Proceedings of Ninth World Conference on Earthquake Engineering
August 2-9, 1988, Tokyo-Kyoto, JAPAN (Vol.VI)

10-3-5

SEISMIC BEHAVIOR OF A ROCK TUNNEL

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SUMMARY

In order to investigate the seismic behavior of a cavern and the surrounding rock, earthquake observations have been carried out in the rock tunnel started July,1983. From the analysis of the observed data and the dynamic response analysis using the boundary element method, the characteristics of the earthquake motion in rock, deforming behavior of the cavern, and the simplified method to estimate the strain of the cavern from the particle velocity of the surrounding rock were clarified. The availavility of this simplified method was verified by comparing the values estimated by this method with the observed data.

INTRODUCTION

In recent years, new type of structures such as underground nuclear power stations, storage caverns for high level radioactive nuclear waste disposal, and oil storage caverns have been planned. In Japan, for these structures which are to be constructed in seismic region, reliable seismic design should be achived based on the observed data.

However, a quantitative method of evaluating seismic stability based on the observed data is yet to be established, and from the viewpoint that seismic designs providing high reliability will be required in the future utilization of rock caverns, it is considered necessary to understand the phenomena based on the observed data.

Therefore, in order to clarify the seismic behavior of a cavern and surrounding rock based on the observed data, we, in cooporation with East Japan Railway Company, carried out earthquake observations in Shin-Usami Tunnel of JR,s Itoh Line started July,1983(Refs.1,2).

This report deals with the seismic behavior of a cavern and the surrounding rock, and the simplified method to estimate the strain of the cavern clarified from the observed data and the dynamic response analysis using the boundary element method.

OUTLINE OF EARTHQUAKE OBSERVATION

Shin-Usami Tunnel is a single tracked railway tunnel having a 3000 m of overall length. Its internal cross section has a circular form with inner diameter of 6 m, and the lining concrete is 30 cm in thickness. The observation section is a 100 m section located at approx. 1500 m from each entrance, and the depth from top of the mountain is approx. 260 m. The observation section is composed mainly of Alternated Basalt, and the velocity of the S wave Vs is 1.1 to 1.6 km/sec.

The earthquake observation is carried out using 8 accelerometers including one at the entrance, 10 strain guages set on the lining concrete, and 6 strain guages set in the rock. Fig.1 and Fig.2 show the layout of measuring instruments for the earthquake observation,and Fig.3 shows the position of epicenters of the earthquake observed.

