COMPARISON BETWEEN SURVEYED AND ESTIMATED DEFORMATIONS OF TUNNEL STRUCTURES IN FOCAL REGION

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SUMMARY

Due to the Izu-Oshima-Kinkai earthquake of 1978, the Inatori Tunnel, a single-track railway tunnel in Japan, was severely damaged. This damage was mainly caused by the main fault and a subsidiary fault which is estimated to have transversed the tunnel. This paper has the purpose of contributing to the earthquake-resistant design procedure of the tunnel in the source region by estimating its deformation using the fault mechanical model, and by comparing it with the surveyed residual deformation.

PREFACE

Due to the Izu-Oshima-Kinkai earthquake of January 14, 1978 (Richter magnitude of 7.0), the Inatori Tunnel of the Izu-Kyuko Corp. was severely damaged. This tunnel, located on the east side of the Izu Peninsula in Japan, is a single-track railway tunnel of 906 meters in length. This damaged situation has been surveyed in detail by several investigators (Refs.1-5), and it is indicated that this damage was mainly caused by the main fault and a subsidiary fault which is estimated to have transversed the tunnel.

The objective of this paper is to evaluate the performance of available mathematical models of earthquake wave propagation by taking advantage of the actual damage data of this tunnel. This paper has also the purpose of contributing to the earthquake-resistant design procedure of the tunnel in the source region by estimating its deformation using the fault mechanical model. This model, which has been developed mainly in seismology, is of great advantage not only to providing a good estimation of the seismic wave especially in the relatively-long-period component, which is closely connected with the safety of underground structures (Ref.6), but also to supplying a method for estimating the incident wave due to a large earthquake in the source region, where few seismograms have been obtained. In this paper, using a previously proposed set of fault parameters, the behavior— the longitudinal, transverse and vertical displacements — of the axis of the Inatori tunnel is computed. And these computed results are compared with the surveyed residual deformation.

FAULT MODELS

The fault models used in this paper are the most fundamental ones and were developed without using the approximation that the observation point is far from the hypocenter, because the ground motion within the source region is dealt in this paper. One of them is a model in the infinite

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medium proposed by N.A. Haskell (Ref.7). The other is a model in the semi-infinite medium developed by Kawasaki, Suzuki and Sato (Ref.8). The latter model seems to give the more accurate result than the former one, because the latter one considers the effects of the free surface. In the calculation a ramp displacement function is approximated as a time function of dislocation.

EXAMINATION OF NUMERICAL SEISMOGRAMS DUE TO POINT-SOURCE FAULT MODEL

In this section the numerical seismograms due to the point-source in each of the above-mentioned infinite and semi-infinite mediums are computed. And the effects of the ground surface on the numerical seismograms are examined(Ref.8).

Fig. 1 shows the coordinate system and the point source which is 10 km in depth and slips in the vertical (x_3) direction (dip slip) or in the horizontal (x_1) direction. And the numerical seismograms at observation points are calculated. In the calculation P and S wave velocities are assumed to be 6 and 3.5 km/s, respectively; the density of the

