Effect of the seismic vibration direction on the water leakage of gravity-type concrete dam

Akira. Kobayashi i), Takuto. Hayashi ii), Yasuhiro. Tsukada iii) and Kiyohito. Yamamoto iv)

i) Professor, Department of Civil and Environmental Engineering, Kansai University, 3-3-35, Yamate-cho, Suita, 564-8680, Japan.
ii) Engineer, West Nippon Expressway Co., Ltd., 1-6-20, Dojima, Kita-ku, Osaka, 530-0003, Japan.
iii) Engineer, Hazama Ando Corp., 6-1-20, Akasaka, Minato-ku, Tokyo, 107-8658, Japan.
iv) Associate Professor, Department of Agriculture, Iwate University, 3-18-8, Ueda, Morioka, 020-8550, Japan

ABSTRACT

Japan is one of the most earthquake-prone countries in the world. Many structures suffered from the great damage in the past. Fortunately any gravity-type concrete dam did not collapse and was not a disaster for the downstream area. However, some damages of the dam body were reported after the earthquake. The most one is the increase of leakage from dam, which accounts 60% of the total damages. The gravity-type dam has many longitudinal and lateral joints in the body. The increase of leakage might be cased from broadened aperture of the joints. In this study, the behavior of the joints in the dam body is examined with the 3-D numerical model by the input waves having the different directions. It is found that the lateral joints at the maximum cross section have the broadened aperture when the wave is inputted from the axial direction, and that the lateral and longitudinal joins near the abutment behave to increase the leakage when the wave is inputted from the up and down-stream direction.

Keywords: earthquake damage, 3-D numerical analysis, gravity-type dam, leakage of water

1 INTRODUCTION

Japan is one of the most earthquake-prone countries in the world. Many structures suffered from the great damage in the past. While any gravity-type concrete dam did not cause the disaster at the downstream area, the increment of water leakage was sometimes observed after earthquake. In comparison with other hydraulic structures, critical accident of dam has a high risk on surrounding areas. Furthermore, as a huge cost is needed in case of a large-scale renewal, it is important to prolong a lifetime of dam with the confidence of the safety. For the sake, it is necessary to conduct appropriate repair after the earthquake. However, the inner damage of dam body is difficult to investigate by the conventional examination. Therefore, it is important to comprehend the seismic behaviour and the possible damage by earthquake.

In this study, the behaviour of the joints of concrete dam caused by the seismic wave in the different directions is intensively examined by the finite element method. The three-dimensional dam model is constructed by using the joint elements for joints of dam body.

2 PAST DAMAGE OF GRAVITY-TYPE DAM

Japanese administrator has an extraordinary inspection of the dam when the earthquake acceleration over 25gal is observed at foundation or a nearest meteorological observatory. The extraordinary inspection is carried out by the visual observation. When the detail investigation is needed, the secondary inspection is carried out to examine the safety. If the additional examination is considered to be necessary, the urgent field investigation is conducted by ministry of Land, Infrastructure and Transport. Fig.1 shows the result conducted after some large-scale earthquakes of recent years (NILM, 2003, 2005, 2008, 2008, 2011). When the dam body is cracked, the crack has to be fixed. It is found in the figure that increase of water leakage from joints accounts large percentage of the damage of concrete dam. The opened joint remains without repair in many cases if the leakage is small. However, if the aperture distribution is known, the countermeasure may be changed. If the lifetime is prolonged by the easy treatment, the treatment has to be conducted even if the damage is judged to be small.

In this study, the sliding and separation distribution of the joint is examined for the different seismic wave direction.

3 ANALYSIS METHOD

3.1 Analysis model

The concrete dam is divided into several blocks in order to prevent crack caused by temperature change. A transversal joint is placed to prevent crack perpendicular to the dam axis. The interval is about 15m empirically.
The longitudinal joints placed to prevent crack parallel to the dam axis. In the case of large-scale dam, the interval of the longitudinal joints is about from 30m to 50m.

The analysis is carried out to examine the behaviour of the joints by earthquake vibration. The dam model having the several joints is created by referring the actual dam specification shown in Table 1. In this study, the dam and bedrock are modelled with FEM. The joints of concrete dam rock are modelled by joint element. The shear and normal deformations of the joints are analysed by the model. Table 2 shows the material properties of the dam body and bedrock. The properties of joints are the same as the dam body except for the damping coefficient. The damping is not considered for the joints. The model of damping of dam body and bedrock are Rayleigh damping of which parameters are decided by the eigenvalue analysis. The damping is set at 5%. Fig. 2 shows the analysis model which is surrounded by the free layer with the viscous boundaries. The seismic wave is inputted at the bottom of bedrock. Fig. 3 shows the location of the joints on the maximum horizontal section. The number of the transverse joints is 26 and the one of longitudinal joints is 37.