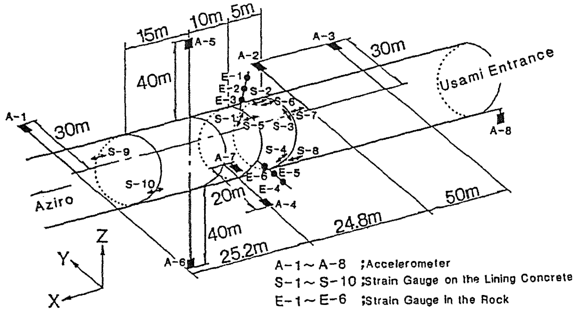


Fig.1 Layout of Measuring Instruments

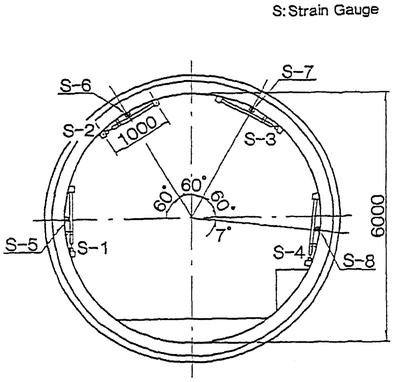


Fig.2 Layout of Strain Gauges on the Lining Concrete

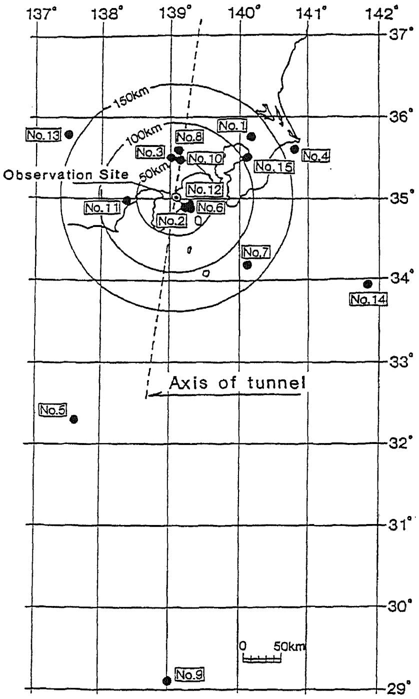


Fig.3 Epicenters of Observed Earthquakes

PRINCIPAL AXIS OF EARTHQUAKE AND WAVE PROPAGATION

Calculation method for principal axis of earthquake To clarify the properties of earthquake motion in rock, the principal axes of observed earthquake were studied. In calculating the principal axes of earthquake motion: 1) principal axes I ... the principal axes varying in time domain (t), where the cross power spectrum at time (t) becomes the maximum, medium,and minimum and 2) principal axes II ... the fixed principal axes, along which the total energy becomes the maximum, medium and minimum, are used out of the methods using the cross power spectrum proposed by Hoshiya(Ref.3).

Direction of fixed principal axis Fig.4 shows the direction in horizontal plane (x-y plane) and the direction in vertical plane (z-x,y plane) of the fixed maximum principal axes of earthquake motion in rock A-4. According to this study performed in a deep rock, both the maximum and intermediate principal axes can be considered to have the possibility to become relatively near the direction of epicenter(Ref.2)

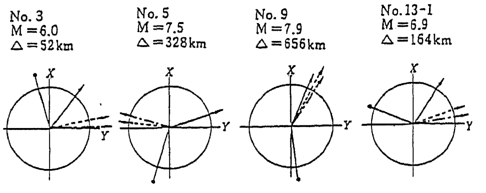
Also,the degree of correspondance of these principal axes with the direction of epicenter cannot be said to be so good as was said conventionally, as a whole. As the reason for this, it may be pointed out that the dominant vibration direction in earthquake motion is influenced not only by the direction of epicenter, but also by the geology along a path through which the earthquake motion propagates to reach the observation point, topographical variation, or reflection and refraction of wave motion at the observation point.

As for the direction of fixed maximum principal axis in a vertical plane, it is considered to be near the horizontal direction, as was reported conventionally. Consequently, it can be assumed that,near the observation point,the earthquake motion propagates vertically in any earthquake.

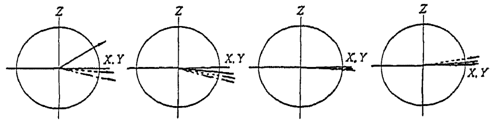
Maximum principal axis varying in time domain Fig.5 shows the variation in time domain of the horizontal and vertical angles of the maximum principal axis of acceleration in rock A-1 - A-7 for earthquake No.3. Here, the horizontal angle is the one extending from the X-axis to the Y-axis at the observation point and the vertical angle is the one extending from the Z-axis to the X-Y plane.

From Fig.5, the principal axes of earthquake motion cannot be said to be fixed throughout the duration time of an earthquake motion, and particularly during and after the main motion, they are considered to vary largely.

Also, the fact that the vertical angle of maximum principal axis is near 0 degree or 180 degrees during the initial motion and it varies around 90 degrees during and after the main motion, is presumably indicating that, during the initial motion, the primary wave propagating vertically becomes eminent,and during and after the main motion, shear wave propagating vertically becomes eminent.