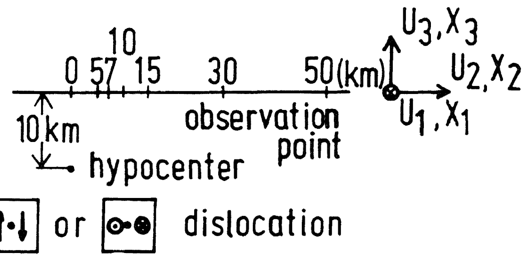

Fig.1 Coordinate System and Point Source

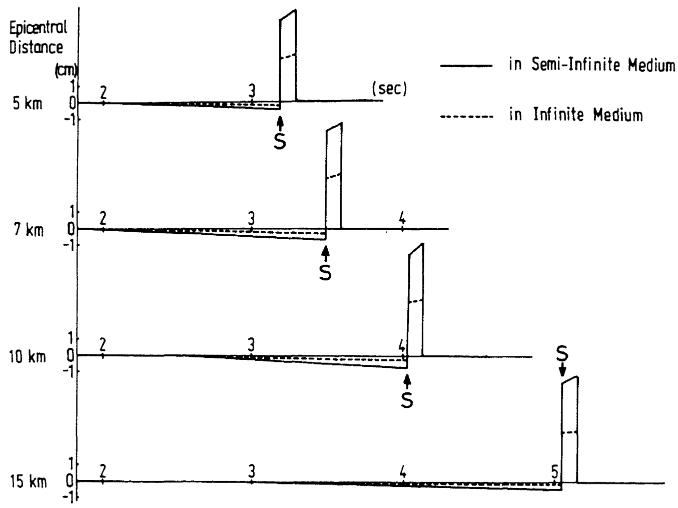

Fig.2 U_1 Component for Various Epicentral Distances

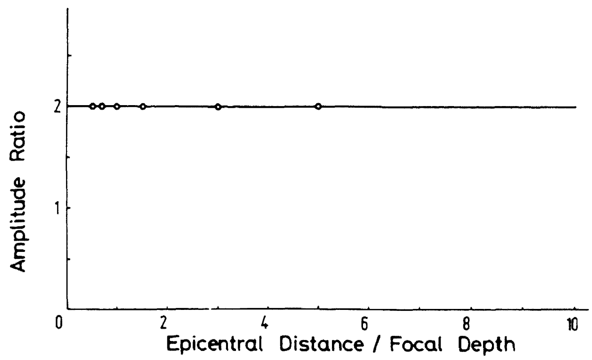

Fig.3 Ratios of Amplitude in Semi-Infinite Medium to That in Infinite Medium

ground is 2.7 g/cm^3; the seismic moment function is a ramp function with rise time of 0.1 sec and the final value of 10^{24} dyn·cm.

Fig.2 shows the U_1 component due to the strike slip at each of the observation points whose epicentral distances are 5, 7, 10 and 15 km. The displacement of SH wave occurs discontinuously, and the duration time of the pulse is just as the same length as the rise time. Defining the amplitude of SH wave as the jump of the displacement, the ratio of this value for the semi-infinite medium against that for the infinite medium is plotted in Fig. 3 as the function of the value of the epicentral distance divided by the focal depth. This ratio is 2 and is in good agreement with the two-dimensional theory of the plane sinusoidal wave, which is shown in solid line.

