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# EARTHQUAKE-RESISTANT DESIGN OF SUBMERGED TUNNELS

# L'ÉTUDE ANTI-SISMIQUE D'UN TUNNEL IMMERGÉ

# DIE ERDBEBENBESTÄNDIGKEIT ABGESENKTER TUNNEL

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SUMMARY

It is shown from the results of earthquake observations and model vibration tests of submerged tunnels that deformations of such tunnels during earthquakes are governed by the deformation of ground. The features of earthquake resistance of submerged tunnels are described and the concept serving as the basis for earthquake-resistant design, points to be kept in mind in designing, and examples are given.

RÉSUMÉ

D'après les résultats de l'observation de tremblements de terre et d'essais de modèles de vibrations sur des tunnels immergés, il est apparu clairement que le comportement d'un tunnel de ce type pendant les tremblements de terre est principalement fondé sur la déformation du terrain selon l'axe du tunnel. Les caractéristiques de la résistance de tels tunnels aux tremblements de terre, le concept fondamental d'une structure résistante aux tremblements de terre pour de tels tunnels, et les considérations faites au sujet de leur structure sont decrites.

ZUSAMMENFASSUNG

Auf der Grundlage von Erdbebenbeobachtungen und Vibrationsmodellversuchen an abgesenkten Tunneln wurde festgestellt, daß das Verhalten eines solchen Tunnels im Verlauf von Erdbeben hauptsächlich durch eine Verformung des Bodens entlang der Tunnelachse bestimmt wird. Der Inhalt befaßt sich weiterhin mit der Charakteristik abgesenkter Tunnel in Bezug auf Erdbebenbeständigkeit, dem Grundkonzept einer erdbebenbeständigen Konstruktion fur solche Tunnel und Punkte, die bei deren Konstruktion berücksichtigt werden müssen.

## 1. INTRODUCTION

Due to the earthquake situation of Japan there has been much concern regarding earthquake resistance of submerged tunnels and studies of this matter have been continued and earthquake-resistant design standards have been established. Recently, submerged tunnels as listed in Table 1 including those under construction have come to be built, mainly as major traffic facilities. In this paper, the behaviors of submerged tunnels during earthquake, their structural features, and methods of response analysis will be described.

## 2. FEATURES OF SUBMERGED TUNNELS SEEN FROM ASPECT OF EARTHQUAKE RESISTANCE

Seen from a structural standpoint a submerged tunnel is comprised of the so-called submerged tunnel, approaches, shafts and ventilation towers. These sections, respectively, have the characteristics described below.

2.1 Submerged Tunnel This is a tubular structure of large cross section usually buried in soft ground at the bottom of water or below the ground water line. Therefore, the stability of the ground during earthquake is an essential condition for earthquake resistance of the tunnel, and the interaction of the ground and the tunnel becomes a fundamental matter. It may be anticipated that there will be portions produced in the tunnel walls which are in stress conditions of more or less pure compression or pure tension. Since concrete is generally used as the principal material, it will be necessary for these stress conditions to be watched.

2.2 Approach This is a section from the submerged tunnel section to the surface which usually is of tunnel or open channel structure, or a combination of both. Examinations of these structures are normally by the seismic coefficient method.

2.3 Shaft, Ventilation Tower These are vertical structures provided at the tunnel portion with the main purposes of construction of the tunnel and ventilation, with some towers rising as high as 40 m above the ground surface. In connection with the tunnel, these structures frequently comprise a part of the tunnel. The behaviors are considered to be similar to those of buildings in general and earthquake-resistant design is being done by the seismic coefficient method.

Tunnels of this type are structures connecting parts such as the above which have differing dynamic properties. Consequently, the manner in which these structural parts which indicate divergent behaviors during earthquake are connected is an important problem of earthquake resistance of the structure. In order to solve this problem, it is necessary not only for the behaviors of the ground and the various structural parts during earthquake, but also behaviors during normal times such as uneven settlement of the ground to be known.

