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EARTHQUAKE OBSERVATION AND RESPONSE ANALYSIS OF A SHIELD TUNNEL

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SUMMARY

The earthquake observation of a shield tunnel has been conducted by the authors since 1983. Detailed examination revealed that the tunnel behavior due to body-wave-predominant earthquakes, which is expected in a large earthquake, is mostly governed by the ground condition of surface layer. On the basis of the observation results, earthquake response analyses for the simulation of the observation have been carried out. The mathematical models used here are a quasi-three-dimensional ground model for ground and Winkler's model for a tunnel with equivalent rigidity determined from the actual behavior of segment itself and a ring joint during earthquakes. As a result, the simulations showed good agreements with the observation.

INTRODUCTION

The authors have been executing earthquake observation of a shield tunnel in soft ground systematically, in order to clarify the mechanizum of a seismicity of a shield tunnel during earthquakes since 1983 (Ref.1,2). The observation site was selected to grasp the tunnel behavior during earthquakes originated from the structure of surface ground. Detailed analyses of the data obtained by recent several earthquakes have brought about pieces of considerable information. This paper mainly deals with the representative behavior of a shield tunnel during earthquakes obtained from the observation and its earthquake response simulations.

EARTHQUAKE OBSERVATION

Outline of Earthquake Observation The observation site is located in the southern part of Yokohama City, Kanagawa Pref., Japan. Fig.1 illustrates the topography of the observation site. Alluvial silty clay is sedimented inbetween separate hills of diluvial mud stone, where a drowned valley is formed. Shear wave velocity of alluvial surface layer ranges from 40 to 260 m/sec. whereas that of diluvial mud stone is about 750 m/sec. The dotted line in the figure shows the boundary between alluvium and diluvium at the level of tunnel crown. The shield tunnel is constructed crossing the valley at a low angle. The tunnel is used for electrical power cables and is composed of reinforced concrete segments with outer diameter of 5.1 m.

Fig.2(a) denotes the cross section of the observation site and the installation of measuring instruments. The ground movement is measured by accelerometers placed underground at four points with variation of depths: i.e., point F and G in Fig.1. The tunnel behavior is observed at five sections A through E, where accelerometers and strainmeters are installed. They are arranged so that characteristic tunnel behavior originated from the valley shape can be obtained. The strainmeters are fixed both in the direction of tunnel axis and along tunnel inner circle. In addition, divergence meters are set at tunnel section C. Fig.2(b) illustrates the arrangement of measuring instruments at tunnel section C.

Observation Results Over 20 earthquakes have been recorded since 1983 at the site. Five major earthquakes shown in Table 1 were selected out of the earthquakes for detailed analyses. The maximum acceleration in the table means the maximum acceleration recorded at point F in the depth of 1.5 m. The magnitude of each earthquake selected is over 6.

a) Dymanic Behavior of the Ground Originated from the Valley Shape Fig.3 shows the ground accelerograms recorded at point F in three different depths due to YKHM-1 earthquake. The amplification of the acceleration from GL.-29.8 m in mud stone to GL.-1.5 m near the surface ranges from 2.7 to 5.6 in horizontal x direction, 3.0 to 5.5 in horizontal y dirction and about 3 in vertical z direction. The predominant frequency of the ground is 1.3-1.6 HZ in x direction, 1.6-1.8 HZ in y direction and almost 3 HZ in z direction, respectively. The amplification and frequency in 3 directions change dependent on the epicentral direction of earthquakes. The ground motion can be divided into two types except for YKHM-3, in which surface wave is predominant: Type 1; The amplification of acceleration in the direction of the valley axis (x) is fairly larger than that in the direction perpendicular to the axis (YKHM-1 & 4), Type 2; contraversely, the amplification in the direction perpendicular to the valley axis (y) is larger (YKHM-2 & 5).