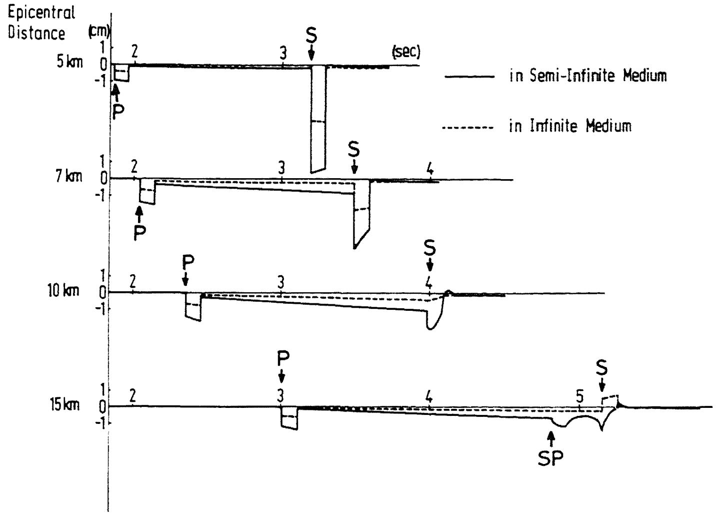

Fig.4 U_2 Component for Various Epicentral Distances

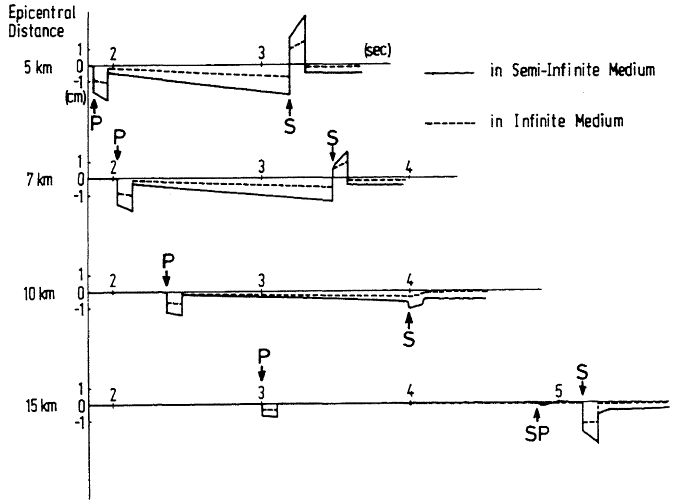

Fig.5 U_3 Component for Various Epicentral Distances

Figs.4 and 5 show the radial and vertical displacements, U_2 and U_3, respectively, for the dip slip, which produces zero displacement in x_1 direction due to its symmetry. For the infinite medium two phases are recognized; each arrival time is coincident with the value of the hypocentral distance divided by the velocity of P or S wave. For the semi-infinite medium two more phases—SP and Rayleigh waves— are recognized. The displacement of P wave and also that of S wave within the critical distance (about 7.2 km) begin discontinuously, and the duration of the pulse is just as the same time as the rise time. Defining the amplitude of P or S wave as the jump of the displacement as the former SH wave case, the ratio of this value for the semi-infinite medium against that for the infinite medium is plotted in Fig. 6 as the function of the value of the epicentral distance divided by the focal depth. These ratios are in good agreement with the two-dimensional theory of the plane sinusoidal wave, which is shown with solid and dashed lines.

One notices that the idea that the ground surface duplicates the surface displacement is approximately true for incident SH and P waves and for SV wave within the critical distance. However, beyond the critical distance even the direction of the displacement due to S wave changes due to the occurrence of the surface wave. The examination in this section is believed to guarantee the accuracy of the mathematical models of earthquake wave propagation, and is also useful to examine the results in the following section.

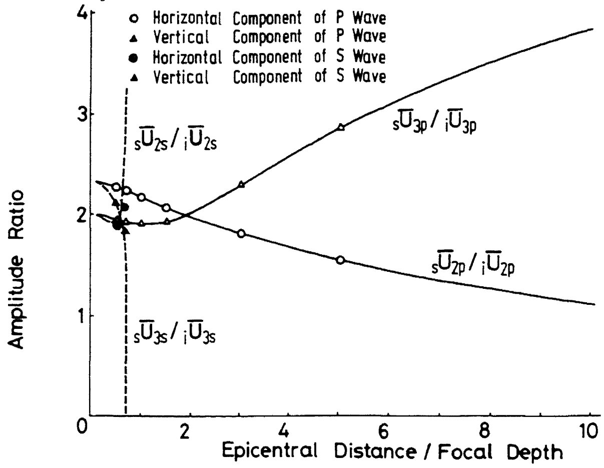

Fig.6 Ratios of Amplitude in Semi-Infinite Medium to That in Infinite Medium

COMPUTATION OF DEFORMATION OF TUNNEL AXIS USING FAULT MODEL

Shimazaki and Somerville (Ref.9) have proposed the fault parameters of the mainshock of the Izu-Oshima-Kinkai earthquake of 1978 based on a number of seismograms, spectral radiation patterns, surveyed level change, extent of the aftershock zone, etc. In this analysis, these proposed values shown in Table 1 and Fig. 7 are used. Moreover, for the subsidiary fault, which is observed on the land and is called the Inatori-Omineyama fault (Ref.9), fault parameters have been estimated as shown in Table 1. The rupture of the main fault is

Table 1 Parameters of Main and Subsidiary Faults

Parameters \ Fault	Main Fault	Sub Fault
Fault Length	17 km	3.0 km
Fault Width	10 km	1.5 km
Fault Strike	N90°W	N51°W
Dip Angle	85°North	75°North
Slip Angle	188°	180°
Dislocation Right Lateral Strike Slip	183 cm	70 cm
Dislocation Normal Dip Slip	26 cm	0 cm
Rupture Velocity	2.8 km/s	2.8 km/s
P Wave Velocity	6.0 km/s	6.0 km/s
S Wave Velocity	3.5 km/s	3.5 km/s
Rise Time	2.0 sec	2.0 sec

assumed to start at its eastern end, to propagate to the west at a constant speed of 2.8 km/s, and to arrive at the western end in about 6 seconds. Then the rupture of the subsidiary fault is assumed to begin successively at the southeastern end and to propagate northwestward.

