A study of shield tunnel's earthquake prevention under a big earthquake

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1. Introduction

To date, the aseismicity of a shield tunnel is usually determined by the "Response Displacement Method" from analysed results of tests performed during an earthquake of magnitude equal to that indicated by "Criterion Utility Tunnel Design". However, by reason as follows, this shield tunnel is also thoroughly checked for aseismicity under a big earthquake by the "Dynamic Analysis Method".

① As part of Telecommunication Disaster Prevention Project in Tokyo Metro Politan Area, it is designed to be a highly reliable cable tunnel capable of immediate and accurate data transmission during a disaster.

② It crosses Class A rivers, and when destruction results, has significant effects on important structures like embankments.

③ The soil in which the shield tunnel drives changed from diluvial clay to sand.

This reports on the results of studies performed to check the aseismicity of the shield tunnel under a large earthquake.

2. Outline of Construction

This shield tunnel was constructed on behalf of Telecommunication Disaster Prevention Project in Tokyo Metropolitan Area. From a starting shaft in Katsushika ward, the tunnel drives under two Class A Rivers, the Nakagawa and the Arakawa, which are 150 m and 50 m wide, to an underground connection point in Edogawa Ward, a distance of 1.6 km.

The construction outlines of the shield tunnel are shown in table 1.

Table 1 Construction Outline

Length	1586 m	Segment Diameter	3.60 m
Horizontal Alignment	R=40 m, 65 m and 250 m	Machine Diameter	3.73 m
Earth Cover	38.6 m~ 33.7 m	Machine Type	Slurry Shield Machine

3. Soil Conditions

The shield tunnel was constructed within the diluvium stratum called the Nanago stratum which is stable after considerations given to the effects of ground subsidence as a result of either a tail void created during excavation. Figure 1 shows the shield tunnel and the soil strata.

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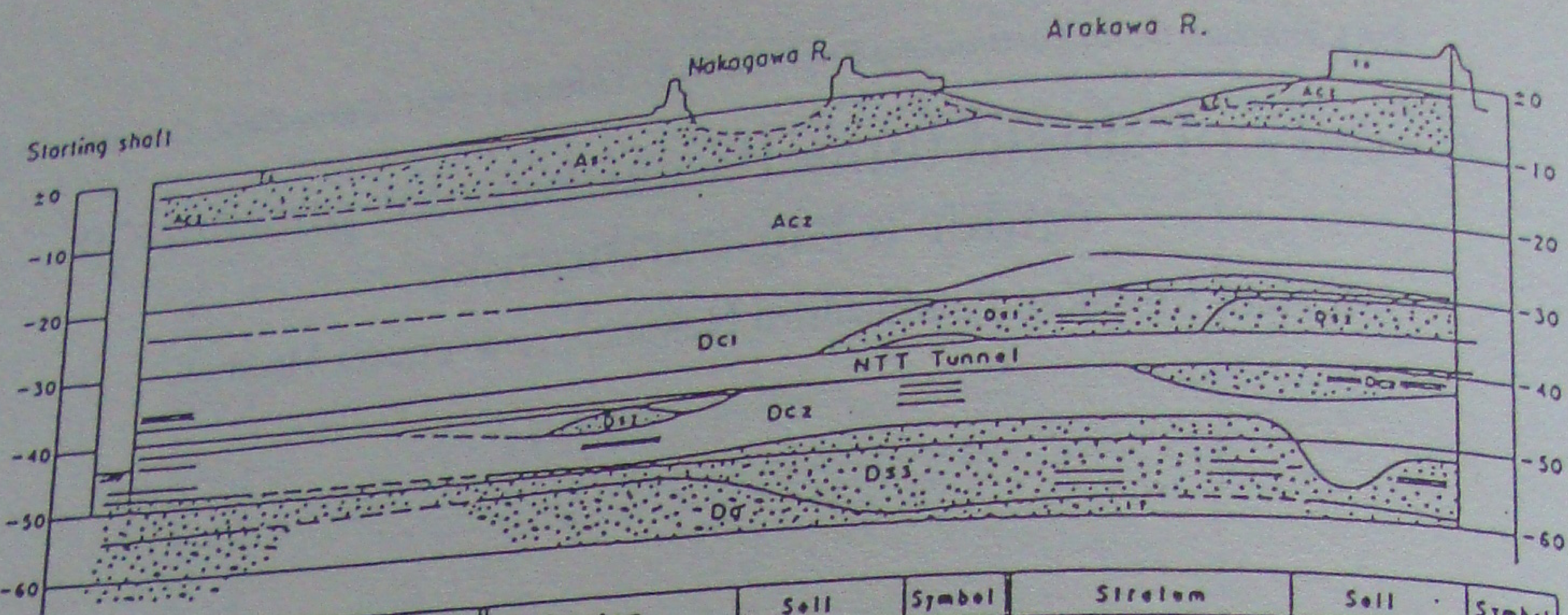


Stratum		Soil	Symbol
Filling earth soil			Is
Alluvium YURAKU-CHO STRATUM	UPPER	Clayey soil	Ac1
		Sandy soil	As
	LOWER	Clayey soil	Ac2

Stratum	Soil	Symbol
Diluvium NANAGO STRATUM	Sandy soil	Ds1
	Clayey soil	Dc1
	Sandy soil	Ds2
	Clayey soil	Dc2

Stratum	Soil	Symbol
Diluvium TOUKYO STRATUM	Sandy soil	Ds3
	Clayey soil	Dc3
Diluvium TOUKYO-REKI STRATUM	Gravel	Dg

Fig.1 Geological Cross Section

4. Investigations on the Aseismicity of the Shield Tunnel

4.1 Assumptions of the analysis

The characteristics of the shield tunnel behavior as an underground conduit are as follows.