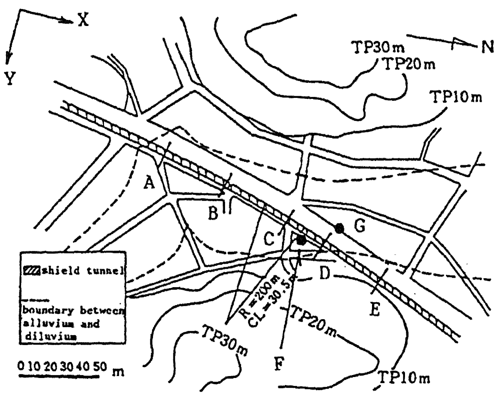


Fig.1 Topographycal Map of the Observation Site

Table 1 Main Earthquakes Recorded at the Observation Site

Earthq.No.	Date	Magnitude M	Epicent. Dist.(km)	Max. Acc. (gal)
YKHM-1	8/ 8/83	6.0	60	86.9
YKHM-2	3/ 6/84	7.9	450	37.6
YKHM-3	9/14/84	6.8	200	12.1
YKHM-4	10/ 4/85	6.2	61	52.7
YKHM-5	12/17/87	6.7	74	85.2

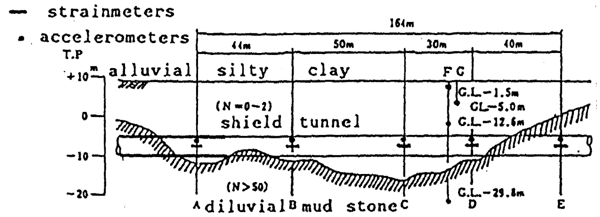


Fig.2(a) Cross Section and Installation of Measuring Instruments

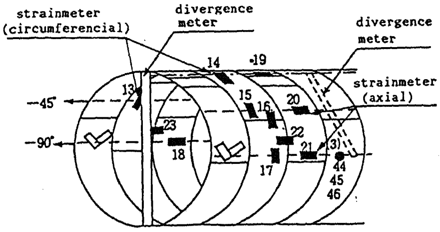


Fig.2(b) Measurement at Tunnel Section C

Various vibration modes appear reflecting the topography and stratigraphy of surface ground and the direction of epicenters, which were corroborated by vibration tests on the model ground made of gel-like-material with complexed boundary condition (Ref.5). The authors concluded, therefore, that the two type of ground vibrations were originated from two distinct vibration modes of the ground produced by the the difference in the epicentral direction of earthquakes.

b) Characteristic Distribution of Tunnel Axial Strain Fig.3 shows the tunnel axial strains at tunnel sections from A through D, respectively, when the tunnel was subjected to YKHM-4 earthquake. They are the strains measured on segments and their maximum values are almost the same, which is one of the characteristic features in Type 1 earthquakes. In the earthquakes of Type 2, on the other hand, the axial strain at section B is comparatively large and that of section C is fairly small. Another characteristic feature is the difference in axial strain modes. Fig.4 illustrates the axial strain distribution at the time when the strain at section A is on the positive peak, zero cross point, negative peak, zero cross point, succesively. The distribution in YKHM-4 (Type 1) is plotted on left hand side and that of YKHM-5 (Type 2) is plotted on right hand side. As shown in the figure, the two distributions are quite different each other. The former means that the surface ground moves entirely from section A to D or from section D to A in consecutive. The latter can be explained by the fact that the second mode vibration of the ground occured in tunnel axial direction. Therefore, the predominant frequency of the ground in Type 1 earthquakes is a little lower than that of Type 2 earthquakes.

