquake observation is 2.2-2.6Hz in up-down stream section, and 2.5-2.7Hz in dam axis section. The natural frequency in the dam axis section model is low compared with the peak frequency of observation. This is considered to be because only for the core to be used as a physical-properties of dam in the dam axis section. When we calculated the response increasing the Vs of core zone given in first stage as about 1.2 times, both natural frequencies in up-down stream and dam axis sections was harmony-like as observation data. Therefore, we used the corrected Vs as physical-properties of core zone in subsequent time history response analysis.
In this analysis, a result is drawn by waveform processing in the frequency domain through the transfer function. That is, a Ricker wave carries out incidence to the model bottom, and time history response analysis is performed. We calculate the response waveform at the crest and core, using the response result due to a Ricker wave and the observation waveform at inspection gallery, which is a control point. In addition, the incident angle of seismic wave at the bottom of model was taken into account in the analysis. On the case of main shock, the incident angle was about 37 degree in clockwise rotation from normal downward.

Result of analysis

In the up-down stream section model of a dam, time history response analysis by the velocity input motion was performed. Here, the analysis result for an aftershock with the hypocenter near a dam is shown in Fig.8. In the figure, the simulation waveform and its spectrum in the crest and core are shown with observation data, and observation waveform of inspection gallery used for control point also is shown. In addition, band path filter processing from 1Hz to 8Hz is performed to all waveforms. Although the analysis result well agrees with observation result about the phase of wave, the tendency for amplitude due to analysis to become smaller than observation is recognized. This is considered, as seen in 4-5Hz of spectrum, to because the phenomenon of negating a wave arose for a certain reason (form of a model etc.). However, it can be said that the response near the peak frequency of a dam was well reproducible in general.

Time history response analysis to the dam axis direction section was performed. The analysis result for the same earthquake is shown in Fig.9. The tendency for a response in a high frequency domain to become small is seen as well as the case of up-down stream section. Moreover, the reappearance for 2 seconds after initial wave arrival is not mainly enough. Here, causes, like that it is not a model aiming at the analysis to P wave and some errors have been born in the stage of waveform processing can be considered. However, like up-down stream section analysis result, the response near peak frequency of a dam was also fully reproduced.

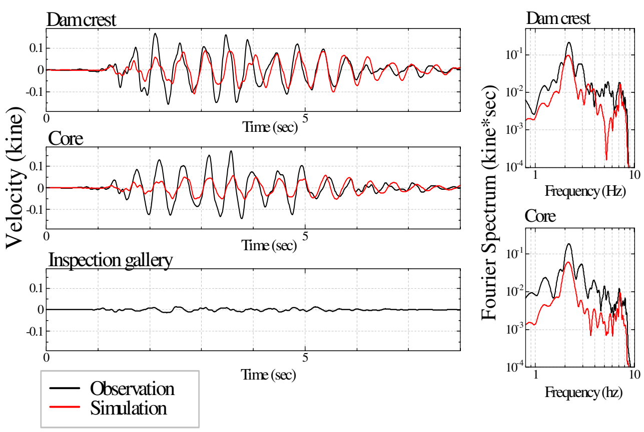

Fig.8 Comparison of analysis with observation for up-down stream direction

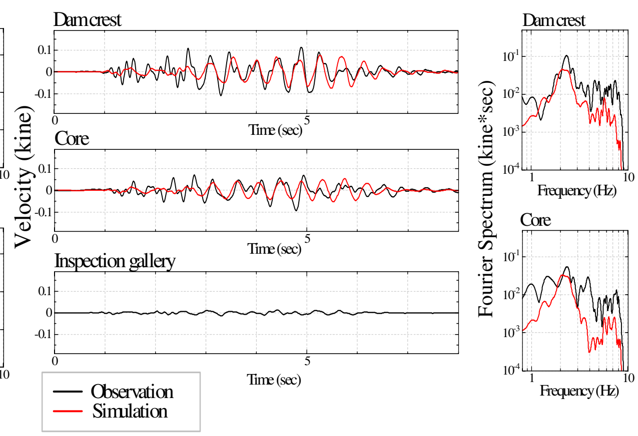

Fig.9 Comparison of analysis with observation for dam axis direction

Analysis of main shock

During the main shock, the response of dam enters to the nonlinear domain. Therefore, in order to reproduce the response of a dam in main shock analysis, it is necessary to reexamine about a physical-properties. Then, the equivalent linear analysis was conducted to take into consideration the strain dependability of the physical-properties in a core zone. We used the strain dependence curve for analysis from the following formula (Ogata et al., 1987), which is given as a function of normal stress concerning a core zone. The strain dependence curve is shown in Fig.10.