① Since the shield tunnel has a cavity cross-section, its mass is comparatively smaller than the surrounding soil.

② Since the shield tunnel is in contact with the ground on all sides, its vibration decays easily.

The shield tunnel does not vibrate during an earthquake for itself and is indicated by the displacement of the soil around the tunnel as proved by past vibration examinations. This analytical method therefore assumes

① that the shield tunnel vibrates together with the surrounding soil during an earthquake.

② that the relationship between the displacement of the shield tunnel and the surrounding soil is similar to that as if the tunnel is a beam on an elastic floor.

③ that it is sufficient for considering the displacement of the shield tunnel to be that of the surrounding soil.

4.2 Structural characteristics of the shield tunnel

The shield tunnel is structurally different from the singlebodied circular tube since its segments are joined together by nuts and bolts.
Various models like "Equivalent rigid beam", "Finite Elements Method" and "Bone Structures" models can be considered for analysis.
This test however, uses the "Equivalent rigid beam" model which are applied for many cases. This model can analyze along the length of the tunnel well.

4.2.1 Segment structures

The dimensions of the standard segment used in this analysis and the allowable stress force and modulus of elasticity for each type of material used in the segments are listed in tables 2 and 3.

Table 2. Segment dimensions

· Segment	outer diameter	$D_o = 3750$ mm
	width	$l_s = 900$ mm
	height	$h = 250$ mm
· Bolts joining the segments	diameter	M24 $l_b = 80$ mm
	number used	$n = 36$
	efective sectional area	3.53 cm²
· Plate thickness of each segment	surface plate	$t_1 = 3.2$ mm
	main beam	$t_2 = 22$ mm
	vertical rib	$t_3 = 8$ mm
	connecting plates	$t_4 = 22$ mm
	reinforcing plates	$t_5 = 22$ mm

Table 3. Moduli of eelasticity, Allowable stress

Material	Standard	Modulus of elasticity (kg/cm²)	Allowable stress (kg/cm²) Force type	Normal condition	During earthquake
Stell	SM50	2.1×10^{6}	tention comprressive bending shear	1,900 1,900 1,900 1,100	2,850 2,850 2,850 1,650
Bolt	8·8	2.1×10^{6}	tention shear	2,400 1,500	3,600 2,200

* Allowable stress during an earthquake is 50% higher than normal conditions.

4.2.2 Equivalent rigidity used in analysis

The equivalent rigidity of shield tunnels have been reported in past researches on dynamic vibrations along the length of the tunnel.

However in this case, the equivalent rigidity is assumed to be the elastic constant of the ring joint calculated from the bending rigidity of the main girder of segments within the limits of elasticity.

The bending rigidity is assumed to be different from that in the compressive or tensile direction. Consequently,

$$(EA)^{T}_{eq} / (EA)^{C}_{eq} = 15\%$$

$(EA)^{T}_{eq}$: equivalent compressive rigidity
$(EA)^{C}_{eq}$: equivalent tensile rigidity

Moreover, the bending rigidity is equal to the resistance in the segmental section when compressing or the resistance in the ring joint bolts when pulling.

Then $$(EI)_{eq} / (E_s \cdot I_s) = 30\%$$

$(EI)_{eq}$: Equivalent bending rigidity
E_s : Segment's modulus of elasticity
I_s : Segment's moment of the second order

