PERFORMANCE OF THE TARUMIZU ROCKFILL DAM DURING STRONG EARTHQUAKE

by

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SUMMARY

Dynamic behavior of the Tarumizu rockfill dam was studied by means of in situ observation of earthquakes and response characteristics of the dam were mentioned. Using the strong motion earthquake records obtained in the gallery of the dam, non-linear response analysis was carried out on a three-dimensional finite element model by considering reduction of rigidity corresponding to strain level. Results of non-linear analysis indicate increase in the maximum displacement and decrease in the maximum acceleration. However reduction in magnification factor due to non-linearity is not so large as is expected.

INTRODUCTION

Behavior of fill dams has been investigated in detail for more than ten years. Since Okamoto tried to observe earthquakes on an earth fill dam (Okamoto, S. et al, 1966), similar studies have been made by many researchers and the behavior of fill dam during earthquakes has been considerably revealed. The observed earthquakes, however, did not include such strong motion as could be applied to seismic design except for the recent data on the San Fernando dams (Seed, H.B. et al, 1973). It could be said that high fill dams in Japan have no experience to strong earthquakes and no substantial damage to the dams had been seen by the past strong earthquakes. Therefore destructive effect of earthquakes on fill dams has been investigated only by model tests (e.g. Okamoto, S. et al, 1977). But numerical model would be also an effective mean to the research on the performance of fill dam during strong earthquake.

The Tarumizu rockfill dam is located in the vicinity of Sendai city, where the Miyagiken-Oki earthquake attacked on June 12, 1978. Seven accelerometers were installed in this dam and many earthquake records were obtained. Unfortunately these instruments were not operated during the earthquake because the electricity supply was interrupted by the earthquake. The strong motion earthquake records, however, were obtained in the dam gallery, but not on the crest. The purpose of this paper is to investigate the dynamic properties of the dam and to estimate the performance of the dam body during the strong earthquake.

SEISMIC RESPONSE OF THE DAM

The Tarumizu rockfill dam, which is located in Natori city, Miyagi Prefecture, is a rockfill dam of centre core type for the irrigative res-

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ervoir. The dam is 43.0m in height and 256.5m in length and has total volume of 550,000m^3. The strata at the dam site are formed of thin topsoil of 0.5 to 1.0m, clayey layer of 3 to 5m mixed with gravels, tuffbreccia and andesite. The tuffbreccia was used as rockfill material and mixture of gravel and decomposed tuffbreccia was used as core material.

In order to investigate response characteristics of the dam, observation of earthquakes has been performed since 1975. Seven acceleration transducers were installed at five observation points in the down stream slope and on the dam base as shown in Fig. 1. That is, two transducers on the crest are used for recording vertical and horizontal acceleration, three on the down stream slope are for horizontal acceleration and two on the dam base are vertical and horizontal acceleration. The transducers are given a number in a numerical order from the base to the crest. The acceleration of earthquake is converted into electric signal by transducers, attenuated and recorded with an electromagnetic oscillograph. The recording device begins to run by working of the automatic starter when a seismic shock of a certain intensity is felt. Many earthquake records were obtained since the observation had begun. Relatively larger earthquake records were selected and main parts of the shocks were chosen by 8 sec long for the analysis. The values of acceleration are picked out at intervals of 0.02 sec from the records, and auto-corelation function and Fourier spectrum were calculated by means of the Fast Fourier Transformation. Fig. 2 shows an example of Fourier spectra of five horizontal components observed on June 12, 1978. The shock is considered to be a foreshock of the Miyagiken-Oki earthquake of 1978. It is well recognized from Fig. 2 that the higher the position of transducer is, the larger becomes the acceleration. Predominant frequencies in this case are 3.2 to 3.6, 4.6 and 6.5 Hz. It should be noted that the predominant frequencies lie within a certain extent, regardless of the predominant frequencies of seismic waves propagated to the dam base.