First, self-weight analysis is conducted. Next, seismic analysis is performed using three-dimensional elastic finite element method based on the results of static analysis. In the seismic analysis, reflected wave occurred at boundary surface of analysis domain. The viscous boundary as infinite boundary is applied in order to avoid the influence (JGS, 2007). It is expected from this treatment that the reflected waves are absorbed.

Table 1 Specification of dam.

| Properties          | Value     |
|---------------------|-----------|
| Height              | 140 m     |
| Length              | 405 m     |
| Volume              | 1,321,000 m³ |
| Slope gradient      | Upstream: 1: 0.81  |
|                     | Downstream: 0   |
| Joints interval     | Longitudinal: 24 – 60 m |
|                     | Transversal: 15 m |
| Number of Joints    | Longitudinal: 37 joints |
|                     | Transversal: 26 joints |

Table 2 Material properties.

| Properties          | Dam body | Bed rock |
|---------------------|----------|----------|
| Unit weight (kN/m³) | 23.1     | 26.9     |
| Elastic Modulus (kN/m²) | 3.3 × 10⁷ | 3.5 × 10⁷ |
| Poisson’s ratio     | 0.2      | 0.3      |
| Damping coefficient | 0.05     | 0.05     |

Fig. 1 Past damage of gravity-type dam.

3.2 Seismic wave

The seismic wave observed at a dam gallery at the southern Hyogo prefecture earthquake in 1995 is used. The maximum horizontal acceleration is 143 gal and the maximum vertical one is 66 gal. Fig. 4 shows the profile of the wave.

3.3 Analysis cases

The analyses are carried out for the following 4 cases.

Case 1: Horizontal wave is inputted.

Case 2: Horizontal wave is inputted and the dynamic water pressure is applied.

Case 3: Horizontal and vertical waves are inputted.

Case 4: Horizontal wave is inputted and the elasticity of joints is reduced.

For all cases, the waves are inputted from three different directions, which are the dam axis direction, the up and down stream direction and 45 degree direction from dam axis.

Case 2 is examined to show the effect of water pressure. The dynamic water pressure is estimated from the equation of Westergard (1938).

Case 3 is examined to investigate the effect of vertical movement, and Case 4 is carried out to examine the effect of degradation of joint elasticity. The elasticity of joints is set at 1/10 of the one in Case 1.
4 ANALYSIS RESULTS

4.1 Eigenvalue analysis

The primary natural frequency is 3.3 Hz. Table 3 shows the results and mode tendency at each natural frequency.

Table 3 Results of eigenvalue analysis.

| Order | Natural frequency (Hz) | Mode tendency                                    |
|-------|------------------------|--------------------------------------------------|
| 1     | 3.36                   | The maximum cross section moves in up and down stream direction |
| 2     | 4.72                   | S shaped curve. The maximum cross section does not move. |
| 3     | 5.31                   | S shaped curve. Deformation to the dam axis direction. |

4.2 Effect of input wave direction

1) Case inputted from dam axis direction

Fig. 5 shows the characteristic relative displacement distributions of transversal joints. As shown in Fig. 5 a), the maximum displacement causes at the downstream slope of No. 4 transversal joint. No. 13 joint at the maximum cross section has the shear displacement of 0.004 m at the downstream slope (Fig. 5 b)) and the vertical displacement of 0.009 m at the upstream slope (Fig. 5 c)). The longitudinal joints have about 1/7 of the displacement of the transversal joints.

Fig. 6 shows the distribution of normal strain in the dam axis direction on the upstream slope. The large strain occurs at the abutment. The distribution of the normal strain in up and down stream direction has the similar tendency. The entire deformation is similar to the one at the third order natural frequency.

2) Case inputted from up and down stream direction

Fig. 7 shows the characteristic relative displacement distributions of joints. The maximum normal displacement of 0.006 m is observed at the downstream slope of No.4 transversal joint (Fig. 7 a)). At adjoining No.5 joint, the shear displacement in up and down stream direction and the vertical direction is 0.007 m (Fig. 7 b), c)). No. 15 joint connecting to No. 5 joint has the normal displacement of 0.004 m (Fig. 7 b)).

Fig. 8 indicates the distribution of normal strain in the up and down stream direction on the upstream slope. The relatively large strain occurs at the lower parts. The part at the abutment has the large strain in dam axis direction. The entire deformation is similar to the one at the first order of natural frequency.

3) Case inputted from 45° direction from dam axis

Fig. 9 indicates the characteristic relative displacement distribution in the case of which wave is inputted from 45° direction from dam axis. The dam shows the behaviors adding with the above two cases. The large displacement is shown at the joints at abutment and at the maximum cross section.