c) Dynamic Behavior of Joints Between Twe Adjacent Segment Rings At three tunnel sections B, C and D, the tunnel axial strain is measured both on segment itself (segment portion) and the section crossing over the ring joint (joint portion) using steel-bar-type strainmeters with 50 cm in length. Fig.6 illustrates one of the examples of the comparison of axial strains between on a segment portion and a joint portion measured at tunnel section D in YKHM-4 earthquake. The strain on joint portion is larger in any earthquake and any tunnel section. In this example, the ratio of the axial strain on segment portion to that on joint portion is about 3. This ratio changes according to the earthquake. The authors proposed the equivalent rigidity of a shield tunnel using the factors and axial and bending rigidity of the segment (Ref.2):

$$(EA)_{eq.} = R_a (EA)_{seg.}, \qquad (EI)_{eq.} = R_b (EI)_{seg} \tag{1}$$

in which, the factor R_a and R_b is called as the axial and bending rigidity reduction coefficient, respectively. Their values are closely related to the rigidity of the ground at the periphery of the tunnel and the mechanizum was clarified by Suzuki and Tamura (Ref.3). The tunnel bending strain is considerably small compared to the axial strain, half or one third of the axial strain. In the bending deformation of the tunnel, the ratio also can be calculated. In the case that the vibration is not so strong, the behavior of the segment portion and the joint portion is almost the same and the ratio mentioned above is around 1.0. In case of strong vibration, however, the ratio becomes a certain value over 1.0 due to the tunnel structure and the rigidity of the ground at the periphery of the tunnel.

Earthquake Response Analysis of the Observation

a) Modeling and Analytical Conditions The ground model used for the earthquake response analysis is the quasi-three-dimensional ground model proposed by Tamura and Suzuki (Ref.4,5). This is the composite model of one degree of freedom system and finite elements. The soil column of surface layer is modeled by a set of spring-mass with the consideration of fundamental vibration mode of the column and each spring-mass system is connected with each other by the finite plate element. Fig.7 shows the mesh of the observation site modeled by the method. The number of nodal points used is 473 and that of plate elements is 437. The modeling was carried out, based on the equidepth map of surface layer and the soil profiles at several boreholes obtained from the geological survey. The upper and lower boundaries in the figure are dealt as free, while the left and right boundaries are dealt as fixed. The mud stone beneath the alluvial soft layer is considered to be the base rock in the analysis.

The earthquake response analysis and its comparison with the actual observation introduced below are on YKHM-5 earthquake occured on Dec. 17, 1987. where the maximum tunnel axial and circumferencial strains were recorded. In the analysis, the damping factor of 0.05 was used based on the actual ground shear strain observed at point F. The input waves in x and y direction are the main part of accelerations recorded at Point F GL.-29.8 m in x and y direction, respectively. Furthermore, the input waves travel with the phase velocity of the earthquiake from the epicentral direction in this analysis. The tunnel was modeled by 12 beam-column finite elements with equivalent rigidities determined

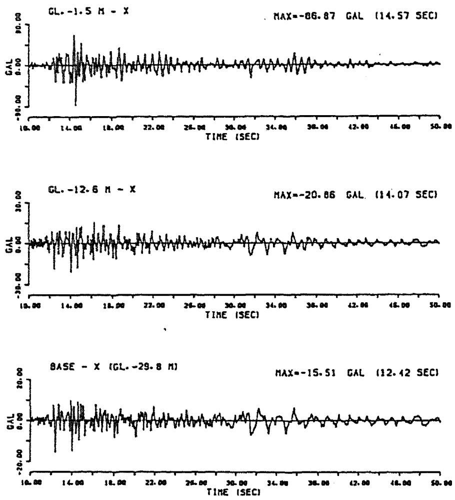


Fig.3 Accelerograms at Point F (YKHM-1)