(a) Direction of Fixed Maximum Principal Axis in the Horizontal Plane



(b) Direction of Fixed Maximum Principal Axis in the Vertical Plane

No: Earthquake No.
M: Magnitude
△: Epicentral Distance

——— Acceleration
- - - - - - Velocity
—·—·— Displacement
———→ Direction of epicenter

Fig.4 Direction of Fixed Principal Axes in Rock(A-4)

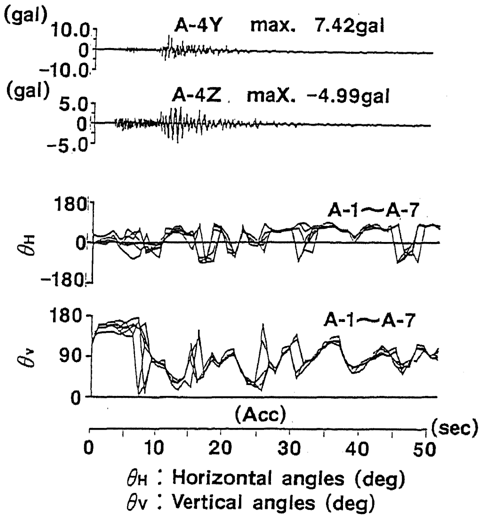


Fig.5 Variation of Maximum Principal Axis in Time Domain,Earthquake No.3

DEFORMATION MODE OF A CAVERN

In the case of this observation site, Vs is 1 to 1.6km/sec, and from the observed results, the predominant period of the spectrum of earthquake motion is 1 to 2 sec for earthquake in remote places and 0.3 to 0.5 sec for those in near places. Therefore, the wavelength passing the cavern is estimated as 1000 to 4000 m at the longest, and 300 to 1000 m at the shortest. Since the tunnel currently observed has a circular cross section of 6 m in inner diameter, the ratio of the diameter of the tunnel to wavelength of incident wave is 1/170 to 1/670 for long wavelength and 1/50 to 1/170 for short wavelength, and it is considered that a first deforming mode is dominant in each case.

Fig.6 relates to the earthquake No.5 and shows the strain waveforms S-1, S-

2, S-3, and S-4 in the circumferential direction of tunnel lining during the main motion for 10 sec. In order to distinguish the correlation of waveforms, these waveforms are applied with 0.2 - 1.2 Hz narrow band pass filter where the power spectrum of strain is eminent.

From Fig.6, by comparing the time history of the main motions among S-1, S-2, S-3 and S-4, the phase of S-1, S-2 and S-4 is nearly the same, and that of S-3 is reverse of those.

From the waveform of circumferential strains, the tunnel in the lateral direction, is considered to be governed by a first deforming mode as shown in the right half of Fig.6.

Fig.7 shows the mode of circumferential strain of the cavern in such the case that the harmonic wave of 1Hz to the upward direction was employed as the input motion of primary wave and shear wave. The in-house program code DCAVERN based on the boundary element method was employed for the harmonic wave response analysis from the viewpoint that the elements necessary to set can be decreased to only at the boundary of the model compared with those by FEM, therefore, this method has the advantage in especially dealing with the cavern existing deep from the surface.

From Fig.7, in the cross section of the tunnel, the strain triggered by the elliptical deformation accompanying the propagation of the primary wave in the upward direction is prominent in the side wall, and the strain triggered by the shearing deformation accompanying the propagation of the shear wave in the upward direction is prominent in the crown. By comparing the calculated results in Fig.7 with the deformation mode of the observed data in Fig.6, it can be pointed out that the cavern is mainly governed by the shearing deformation during the main motion.