Calculating the ratio of acceleration spectrum at each observation points to that of the dam base, resonance curve can be obtained. Fig. 3 is the resonance curve corresponding to the previous figure. It is clearly seen from this figure that the natural frequency of the first order is 3.7 - 3.8 Hz and that of second order is 5.1 Hz and that the vibration is amplified in proportion to the height. Damping factors estimated from the resonance curves are in the range of 0.042 to 0.091 and the average value is 0.067. Damping factor seems to increase as the maximum acceleration at the base increases. For each resonant frequency the vibrational mode can be derived from the resonance curves as shown in Fig. 4. These figures indicate that the first and second modes of vibration dominate during earthquakes and large amplitude would be expected at the upper part of the dam body. The maximum input acceleration α_g observed at the base is related to the maximum response acceleration at the crest α_c as shown in Fig. 5. The relation can be described as

$$\alpha_c = 1.95\ \alpha_g^{0.90} \quad \text{for horizontal component} \qquad (1)$$

$$\alpha_c = 1.92\ \alpha_g^{0.84} \quad \text{for vertical component} \qquad (2)$$

The validity of these equations for strong earthquakes should be ascerby further investigation.

LINEAR RESPONSE ANALYSIS

The method of earthquake response analysis made remarkable progress with the development of electronic computers. Especially finite element method is one of the most applicable technique for soil dynamic. In order to calculate response of fill dams to earthquakes, dam body is often idealized in two-dimensional finite element model. In case of the Tarumizu rockfill dam, however, the dam body was constructed on a narrow valley and the effect of lateral constraint by the configuration could not be neglected. Accordingly a three-dimensional finite element model was considered for major part of the dam body, and the left bank side of the embankment was excluded from this model. The model consists of 104 nodal points, 321 tetrahedral elements or 66 frustum elements. Material constants affecting the natural frequencies of the model are Young's modulus, Poisson's ratio and density of fill materials. Among these constants the last two were given from the test data. Young's modulus of core material and rockfill was so decided that the natural frequency of the first order coincides with the observed value of 3.8 Hz. Namely Young's modulus of core material Ec was assumed as 50,000 t/m^2 and that of rockfill material as 90,000 t/m^2.

In order to calculate the response of the dam model by modal analysis, first ten modes and natural frequencies were obtained. Fig. 6 shows some vibrational modes obtained by this analysis. The first mode is a horizontal symmetrical mode in X-axis direction with the natural frequency of 3.8 Hz. The second mode is also horizontal symmetrical one in Y-axis direction. The fourth is a vertical vibrational mode with the natural frequency of 5.1 Hz, which would be good approximation of observed natural frequency of 5.1 to 5.7 Hz for vertical vibration.

The acceleration records observed at the base were used as input earthquake to this model. The first ten modes were taken into consideration in order to calculate the response. Damping factor was assumed as 0.15 to get a good approximation of the response. This value of damping is very large in comparison with the observed values. The difference may be caused by the energy dissipation from the boundaries. An example of the response at the crest of the dam to the input wave is shown in Fig.7. Observed acceleration is also shown as a dotted line in the same figure. Since the two resembles each other very much, the assumption would be acceptable.

NON-LINEAR RESPONSE ANALYSIS

In the previous section some results of linear response analysis were mentioned. But in case of strong earthquake fill material would no longer be linear elastic. If the earthquake were so strong that the rockfill dam were damaged, some parts of soil element in the dam body would have been in plastic state. There are two ways of thinking in order to evaluate the non-linearity of soils. One is the elasto-plastic analysis based on the yield function of soils, and the other is the psuedo-elastic analysis based on the strain dependency of elastic constants of soils. The former is the best way to evaluate the dynamic stability of dams, and the latter is the suitable method for evaluating the hysteretic characteristics of soils. The purpose of this research is not to study the stability of dams but to investigate the dynamic behavior of dams during strong earthquakes. Therefore the hysteretic characteristics of soils are taken into consideration.