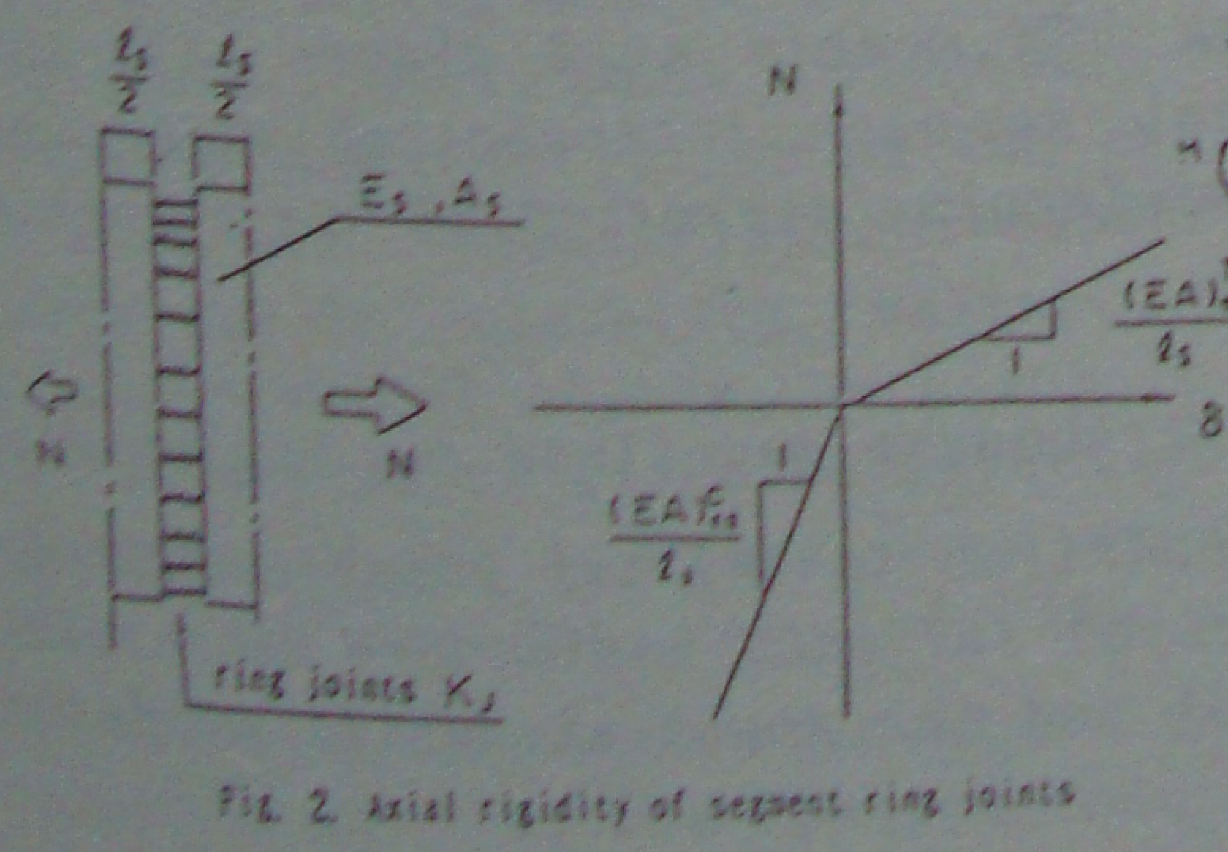


Fig. 2. Axial rigidity of segment ring joints

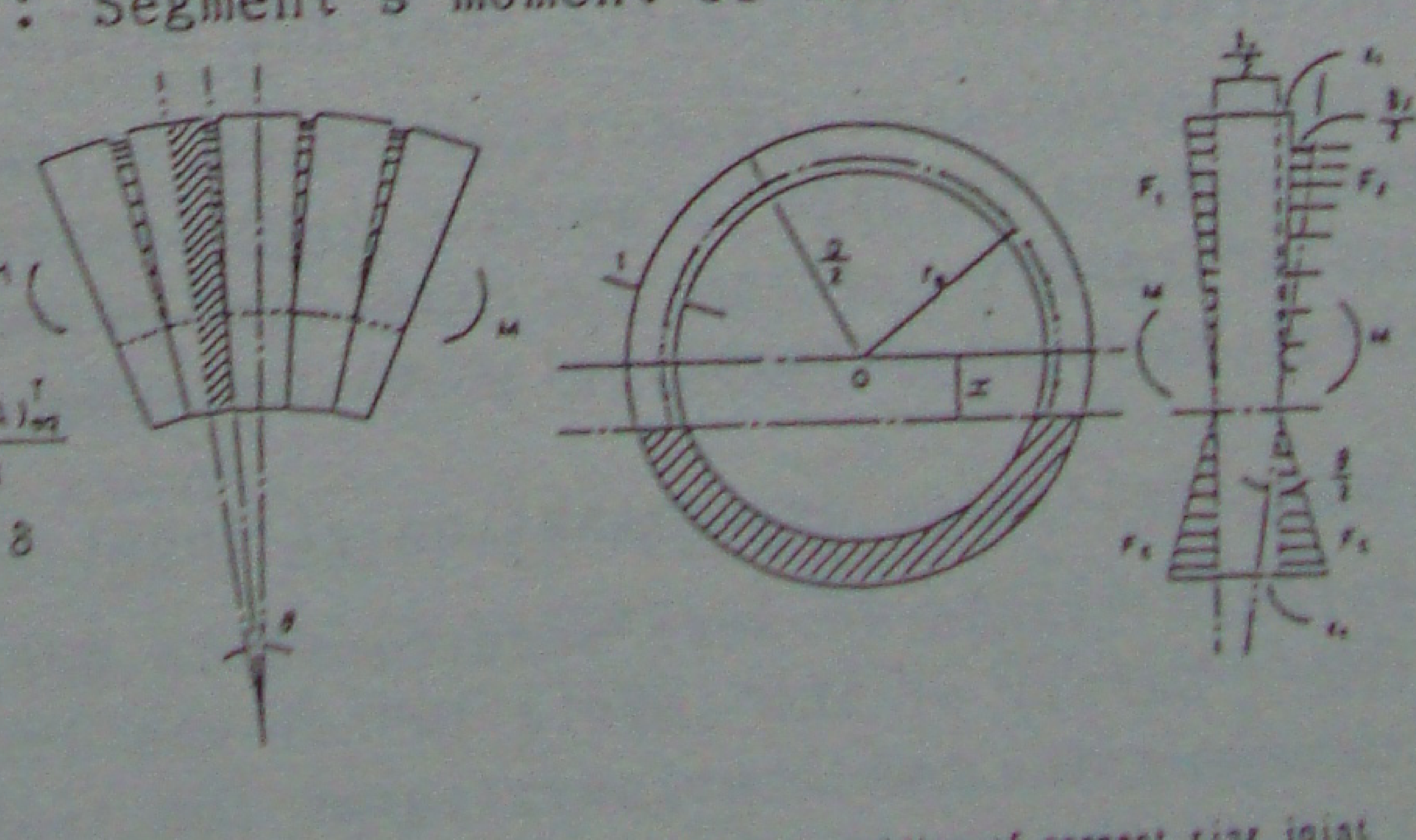


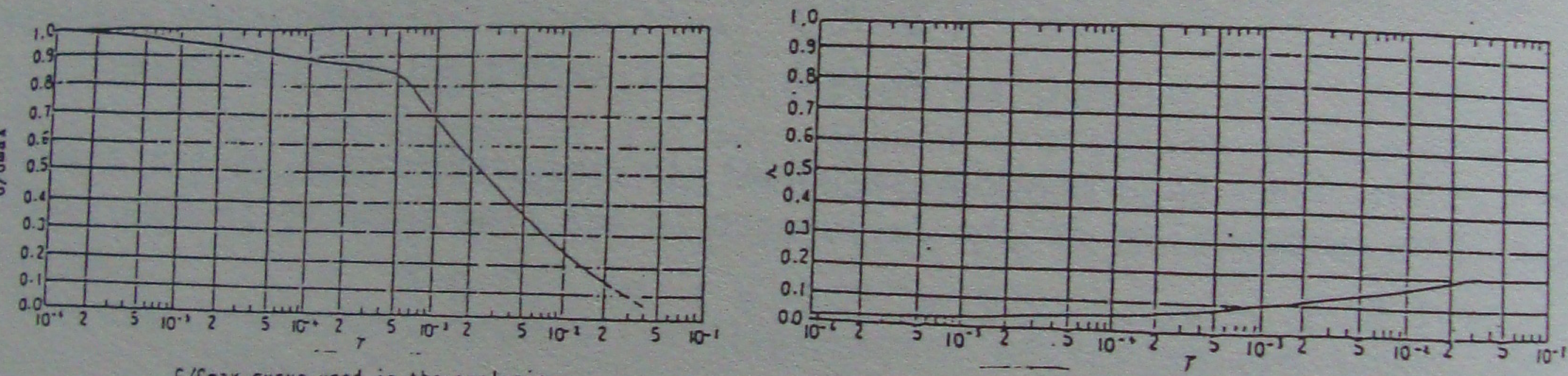
Fig. 3. Equivalent flexural rigidity of segment ring joint

4.3 Determination of dynamic characteristics of soil

Soil constants used in dynamic analysis are based on results of soil tests. However, since it is believed that the speed of shearing greatly affects the analysed results, boring test of PS logging was done. To determine the decrease in rigidity during an earthquake, dynamic strain curves at 6 places within the areas of displacement in the soil strata are determined by the theory of multiple reflection.
The soil constants used in this analysis is shown in Table 4.
Figure 4 shows an example of a dynamic strain curve measured within the Dcl soil layer of the shield tunnel.

Table 4. Soil types used for analysis

Stratum		soil	symbol	Thickness (m)	N value	Unit weight (t/m)	Shear force speed (m/sec)	poisson's ratio
Stratum Top stratum			ts	1.2~2.7	4	1.77	135	0.49
Silt stratum			Ac1	2~2.5	0	1.4	50	0.50
Alluvial YURAKU-CHO STRATUM	UPPER	Clayey soil	As	4~3	10	1.93	120	0.49
		Sandy soil	Ac2	0.7~2.9	1	1.6	100	0.49
	LOWER	Clayey soil	Ac3	17~23	1	1.65	140	0.49
Diluvium NANAGO STRATUM		Sandy soil	Ds1	4~10	15	1.96	200	0.49
		Clayey soil	Dc1	2~13	3	1.75	200	0.43
Diluvium TOKYO STRATUM		Sandy soil	Ds2	11~13	30	1.93	240	0.43
		Clayey soil	Dc2	3~10	23	1.77	225	0.43
		Sandy soil	Ds3	2~11	60	2.17	240	0.47
		Clayey soil	Dc3	1~1.9	17	1.86	225	0.43
Diluvium TOKYO-REKI STRATUM			Dg	—	119	—	—	0.46



G/Gmax curve used in the analysis

h~r curve used in the analysis

Fig. 4 Dynamic strain curve measured within the Dcl soil layer

4.4 Determination of elastic constant between tunnel and soil

The elastic constant is determined by using FEM models at 6 places with soil changes and calculated from the displacement at each intersection where unit weights are applied along the axial and perpendecular direction of the tunnel as well as directions perpendicular to the axis.