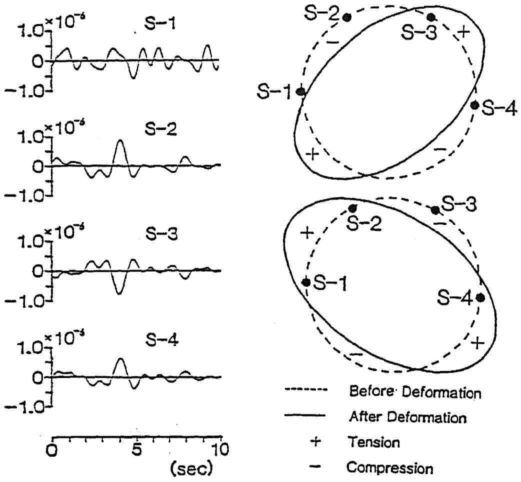


Fig.6 Filtered Strain of the Lining and Deformation Mode of the Cavern

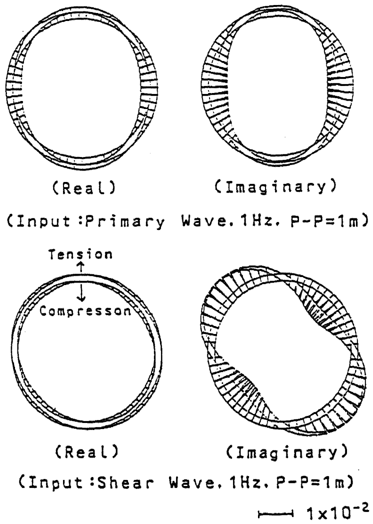


Fig.7 Strain of Cavern (Harmonic Wave Response Analysis)

SIMPLIFIED METHOD TO ESTIMATE THE STRAIN OF THE CAVERN

It has been currently pointed out that the strain of the surrounding rock is in good proportion to the particle velocity of the point. And,additionally,as the rock cavern behaves together with the surrounding rock as mentioned before when it is subjected to earthquake motion which propagates nearly vertically ,the strain of the cavern can be supposed to be dominated by the strain of the surrounding rock. In this chapter, based on these facts, the simplified method to estimate the strain of the cavern from the particle velocity of the surrounding rock is investigated.

Relation between the strain and the particle velocity in the surrounding rock In the surrounding rock of the cavern, the relation between the strain and the particle velocity can be shown as follows if the earthquake motion at that point is defined by only incident wave(Ref.4).

Er(t) = V(t) / Vp,s (1)

Er(t) ; strain of the surrounding rock
V(t) ; particle velocity
Vp,s ; propagation wave velocity

In such the case as Shin-Usami Tunnel that the cavern exists deep enough from the surface, this equation may be applied to estimating the strain of the surrounding rock judging from the fact that the degree of the influence of the reflecting wave on the incident wave may be small.

Relation between the strain of the cavern and that of the surroundig rock The ratio of the circumferential strain of the circular shape cavern to the strain of the surrounding rock was calculated by the harmonic response analysis using boundary element method. Fig.8 shows the ratio of the strain at the side wall(s-1) to the axial strain of the surrounding rock(r_p) when the primary wave propagating vertically was employed and the ratio of the strain at the crown(S-3) to the shear strain of the surrounding rock(r_s) when the shear wave propagating vertically was employed on each normalized frequency. These ratios in Fig.8 are the results on the cavern without lining concrete.

Fig.9 shows the reduction factor which should be considered when the lining concrete is taken into account. This reduction factor was calculated using the above mentioned harmonic response analysis on the cavern with lining concrete, the shear modulus of which was set to be $2.2\text{x}10^6 \text{tf/m}^2$ available in Shin-Usami Tunnel.

From Fig.8 and Fig.9, the relation between the circumferential strain of the cavern and that of the surrounding rock can be estimated as follows, if the earthquake motion of the surrounding rock is dominated by the frequencies in which the ratios shown in Fig.8 are constant.

Es(t) = a1*a2*Er(t) (2)

Es(t) ; circumferential strain of the cavern
a1 ; ratio of the circumferential strain to that of surrounding rock on the cavern without lining concrete
a2 ; reduction factor when lining concrete is taken into consideration
Er(t) ; strain of the surrounding rock obtained from equation (1)

Verification of the estimating method Fig.10 and Fig.11 show the observed circumferential strains and those calculated by the above mentioned estimating method. As the particle velocity in estimating the circumferential strain, the