Evaluation of earthquake resistance is carried out not only from the viewpoint of structural dynamics, but also based on various factors such as type, function, importance, scale, etc. of the structure. When cases of these long structures built at the bottom of water and moreover in the ground being used as major traffic routes are visualized, it is necessary for special considerations to be given to functioning of safety facilities such as fire extinguishing and water drainage in case of emergencies, and securing of sureness of action during emergencies. Since this will also influence the structure itself, investigations and examinations will be necessary from the planning stage.

The above indicates features regarding the earthquake resistance of submerged tunnels.

## 3. BEHAVIORS OF SUBMERGED TUNNELS DURING EARTHQUAKE

3.1 Earthquake Damage to Tunnel   Submerged tunnels have not yet experienced major earthquakes, and thus, there is an important significance with respect to determining earthquake resistance in knowing the behaviors and the kinds of damage suffered when similar structures are subjected to strong earthquake motions.

In general, earthquake damage to mountain tunnels is restricted to limited portions at epicentral areas with damage conditions being comparatively constant, and with most of the damage occurring at portals or their vicinities, while at middle portions of tunnels where the geology is generally good, damage is small. When there has been damage at the middle portions of tunnels, that this was due to the poor conditions of the ground at the location of the damage can be pointed out from cases during the Kanto Earthquake, Kitamino Earthquake and the Niigata Earthquake. This indicates that the conditions of the ground around the tunnel exert a great influence on the tunnel. It has been reported that the conditions of the natural grounds of damaged tunnels at relatively long distances from epicenters were all poor.

Komine Tunnel on the Atami Line (present Tokaido Main Line) is an example of damage of a tunnel in soft ground. At this tunnel, the portion 184 ft from one of the portals had retaining walls built on excavating ground consisting of red clay by open cut, with reinforced concrete girders crossed over to provide a cover for a backfilled structure, a structure extremely different from the case of an ordinary mountain tunnel. This open-cut section crumbled, but going in further toward the Atami side, the geology became better and there was almost no damage. This damage is considered to have been caused due to the structure having been in soft ground with little coverage so that structurally the earth pressure during earthquake could not be resisted.

At the time of the Niigata Earthquake ($M$ = 7.5), the city of Niigata at a distance approximately 40 km from the epicenter suffered extreme damage with liquefaction of the ground as the main cause. Near Niigata Station there was jetting of soil at the surface of the ground. An underground passageway at this station was a reinforced concrete structure of a box cross section supported by foundation piles and the cross section itself was not damaged at the time of the earthquake, but misalignment and rotation occurred at joints in the longitudinal direction so that the surface of the bottom slab became uneven and ground water entered the tunnel from the joints.

The examples of damage described above indicate that for tunnels in soft ground both earthquake resistance of the transverse cross section and earthquake resistance in the longitudinal direction must be considered in structural design.

Since submerged tunnels are buried near the surface of soft ground, these examples of damage serve as valuable references, but because water pressure comprises a great part of the load, the transverse cross section is made strong in design in any event, and the structure and strength in the axial direction will consequently become subjected to serious consideration.

3.2 Earthquake Observations   The behaviors of submerged tunnels buried in soft ground will be described based on the results of several earthquake observations. As far as the authors know, earthquake observations are being carried out at the submerged tunnels of Haneda, Kinuura Port, Tokyo Port and Ohgishima. The items of measurement do not necessarily coincide, but acceleration, strains and displacements of tunnel walls are main, besides which there are reinforcing bar stress transducers and joint meters installed. There are also cases of accelerometers installed at the ground surface and in the ground in connection with the behaviors of the structures. The following discussion is centered around earthquake observations on Haneda Submerged Tunnel (Japanese National Railways) which have been going on since 1970.

3.2.1 Haneda Submerged Tunnel   This tunnel extends from a point at the left bank of the Tama River somewhat upstream from the entrance to Haneda Airport, crossing the river in a slight arc convex in the upstream direction to reach the Kawasaki side, and the length of the submerged tube part is 480 m. The tube is composed of 6 reinforced concrete elements of oval-shaped cross section each having a length of 80 m, height of approximately 8 m, and width of approximately 13 m with corrosion-proofed steel plates 6 mm in thickness forming an outer shell. These elements will be tentatively numbered herein as 1, 2, ...., 6 in order from the Kawasaki side.