4.5 Basic policy in determination of input earthquake magnitude and aseismicity

Two aseismic standards were determined in proportion to the two input earthquake magnitude. Safety of the shield tunnel was tested for each earthquake magnitude. Table 5 shows the basic principles of the test and the input standards which are targetted to be the aseismic standards.

Table 5. Input standards which are the aseismic targets

Input standards	Earthquake magnitude	Basic principle of aseismic tests	Aseismic tests
L－1	Common channel spectrum (equivalent to M=7.0, Δ=50km) ★That whose response spectrum maximum.	Ensure that structures are sufficientry safe during the occurence of a relatively major earthquake, these same structures should also be safe to use after an earthquake.	Stresses generated in bolt joining the segments or the joints (surface plates) should be below the allowable stress value.
L－2	Major earthquake (Kanto Earthquake) (equivalent to M=8.0, Δ=50km) ★Imagine an earthquake of the maximum possible magnitude in this area.	Earthquakes of this magnitude are quite rare in this area. Structures should not be functionally damaged and should be able to withstand further damage. Above all, the structures should be safe.	Stresses generated in bolts joining the segments or the joints (surface plates) should be below the yield stress value.

4.5.1 Input earthquake magnitude

① The seismic movements of magnitude L1 are generated by the common channel method (equivalent to M=7, Δ =50 km) whose waveform is very similar to that the 1983 Nihonkai Chubu earthquake observed near a place called Tsugaru Ohashi. The amplitude of the dynamically analysed acceleration response spectrum is adjusted to match that recorded on the actual quake.
② The seismic activity of magnitude L2 is assumed to be a major earthquake (Kanto earthquake class)(M=8.0, Δ =50 km). The forces generated on the cross-section of shield tunnel are estimated from the design results at the L1 level. The estimation is described below.