$$\frac{G}{G_0} = \frac{1}{1 + \dfrac{\gamma}{6.8 \times 10^{-4} \sqrt{\sigma_m^{'}}}}$$

$$h = 14.7 - 11.4 \frac{G}{G_0}$$

G : Shear elastic coefficient

G_0 : First shear elastic coefficient

γ : Shear strain

$\sigma_m^{'}$: Normal stress

h : Damping ratio

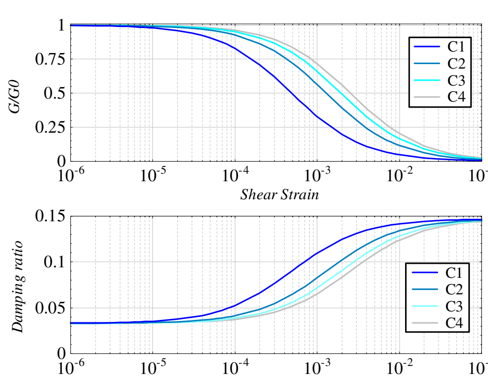

Fig.10 Strain dependence curve

In plane analysis

The analysis result of up-down stream section and the dam axis direction section to the main shock is shown in Fig.11 and Fig.12 respectively. In the dam axis section, although the spectral amplitude falls near 4Hz, it can be said that the response in dam crest and core of both sections was reproduced well. The simulation of the main shock has given the good result as compared with that of aftershock. As for aftershock, the depression of the spectrum in the high frequency range influences a calculation result. Since the main shock has large power in low frequency range, it is thought that a simulation becomes easy comparatively.

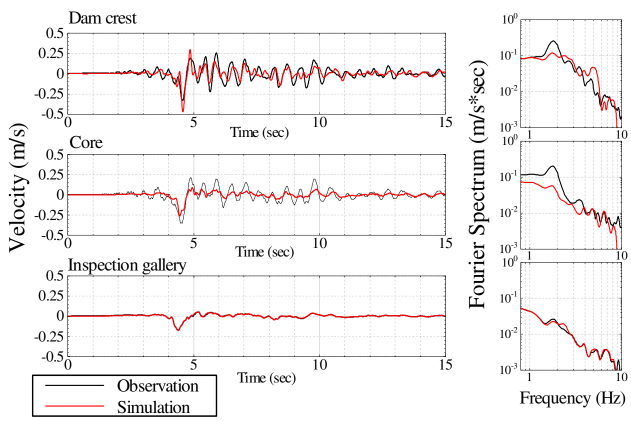

Fig.11 Comparison of analysis with observation for up-down stream direction

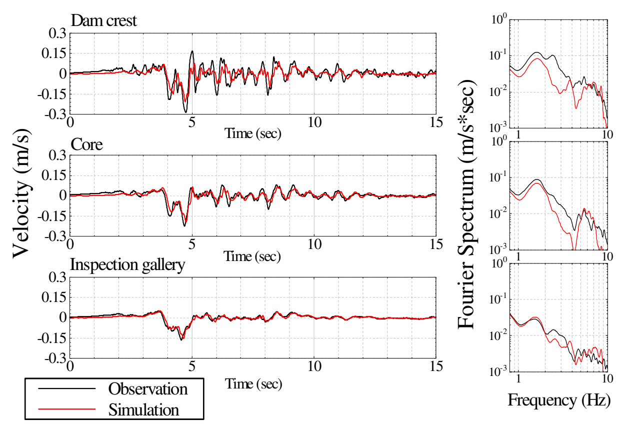

Fig.12 Comparison of analysis with observation for dam axis direction

Out plane analysis

As a result of equivalent linear in plane analysis using dam axis section model, the final physical-properties in each element of a core zone is computable. Since the strain dependability could not be taken into consideration in the shell element used for out plane analysis, the time history response analysis was carried out using the last physical-properties. The result is shown in Fig.13. Although the fall of spectrum amplitude is seen near 3Hz, the good calculation result could be obtained in general in a core and crest. The phase of calculation wave well corresponds to that of observation and it can be said about the main phase near 2Hz that it was mostly reproducible.