4.2 Effect of reservoir water

In Case 2 considering the dynamic water pressure, the displacement of joints becomes small. This tendency is seen in the results inputted from different directions. The stress in the dam body becomes small by supporting by the water pressure.
comparison with Fig. 6 in Case 1, it is found that the strain becomes a little large. The relative displacement also becomes a little large while the location with the maximum displacement is not changed. Since the maximum acceleration of the vertical wave is about 1/2 ~ 1/3 of the one of the horizontal wave in many actual seismic waves, it can be concluded that the seismic behavior can be examined with only horizontal wave.

4.4 Effect of degradation of joints

Fig. 11 indicates the characteristic relative displacement of joints in Case 4, in which the wave is inputted from the dam axis direction. It is found that the displacement becomes large in comparison with Fig. 5. In particular, the shear displacement increases more than the normal displacement.

5 COMPARISON WITH ACTUAL DAMAGE

The leakage of water after earthquake is investigated from the past extraordinary inspections. Table 4 shows the location where the leakage increased and the angle between the direction to seismic center and the dam axis. In the case which the seismic wave came in from the dam axis direction, the leakage occurs more at the Transversal joints than at the Longitudinal joints.
axis direction, the leakage occurred at only the maximum cross section. On the other hand, when the seismic wave entered from the up and down stream direction, the leakage occurred at only the abutment. In the case when the wave came in from 45° direction from the dam axis, it was reported that the leakage occurred in both the maximum cross section and the abutment. The same tendency is presented by the numerical analyses as mentioned above.

Therefore, when the seismic shaking occurred in dam axis direction, the joints existing at the maximum cross section is more likely to have a leakage. When the seismic shaking occurred in the up and down steam direction, the leakage possibly happen at the joints near abutment. Moreover, in the case when the seismic wave enters from 45° direction from the dam axis, there is possibility of the leakage at both maximum cross section and abutment.

Table 4 Input direction of seismic wave and location of leakage at actual earthquake.

| Earthquake         | Dam Acc.(gal) | Max. Section | Abutment |
|--------------------|---------------|--------------|----------|
| Niigata-Chuetsu-oki | A 91 U-D      | ○            | ○        |
| Iwate-Miyagi-Nairiku | B 276 45°   | ○            | ○        |
| Tohoku-Pacific ocean | C 90 D-A   | ○            | ○        |
|                    | D 320 D-A   | ○            | ○        |
|                    | E 274 U-D  | ○            | ○        |
|                    | F 393 45°  | ○            | ○        |
|                    | G 257 45°  | ○            | ○        |
|                    | H 119 45°  | ○            | ○        |
|                    | I 462 45°  | ○            | ○        |

Direction: direction of input seismic wave U-D: Up and down stream direction, D-A: dam axis direction, 45°: 45° direction from dam axis.

6 CONCLUSIONS

To understand the characteristics of leakage from joints of gravity-type dam by earthquake, the seismic behavior of joints in the dam body was analyzed with three dimensional FEM model by using the different directions of input seismic waves. Moreover, the analyzed results were compared with the actual damage of gravity-type dam, and it was found that the numerical results consisted with the actual tendency of the damage. The following results about the joints behavior and the leakage from joints were obtained:

1) In the case when the shaking occurs in the dam axis direction, the shear deformation in the up and down steam direction and vertical direction occurs on the transversal joints near the maximum cross section. The aperture of the joints may be widen to make a seepage channel in the up and down stream direction by the dilatancy of shear deformation. This might be the reason of the leakage at the maximum cross section.

2) When the dam is vibrated in the up and down stream direction, the longitudinal joints at the maximum cross section has a large shear deformation while the transversal joints dose not move so much. On the other hand, the transversal joints at the abutment has a large shear deformation and the longitudinal joints deforms so much in normal direction. By the widen aperture of longitudinal joints and dilatancy behavior of transversal joints, the seepage channel may occur in up and down direction. This may be reason why the leakage occurs near the abutment.

3) When the seismic wave enters from 45° direction to the dam axis, the joints behaves as mixing the behaviors seen in the cases of both waves mentioned above. The transversal joints at the maximum cross section may have the seepage channel, and the seepage channel at abutment also may be caused by the interaction of transversal and longitudinal joints.

4) When the reservoir water is impounded, the behavior of the joints of gravity-type dam is restrained. In the case when the vertical seismic wave is not so much in comparison with the horizontal one, the effect of vertical wave on the joint behavior is small. Moreover, the degradation of joints causes the large shear strain and so the large aperture by dilatancy of joints.

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