It is already well known that Hardin and Drnevich found that the rigidity of soils varies with void ratio, mean stress and strain itself. (Hardin, B.O. et al, 1972) They defined hyperbolic strain γ_h as

$$\gamma_h = \frac{\gamma}{\gamma_r} \left[1 + a \exp\left(-b\frac{\gamma}{\gamma_r}\right)\right] \tag{3}$$

where a and b are constants and

$$\gamma_r = \tau_{max} / G_{max} \tag{4}$$

Gmax is the maximum value of shear modulus, which is given from the initial value of Young's modulus Emax.

$$G_{max} = E_{max} / 2(1+\nu) \tag{5}$$

τ_{max} is shear strength of material, which is given for each element. Shear modulus G can be calculated from the equation

$$G = G_{max} / (1 + \gamma_h) \tag{6}$$

In this study only one component of shear strain γ_{zx} is considered as the parameter strain which is affecting the shear modulus. The vertical and the horizontal normal to the dam axis are defined as Z and X coordinate axis respectively.

Fig. 8 shows the horizontal accelerograms recorded in the dam gallery. Maximum acceleration in the direction of normal to dam axis is 180.6 gal and 234.9 gal in the direction of the dam axis. These two components are used as input waves to the finite element model. Non-linear analysis is carried out for a time interval of 2 sec, in which the maximum response is expected. Initial values used for this calculation are obtained by linear analysis. In each time step the stiffness matrix is reconstructed, untill the strain converges to a certain value within a certain range of errors. The calculated response at the crest is shown in Fig. 9. The maximum acceleration in X direction (normal to dam axis) is 354.0 gal and this is smaller than that of linear analysis by 7.4%. The magnification factor is 1.96 for non-linear analysis. In the same figure the response in Y direction is also given. In this case difference between non-linear analysis and linear analysis is not clearly seen. This is quite understandable because the reduction in the shear modulus was considered only in one direction. The variation of natural period due to the reduction in rigidity of the system is shown in Fig. 10. Natural period of the first order becomes 1.21 times longer than the initial value at the maximum.

In the analysis mentioned above the damping factor is defined as a constant, and relatively large value is given to the system. If we assumed that the damping factor is strain dependent, then smaller value shall, in general, be given as the damping factor. But with such a smaller value of damping good approximation can not be attained. So we could assume that the damping factor increases as the natural period increases and that this is given by the equation

$$h = h_o \left(\frac{T}{T_o} \right)^{\beta} \tag{6}$$

where ho and To are respectively initial values of damping factor and natural period. As is mentioned above, the natural period varies as the rigidity changes. Effect of β in Eq. 6 on the response is shown in Fig. 11. Maximum acceleration in X direction is 344.1 gal for β=2.0 and 334.9 gal for β=4.0. Magnification factors are 1.91 and 1.86 respectively. These facts indicates that the effect of damping factor is much larger than that of non-linearity of elastic modulus. The reduction in Young's modulus in the maximum strain state is illustrated in Fig. 12, in which γ_{zx} is in the range of 1.0 to 2.5 x 10^{-4}. Reduction in the Young's modulus is quite a lot in the elements near slope surface. This could give an explanation of the cause of slope failures. However it must be stressed that the Tarumizu rockfill dam was not damaged by the earthquake although the response acceleration was estimated to be more than 300 gal.

CONCLUSIONS

Observation of earthquakes on a rockfill dam was carried out and vibrational characteristics of the dam were investigated. The results may be summerized as follows:

1. The response of the dam can be well approximated by the three-dimensional finite element model.
2. Non-linear response analysis indicates that the reduction in elastic constant results in increase in maximum displacement and decrease in maximum acceleration.
3. Reduction in magnification factor due to non-linearity is not so large as is expected.
4. The rockfill dam is still safe to this class of intensity of earthquake.