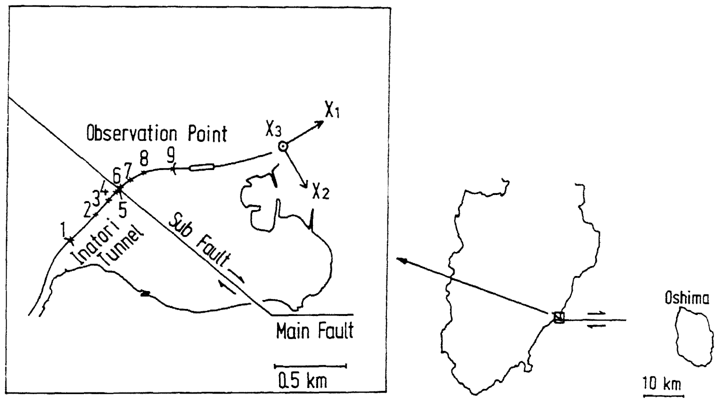

Fig.7 Main and Subsidiary Fault, Inatori Tunnel and Observation Points

The Inatori tunnel of the Izu-Kyuko Corp. is located near the western end of the main fault, and was traversed by the subsidiary fault as shown in Fig. 7. This tunnel is a single-track railway tunnel of 906 meters in length. The depth of this tunnel is about 100m at its central portion. It is excavated through deposit of volcanic mud and is covered with concrete lining structures of about 70cm in thickness. The southwestern half of this tunnel is in a straight line, while the northeastern half is in a curved line with a radius of 500 m. In this section the displacements at each of the points from 1 through 9 along the Inatori tunnel (see Fig.7) are computed. The points 1 and 9 locate near the both ends of the tunnel. Then by transforming the coordinates, the longitudinal, transverse and vertical displacements in the coordinate system x_1-x_2-x_3 shown in Fig. 7 are computed at each second since the rupture of the main fault has begun till the final residual deformation is attained. In this computation the coupling between the ground and the structure is ignored, based on the results of the previous investigations that the behavior of the underground structure is similar to that of the surrounding soil (Ref.6).

The displacement of the tunnel axis are computed by the use of the fault model in each of the infinite and semi-infinite mediums. The longitudinal, transverse and vertical displacements due to the main and subsidiary faults in the semi-infinite medium are shown in Figs. 8 through 10, respectively. The parameter in Figs. 8 through 10 indicates the time in second since the main fault has begun rupturing. The thick solid lines in these figures show the computed residual displacements of the tunnel axis, while the thin lines show the surveyed residual displacements, which will be explained in the following section.

COMPARISON BETWEEN SURVEYED AND COMPUTED DISPLACEMENTS

The longitudinal displacement, which has not been surveyed precisely, is estimated as follows based on the measured clearance of the rail joint of ajoining rails and the relative displacement between the rail and the ground which was measured as the scratched length on the flange of the rail by the dog-spike fixed in the sleeper on the ballast.

(Longitudinal displacement at a point) = Σ [(Clearance of the rail joint after the earthquake)-(Clearance of the rail joint before the earthquake)]+ (Relative displacement between the rail and the ground at the point)

In this equation the summation should be taken for all clearances between the southern (northern) entrance of the tunnel and the observation point, when the relative displacement against the displacement at the southern (northern) entrance of the tunnel is estimated. In this study the measured values by Tsuneishi, et al.(Ref.3) are used as to the clearance of the rail joint after the earthquake and the relative displacement between the rail and the ground. The clearance before the earthquake is assumed to be a standard length of 6 mm. The estimated real displacement from the above equation is shown in the solid thin line in Fig. 8.

The transverse and the vertical displacements have been surveyed accurately by the Izu-Kyuko Corp.(Refs.2,5). The transverse displacement of the center line is shown by solid thin lines in Fig. 9. And the vertical displacements at the rail and ceiling levels are shown by thin lines in Fig. 10.

Comparing the computed and surveyed results, one notices that the computed result cannot explain the detail of the surveyed one. As for the longitudinal displacement the point where remarkable elongation occured actually is apart from that point estimated from the calculation by about 120 m. This difference can be explained by the observation that "during the repairing work of the tunnel, horizontally slipped lines were recognized on the inner surface of the tunnel behind the removed lining (Ref.4)", which indicates that the tunnel lining was dragged along the longitudinal direction in the ground. This is one example that coupling between the ground and the underground structure existed.

However, the computed results are similar to the smoothed ones of the surveyed displacements. In order to compare the computed and surveyed results roughly the difference of the residual displacements near the both entrances of the tunnel, the observation numbers 1 and 9, is read for each direction and for each medium.

As for the longitudinal displacement tension is caused in each cases; about 30 cm for the infinite medium, about 50 cm for the semi-infinite medium and about 40 cm for the surveying. As for the transverse direction the ground produces a righthanded rotation in all of three cases; about 30 cm for the infinite medium, about 60 cm for the semi-infinite medium and about 75 cm for the surveying. As for the vertical direction the northern entrance of the tunnel subsides more than the southern entrance by about 5 cm for the infinite medium, by about 15 cm for the semi-infinite medium and by about 15 cm for the surveying. Then for each of three components the trend of deformation in three cases coincide with one another in a qualitative sense, and in a quantitative sense a good coincidence is recognized between the displacement for the semi-infinite medium and the surveyed value.