4.5.2 Estimation of response values to major earthquake

The response of subterranean structures during seismic activity is similar to the shield tunnel and can be expressed as follows :

$$S\gamma(\omega) = S1(\omega) \cdot S2(\omega) \cdot S3(\omega)$$

$S\gamma(\omega)$: tunnel response
$S1(\omega)$: response of input seismic force
$S2(\omega)$: response of surface soil
$S3(\omega)$: tunnel's vibration coefficient

Previous experiments have proved that the tunnel does not vibrate for itself, $S3(\omega)$ can be assumed to be a constant independent of frequency. $S2(\omega)$ is not expected to change very much when the shearing strain of the surface soil during an earthquake is only a few percent.
Therefore, the tunnel response $S\gamma(\omega)$ will mainly be affected by the response characteristics of the applied seismic force $S1(\omega)$. Once the ratio between the characteristic frequency of the soil to the strength of the seismic force can be determined, seismic response values at other areas can be deduced if those values at any one place is known.
The deduction of response values during a major earthquake, uses the attenuation equation in the acceleration response spectrum suggested by Kawashima et.al.. By inserting into his equation, the values of soil type at the construction site, distance from the epicenter and the magnitude of the earthquake, the acceleration response spectrum can be determined.

Next, existing records of major earthquakes are checked for something whose waveform matches that of the spectrum determined theoretically. The amplitude within the band width is then ajusted. The imaginary surface earthquake can be altered to the applied seismic waveform at the foundation by using the multiple reflection theory. The response spectrum at the foundation can then be determined.
By comparing this spectrum and that of the common channel, the response values during a major earthquake can be deduced from calculations performed on the common channel spectrum if the ratio near the characteristic frequency of the soil is determined.
Figure 5. shows the flowchart for deducing tunnel response during a major earthquake.

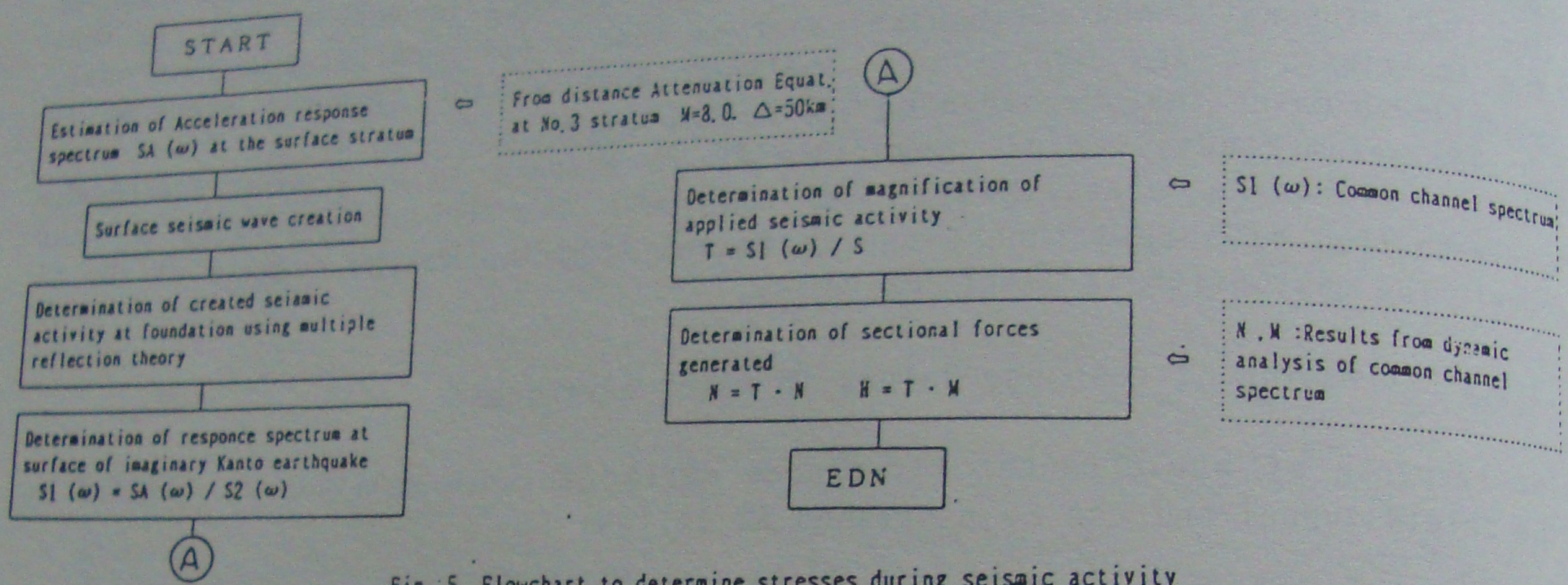


Fig. 5. Flowchart to determine stresses during seismic activity

4.5.3 Results of an deducing major earthquake

This analysis assumes a major earthquake of magnitude equivalent to Kanto Earthquake (M=8, Δ =50 km).
Figure 6 shows the acceleration response spectrum during the occurrence of a major earthquake.

Figure 7 shows the amplitude adjusted waveforms for the acceleration response spectrum by matching them with records of the Nihonkai Chubu earthquake observed at a place called Tsugaru Ohashi. This waveform is then transformed into a waveform at basic stratum by using SHAKE formula to give the results shown in figure .
For the characteristic cycle of the relative stratum is 1.0 ～ 2.0 seconds, the seismic activity is amplified by least 1.8 times. In other words, the response magnification generated in the tunnel during the Kanto earthquake is about 1.8 times that of the applied seismic activity determined by the common channel spectrum.
Figure 9 shows the acceleration response magnification at the basic stratum within a cycle of the relative stratum.