ACKNOWLEDGEMENT

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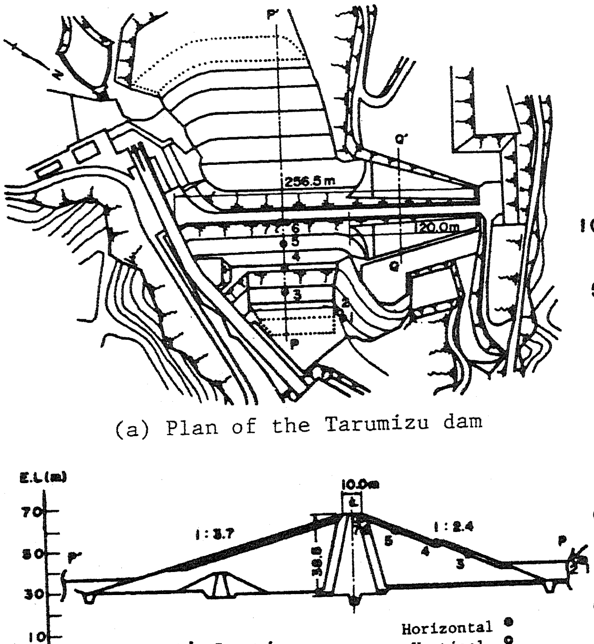