In addition to the surveyed results mentioned above, several investigators have made comments on the deformation of this tunnel. Hakuno et al. (Ref.1) pointed out that the tunnel was elongated near the location where the subsidiary fault traversed based on their own measured results of the joint clearance of ajoining rails. They also indicate that the tunnel was compressed near its southern entrance based on the fact that the buckling of the rail occured at that location. In this paper without using the heterogeneity of the ground it is clarified that the computed results can explain both the occurrence of enlarged cracks (elongation) at the section where the subsidiary fault transversed the tunnel, and also the buckling of the rail (compression) at the southern entrance of the tunnel.

CONCLUSIONS

In this paper, the fault mechanism model, which has been developed mainly in seismology, is applied to the estimation of the behavior of the underground tunnel structure when it was hit by the faulting and the released wave from it. This model not only provides a good estimation of the seismic wave especially in the relatively-long-period component, which is closely con-

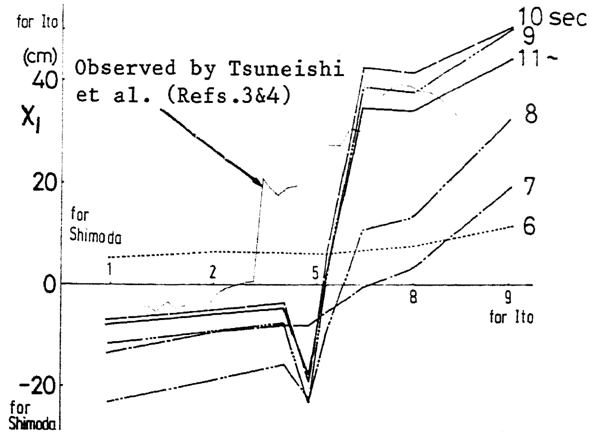

Fig.8 Longitudinal Displacement due to Main and Subsidiary Faults in Semi-Infinite Medium

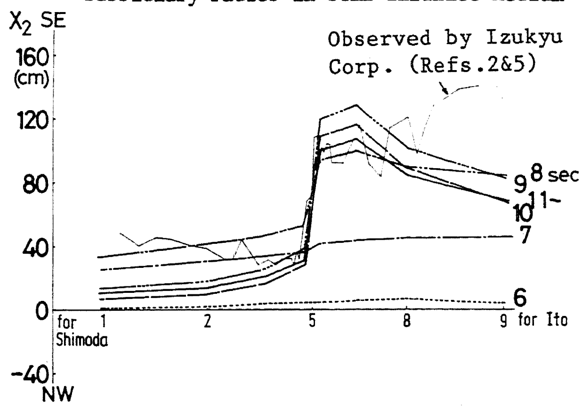

Fig.9 Transverse Displacement due to Main and Subsidiary Faults in Semi-Infinite Medium

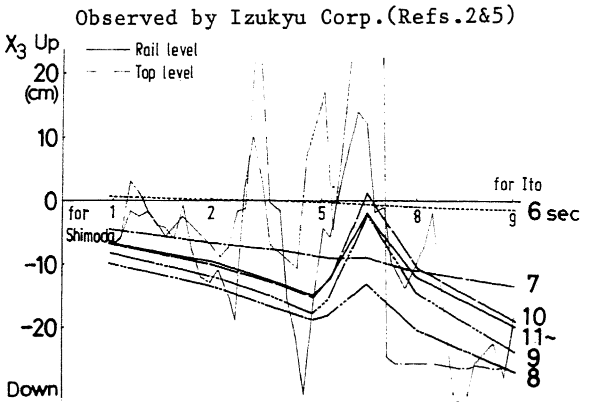

Fig.10 Vertical Displacement due to Main and Subsidiary Faults in Semi-Infinite Medium

nected with the safety of underground structures, but also supplies a method for estimating the incident wave in the source region of a large earthquake.

Then, using the previously proposed set of fault parameters the longitudinal, transverse and vertical displacements of the tunnel axis are computed. And these computed results are compared with the residual deformation surveyed by the Izu-Kyuko Corp.

The results are summarized as follows:
1) For each of three coordinates a similar trend can be recognized, and the comparison indicates that a reasonably good correlation exists between these surveyed and computed displacements.
2) The computed results explain the occurrence of enlarged cracks (elongation) at the section where the fault transversed the tunnel, and also the buckling of the rail (compression) at the entrance of the tunnel.

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