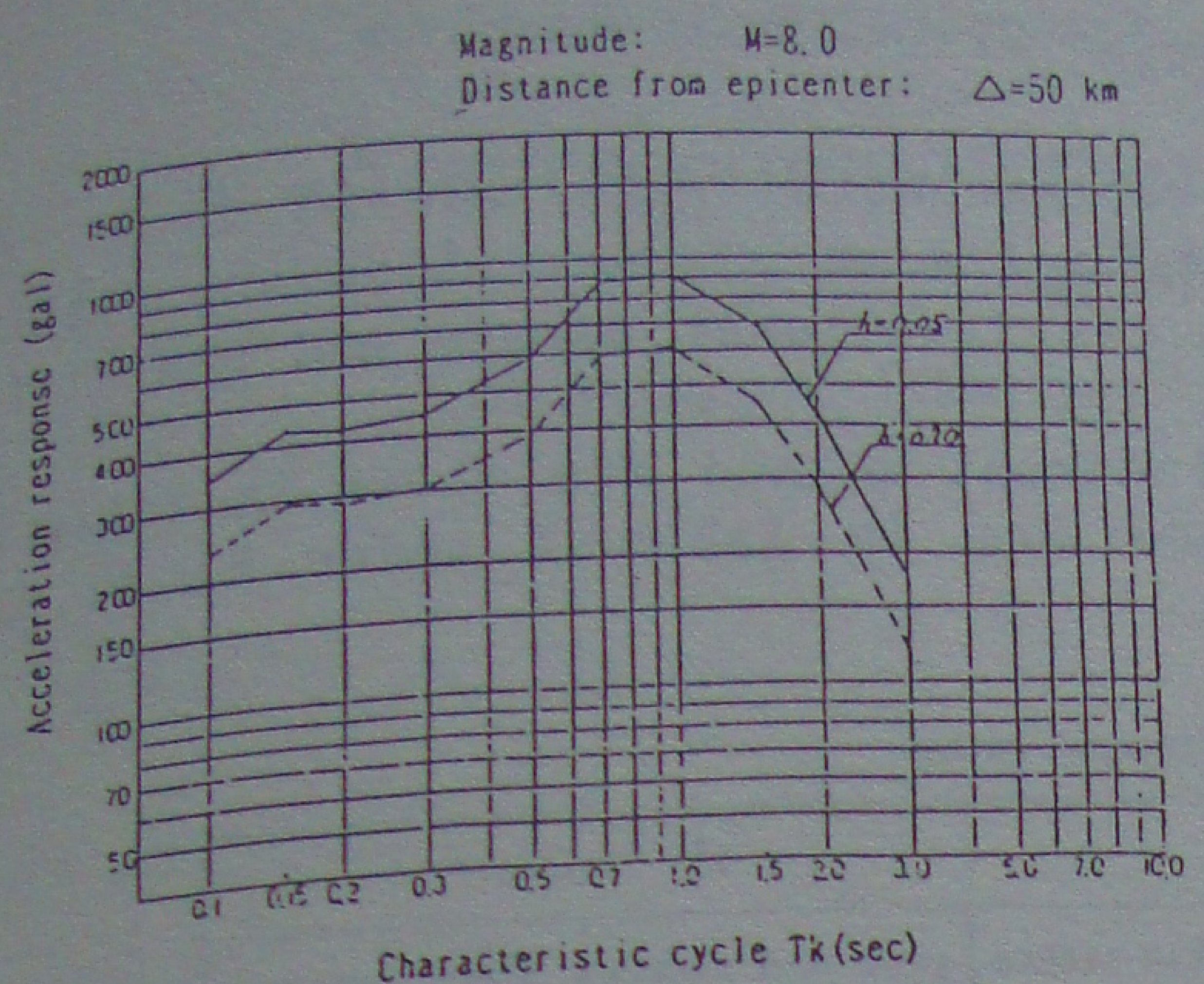


Fig. 6. Acceleration response spectrum of imaginary Kanto Earthquake

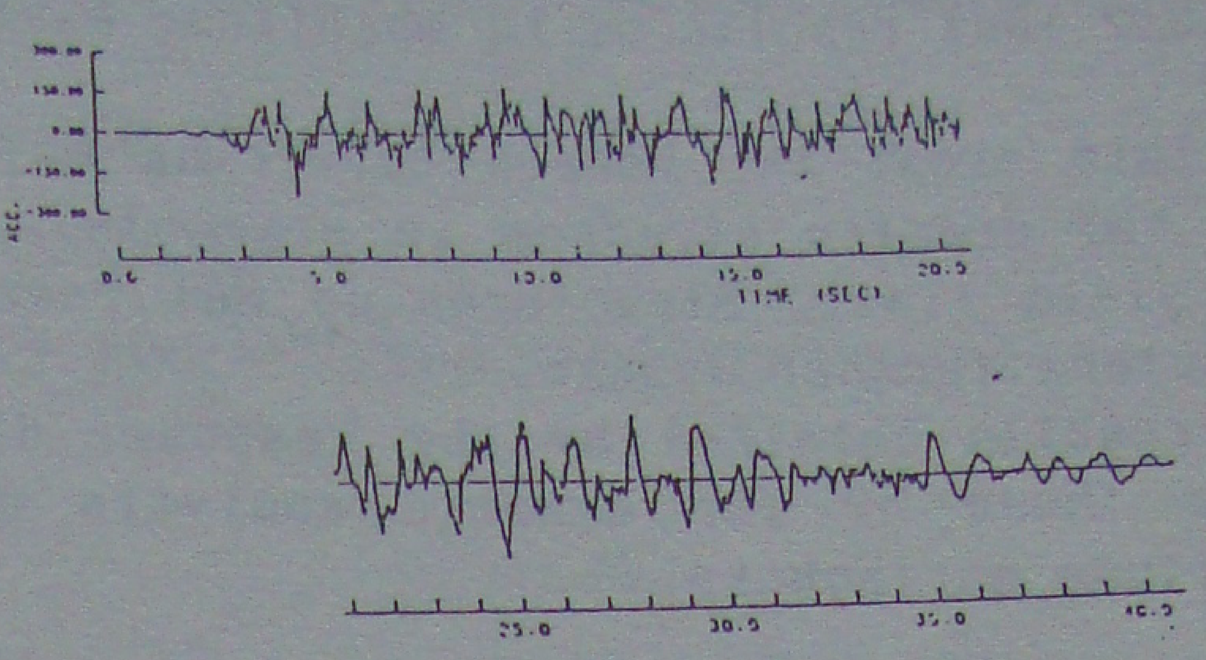


Fig. 7. Acceleration waveform generated during imaginary Kanto Earthquake

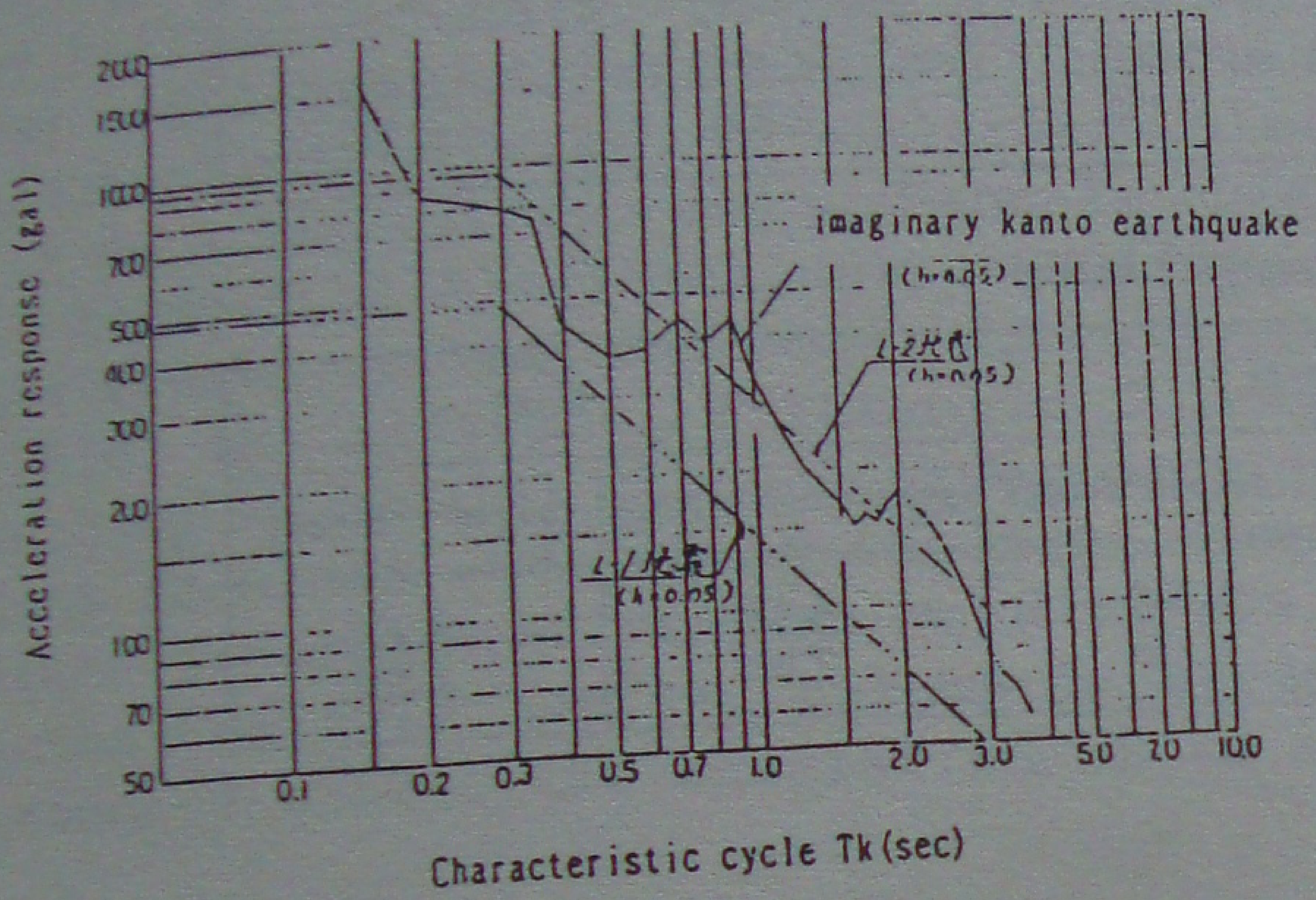


Fig. 8. Acceleration response spectrum at the basic stratum

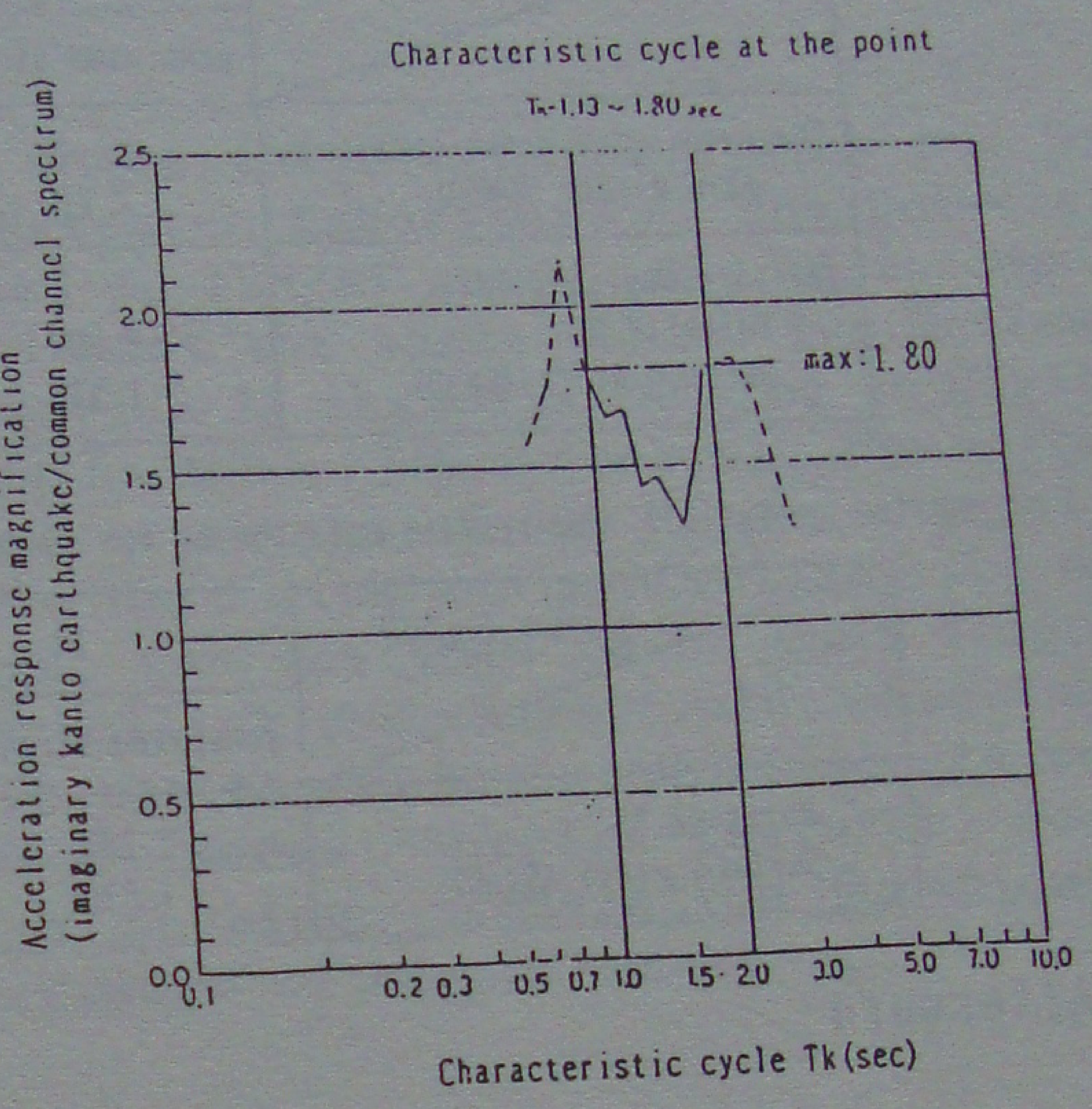


Fig. 9. Acceleration response magnification at basic stratum

4.6 Results of aseismicity tests

The places of testing is as follows :

① Response displacement method (tested at shield's horizontal cross-section)

・4 places (a) vicinity of starting vertical shaft (b) left levee of Arakawa river (c) riverbed of Arakawa river (d) right levee of Arakawa river

② Response displacement method (tested at shield's vertical cross-section)

・5 places (a) arc with radius of curvature R=45 m (b) arc with radius of curvature R=65 m (c) vicinity of left banks of Arakawa river (d) Arakawa riverbed (e) vicinity of right banks of Arakawa river

③ Dynamic analysis method

・A model with 60 test points each 20m apart along a total distance of 1200m from the vicinity of the right banks of the Arakawa river