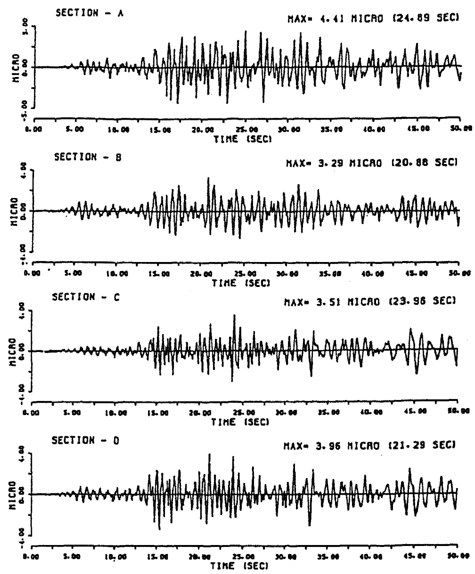
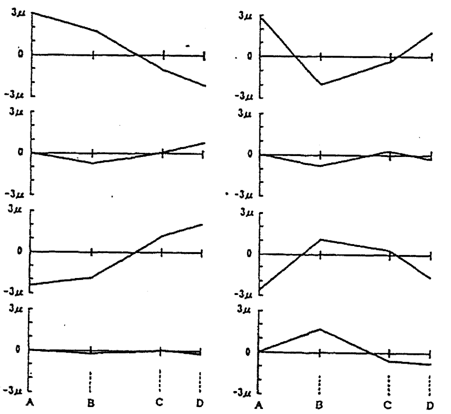


Fig.4 Tunnel Axial Strain Plotting (YKHM-4)



(a) x-direction (b) y-direction

Fig.5 Tunnel Axial Strain Distribution

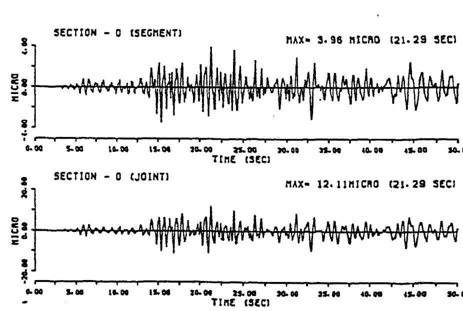


Fig.6 Comparison of Axial Strains on between Segment portion and Joint Portion (YKHM-4)

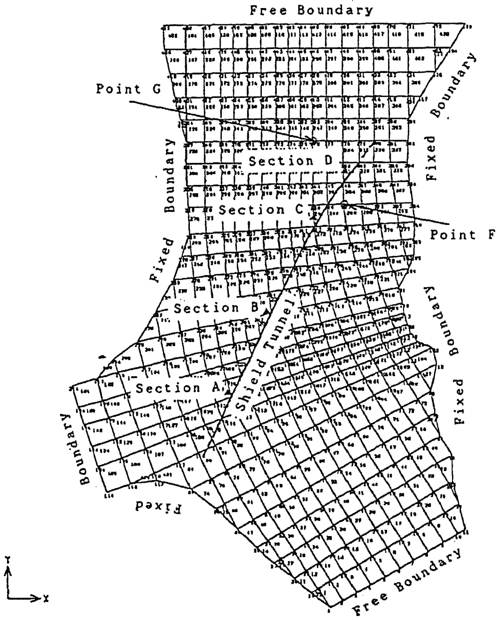
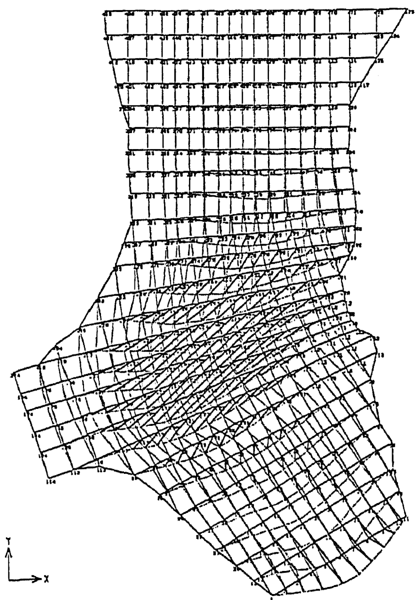
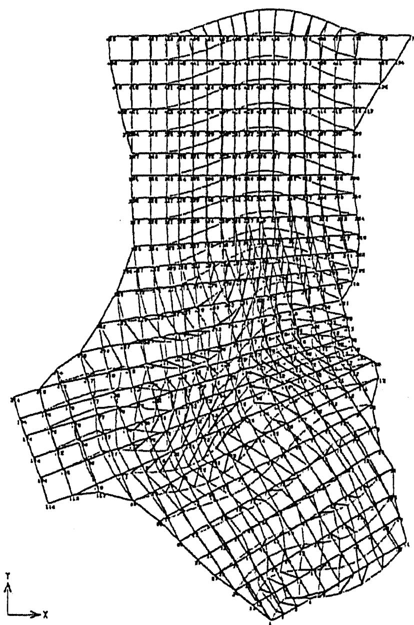