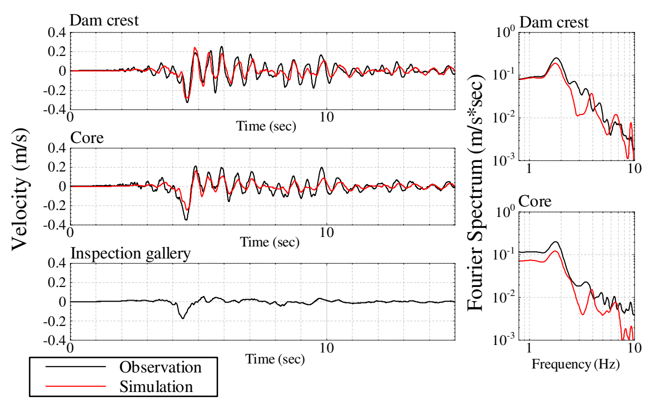

Fig.13 Comparison of analysis with observation for up-down stream direction of dam axis model

DISPLASEMENT OF UP-DOWN STREAM DIRECTION ON DAM CREST

From of out plane analysis using dam axis section model, the displacement response of up-down stream direction in dam crest was examined. The output of response was calculated at each point of dam crest as shown in Fig.14.

Displacement behavior of dam crest

The time series of up-down stream direction displacement in each point on dam crest during main shock is shown in Fig.15. As shown in the figure, the calculated displacement well coincides with that of observation at the point D6 where dam becomes the deepest section. Then, we extracted the displacement on each point at a time of near main shaking as shown A, B in the figure. The displacement mode of up-down stream direction in these two times is shown in Fig.16. This figure shows that the displacement amplitude becomes the largest near the maximum section, and also shows a mode which makes a joint at the position where the dam thickness changes suddenly at the left bank side. It can be thought that the dam axis direction section is the asymmetrical form, which has a long and slender bank in a left-bank side unlike the usual dam, as one of the causes by which such a phenomenon happens.

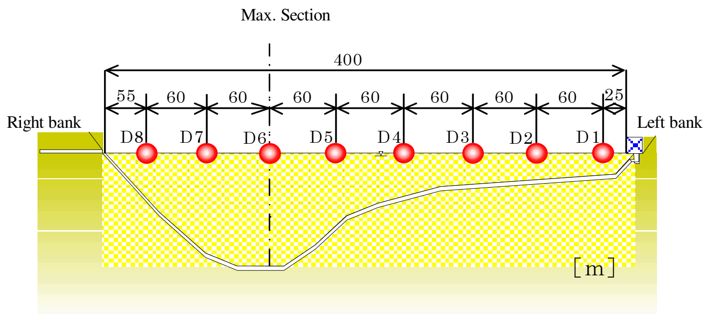

Fig.14 Output point of dam crest

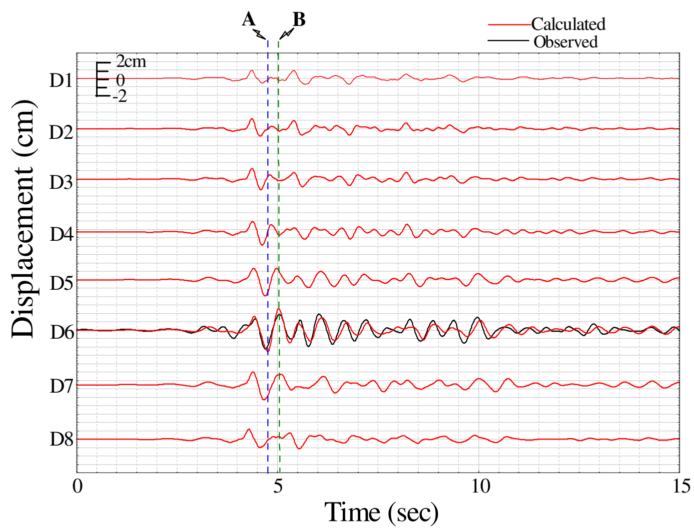

Fig.15 Displacement behavior on dam crest

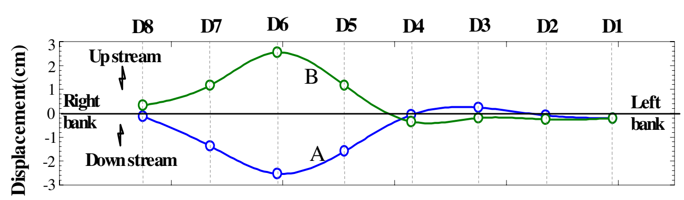

Fig.16 Displacement mode on dam crest at time A and B

Influence of incident angle and symmetric form

Above mentioned phenomenon originates in the asymmetrical form of dam axis section, and also the influence by the incident angle of a seismic wave is considered. The 2000 Tottori earthquake has input angle of about 37 degree as already stated. In this case, earthquake wave inputs to dam bottom from a right-bank side. Then, we examined the influence for displacement behavior due to incident angle using a Ricker wave. The displacement responses on dam crest in each incident angle are shown in Fig.17. Where, 0 degree means the normal input, and -30 degree is input from a left-bank side. According to the figure, the displacement mode scarcely affected from incidence angle.