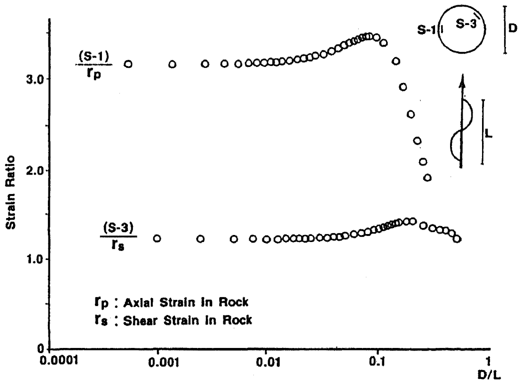


Fig.8 Ratio of Strain of a Cavern to That of Surrounding Rock

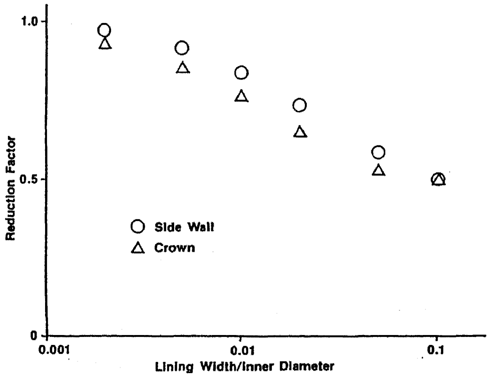


Fig.9 Reduction Factor of Strain Ratio

particle velocity to upward direction(A-7Vz) for the strain of the side wall(s-4) and that to horizontal direction (A-7Vy) for the strain of the crown(s-3) were used. The ratio 'a1' in equation (2) can be set as 3.16 and 1.22 for side wall and crown respectively from Fig.8. And the ratio a2 can be set as 0.59 and 0.53 respectively from Fig.9. So, a1*a2 leads to 1.85 and 0.65 for side wall and crown respectively. From Fig.10 and Fig.11, the simplified method to estimate the strain of the cavern illustrated by equation (1),(2) is available for the cavern deep in the rock.

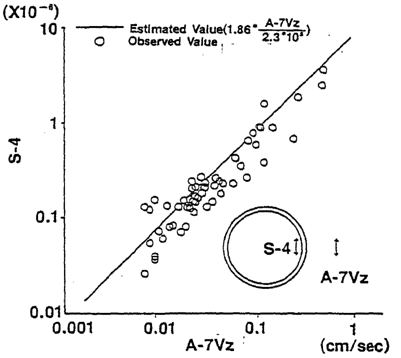


Fig.10 Relation between the Strain of Cavern and the Particle Velocity in Rock(S-4 and A-7Vz)

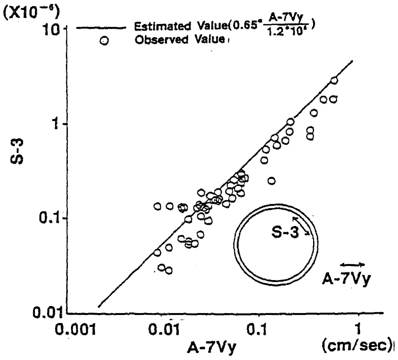


Fig.11 Relation between the Strain of Cavern and the Particle Velocity in Rock(S-3 and A-7Vy)

CONCLUSION

From the analysis of the observed data and the dynamic response analysis using boundary element method, the following effective results on the seismic design of the underground structures were obtained.

1. In the rock around the cavern, the primary wave of the initial motion and the shear wave of the main motion propagate in the upward direction neraly vertically.
2. In the cross section of the tunnel, the strain triggered by the elliptical deformation accompanying the propagation of the primary wave in the upward direction is prominent in the side wall, and the strain triggered by the shearing deformation accompanying the propagation of the shear wave in the upward direction is prominent in the crown.
3. The strain of the cavern can be estimated from the particle velocity of the surrounding rock by making use of the ratio of the cavern to that of the surrounding rock obtained from harmonic response analysis.

ACKNOWLEDGMENTS

As aforementioned, this observations was conducted in cooperation with JR, and in this connection, we would like to express our sincere thanks to those concerned to East Japan Railway Company and Railway Technical Research Institute for kindly permitting the publication of the observed results.

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