Fig.7 Mesh of the Analysis

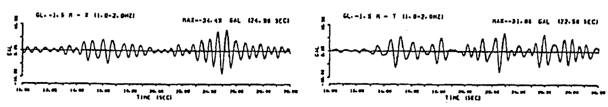


Mode (a)
Freq.=1.32 HZ



Mode (b)
Freq.=1.42 HZ

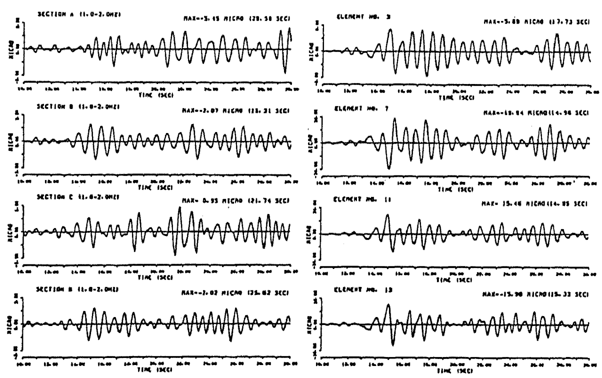
Fig.8 Vibration Modes



(a) observation (a) observation

(b) analysis (b) analysis

Fig.9 Comparison of Accelerations at Point F GL.-1.5 m (YKHM-5)



(a) observation (b) analysis

Fig.10 Comparison of Tunnel Axial Strains (YKHM-5) from the observation with equation (1). The analysis introducued below is the simulation of the behavior during YKHM-5 earthquake. The axial and bending strain reduction coefficient in YKHM-5 earthquake is 0.17 and 0.27, respectively.

b) Comparison of the Results between Actual Observation and Analysis The typical vibration modes of the observation site are shown in Fig.8. The authors presume that the mode (a) with effective mass ratio of 0.37, where the amplitude of the vibration in tunnel axial direction is large in the central region of the mesh, is predominant in Type 1 earthquakes and the mode (b), where second or third vibration modes are seen in entire region of the mesh, is predominant in Type 2 earthquakes. The effective mass ratio of mode (b) is not so large as that of mode (a). There are several modes similar to this mode, however, the total of their ratios reaches to 0.34.

Fig.9 shows the comparison of the accelerograms at point F GL.-1.5 m between observed and analyzed both in x and y directions. They are filtered through 1.0-2.0 HZ for the purpose of the comparison. As shown in the figure, the analytical results show considerably good agreements with the observation results, both in quality and quantity. The earthquake response analyses were carried out on other earthquakes YKHM-1, 2 and 4. The observed accelerograms were also simulated fairly well by the analyses.

Fig.10 illustrates the comparison of the tunnel axial strains between actually observed at tunnel sections A through D and analyzed at the positions corresponding to the observed tunnel sections. Since the time histories of both the observation and the analysis resemble each other, it was shown that the trend can be simulated well even when the analysis was performed with the rough division of tunnel elements. The values of the strains analyzed are also close to those of the observation in the simulation of any earthquake.

CONCLUSIONS

In this paper, the authors mainly focus on the dynamic behavior of a shield tunnel in soft ground during body-wave-predominant earthquakes. In this type of earthquakes, the damage of the tunnel is anticipated to be occured due to the ground response originated from the structure of the surface layer. The coincidence between the simulation and the observation mentioned above was considered to be obtained mainly by the appropreate modeling of the ground. In the seismic design of a shield tunnel, therefore, the dynamic property of the surface layer is considerably important and the analysis proposed by the authors is desirable for detailed examinations.

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