4.6.1 Test results of L1 magnitude earthquake

During a relatively frequently occurring earthquake of magnitude L1 (M=7, △=50 km), similar in magnitude to that created by the common channel method, the stresses generated in the various segments, bolts and surface plates of structures supposed to be still durable were all within the allowable stress limit.

4.6.2 Test results of L2 magnitude earthquake

In this area, the rarely occurring major earthquake of magnitude L2 (M=8, Δ=50 km) creates stresses in segments, bolts and main girders which are within the yield limit. Structures do not receive any functional damage and can still withstand further damage.
The results obtained by the response displacement method are shown in Table 6 while those by the dynamic analysis method are in Table 7 under L1 or L2 magnitude earthquake.

Table 6. The results obtained by the response displacement method

stress (kg/cm²)	L1 level		L1 level	
	generated stress	allowable stress	generated stress	yield stress
[Perpendicular cross-section] Main girder (SM50)	2.210	2.850	2.432	3.200
[Axial cross-section] Bolts (8.8) Surface pleta (SM50)	2.293 1.575	3.600 2.850	4.127 2.835	6.400 3.200

Table 7. The results obtained by the dynamic analysis method

stress (kg/cm²)	L1 level		L1 level	
	generated stress	allowable stress	generated stress	yield stress
Bolts (8.8) Surface pleta (SM50)	2.293 1.575	3.600 2.850	4.127 2.835	6.400 3.200

5. Afterword

This shield tunnel's construction (primary lining) was completed in November 1989. After completion of the secondary lining, measuring instruments will be installed and seismic tests will be performed.
The necessity for a highly reliable telecommunications network system in this age of information is increasing.
NTT recognizes this need and will continue performing tests on how to improve the quake resistance of cable tunnels with due considerations given to the results of this report.

6. References

(1)Kawashima, Aizawa :*Attenuation of Earthquake Response Spectra Based on Multiple Regression Analysis of Japanese Strong Motion Data*, Proceedings of Japan Society of Civil Engineers No.350.

(2)Suzuki, Yagi, Kobayasi :*An Aseismatic Study on Tunnels Under an Imaginary Major Earthquake*, Proceedings of the 44th Annual Conference of the Japan Society of CIvil Engineers, 3, 1989.