At last, we created the dam section with a symmetric form in dam axis direction, and compared the displacement mode of asymmetric section with that of symmetric section. The result is shown in the case of incident angle 0 degree in Fig.17. From the figure, it can be said that the both displacement modes is almost the same in main section of the dam. This means that it is enough like symmetric dam when examining the earthquake resistance of asymmetric dam, if the maximum section is examined.

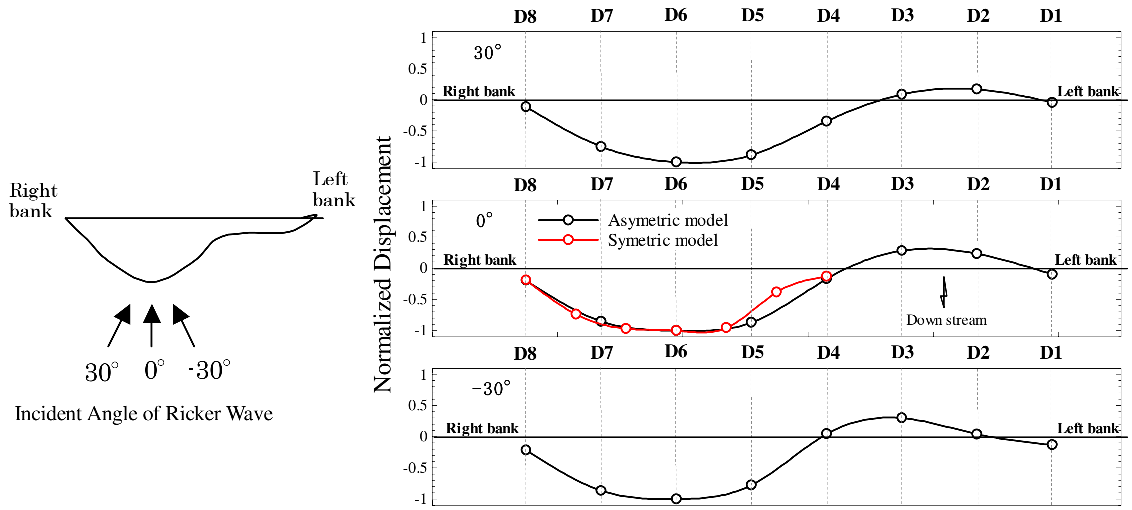

Fig.17 Behavior of the displacement on dam crest in each incidence angle

CONCLUSIONS

As a result of earthquake response analysis for the rock-fill dam, which has asymmetrical section form, the following results were obtained.

(1) It was confirmed that the dam reached to nonlinear response domain during main shock from comparing aftershock records with main shock record.

(2) The responses of the dam due to main shock are well reproducible using the 2-dimensional FEM with equivalent linear analysis method.

(3) The displacement of up-down stream direction on the crest in the dam axis section shows a mode, which makes a joint on the location where the dam thickness changes suddenly at the left bank side.

(4) It was clarified that the incident angle of input wave dose not influences the vibration mode, and the dam which has an asymmetrical form indicates the same vibration mode as the dam of a symmetrical form.

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REFERENCES

Chuden Technical Consultant Co. Ltd (1995), Long tem evaluation of physical- property of rock-fill dam, Report, 11-23 (in Japanese).

Kondo, M. (1992), Research on behavior of rock-fill dam based on long tem observation, large Dam, No. 140, 71-83 (in Japanese).

Ogata,N. et al. (1987), Dynamic deformation properties of Doyou dam materials-examination by using PS logging and three axis dynamic vibration test-, CRIEPI Report, U86519 (in Japanese).

Okamoto, T. (2002), Analysis of past data about elastic wave velocity of rock-fill dam and comparison with Sawada's formula, 11th JCEE, CD-ROM (in Japanese).

Sawada, Y. et al. (1977), Distribution of physical-property in rock-fill dam and vibration characteristics-examination based on elastic wave-, CRIEPI Report, 377008 (in Japanese).

Shono, H. (1984), Construction of Doyou dam, Dam Japan, No. 478, 2-4 (in Japanese).