(a) Plan of the Tarumizu dam

(b) P-P' Section

Fig. 1 Plan and Section of the Dam

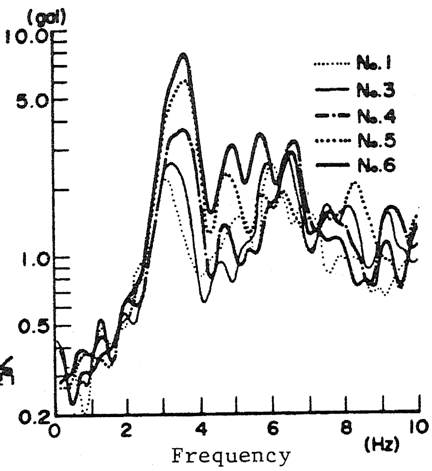

Fig. 2 Fourier Spectra

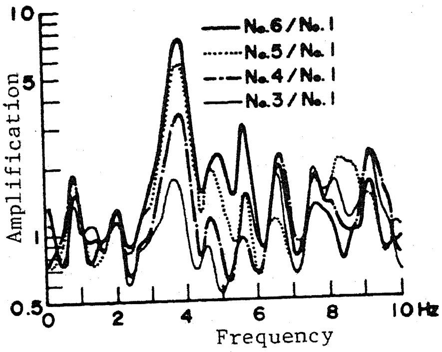

Fig. 3 Resonance Curves

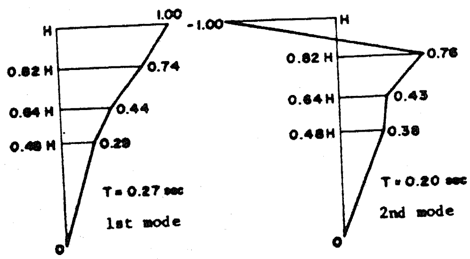

Fig. 4 Vibrational Modes

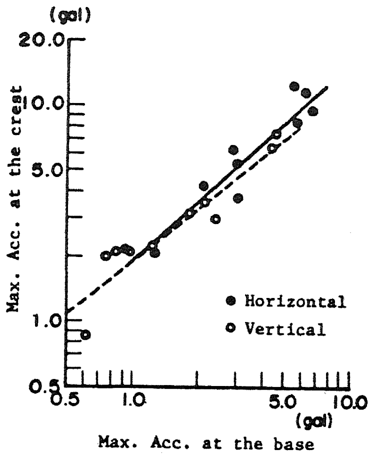

Fig. 5 Relation of Maximum Acceleration

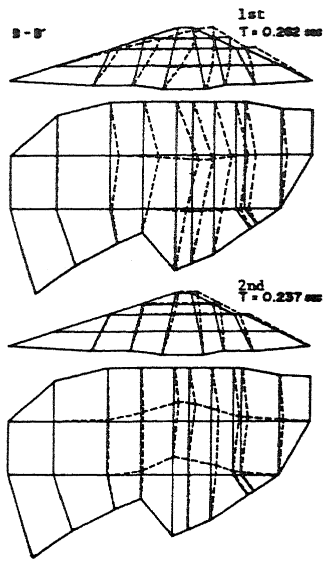

Fig. 6 Vibrational Modes

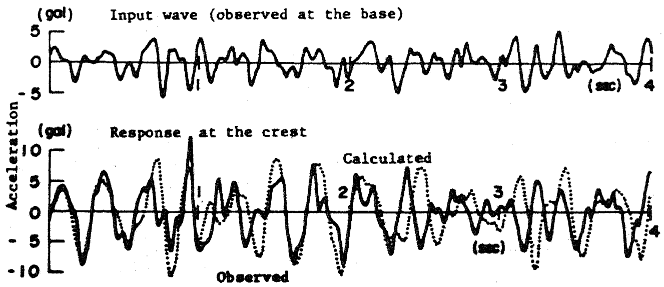

Fig. 7 Response of the Dam to an Input Wave

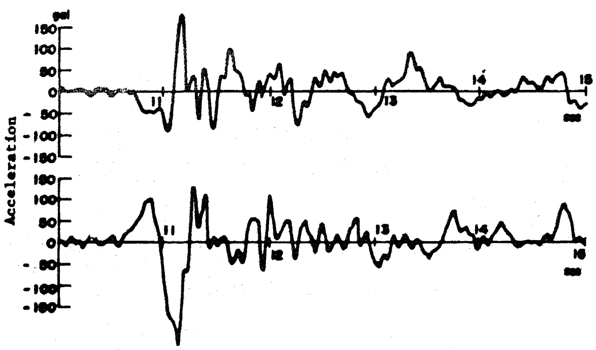

Fig. 8 Strong Motion Earthquake observed in the Gallery

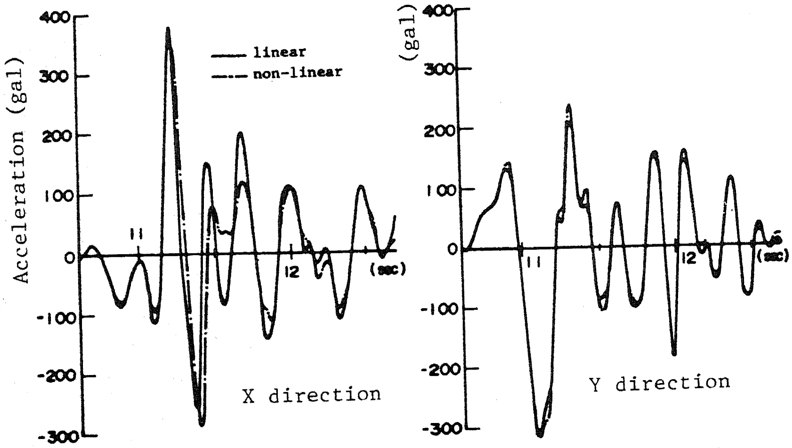

Fig. 9 Results of Linear and Non-linear Analysis

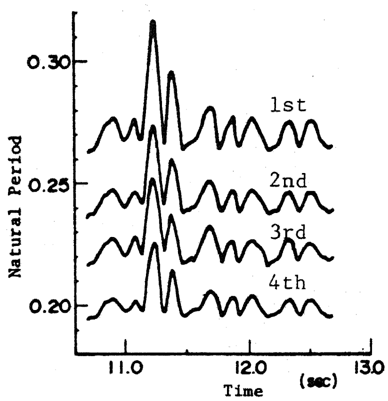

Fig. 10 Variation of Natural Period

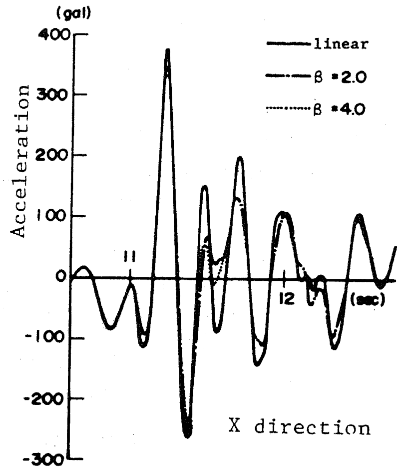

Fig. 11 Effect of β

Fig. 12 Reduction of Young's Modulus in Dam Body