With respect to the ground, a soft alluvial layer of about 40 m at the middle of the river and 10 and several meters at the Kawasaki side cover the well-compacted so-called Tokyo Sand-Gravel Stratum. The predominant frequencies of the ground obtained from microtremor observations were 0.23 to 0.33 Hz, 0.5 to 0.79 Hz, and 0.9 to 1.1 Hz. As observation instruments two accelerometers each were installed at Element No. 2 and No. 4, while four strain meters each were provided to measure strains of side walls in the axial direction.

From April 1970 until the present it has been possible to record more than 30 earthquakes where strains and accelerations were of extents considered to be significant for analyses. Fig. 1 shows a portion of the record for an earthquake of $M$ = 7.3 which occurred east of Hachijo Island on December 4, 1972 in which the maximum strain for all earthquakes up to the present was recorded. In this figure, No. 4 TSA is the horizontal acceleration in the direction orthogonal to the tunnel axis observed at Element No. 4, while Nos. 5 to 8 are strains in the direction of the tunnel axis recorded at the tunnel walls. Although measurements of strain were made at two points 50 m apart, that the strain waveforms are very closely similar, and moreover, that there is practically no phase differential, that the predominant frequency of the strain waveform agrees well with the low-order predominant frequency, and that predominant vibrations of approximately 7 sec are seen at the end of the record, are prominent features.

Fig. 2 is the record of an earthquake of $M$ = 4.9 and epicentral distance of 17 km which occurred at the northern part of Tokyo Bay on March 27, 1973. Compared with Fig. 1, vibration components of short periods are predominant in the acceleration waveforms indicated by TAA and TSA from which it is seen that strains in the direction of the tunnel axis are extremely small for the degree of acceleration.

Fig. 3 illustrates maximum acceleration and maximum strain by earthquake. The greater part of the measurement results are contained between two roughly parallel straight lines and the two lines are surmised to represent the upper and lower limits. The points in the vicinity of the lower limit line are for cases of earthquakes in which the magnitudes were small (5.1 and under) and the epicentral distances were short, and vibration components of relatively short periods of 2 to 3 Hz or more are predominant. The points near the upper limit line are for cases with practically no vibration components of relatively short periods as mentioned above, and vibration components of periods of 1 to 2 sec or longer are predominant where large strains are produced considering the degree of acceleration. It is important that for the same maximum acceleration sizes of strains varied as much as 15 to 20 times, and this can be considered as representative of the frequency response properties of tunnel strains against acceleration. At the upper limit line the strains were 1.5 to 2.0 x $10^{-6}$ per gal, while at the lower limit line they were about 0.1 to 0.15 x $10^{-6}$.

Fig. 4 indicates the relation between maximum strain and epicentral distance with magnitude as the parameter. When magnitude is at a constant level, it is seen that the degree of reduction in maximum strain with increase in epicentral distance is extremely small compared with the maximum acceleration of earthquake motion, and that there is not very much reduction according to distance. It is thought this is because the low-order predominant period of the ground is long and earthquake motion components having this period are not decreased very much by the increase in distance. Also, it may be considered that in the range of short epicentral distances, vibration components of short periods become relatively large in number. Based on the figure, for the range of around $M$ = 5-7, the following experimental formula holds between maximum strain $\varepsilon_m(\mu)$ produced at this tunnel during earthquake, and magnitude $M$ and epicentral distance $\Delta$ (km):

$$\log_{10}\varepsilon_m = 0.7M\frac{\Delta}{450} - 3.2$$

Figs. 5 and 6 are power spectra of strain waveforms and acceleration waveforms for 107.8 sec of the initial part (indicated by (a) in the figure) and the part between 56 and 80 sec (indicated by (b) in the figure) of maximums in the earthquake record of Fig. 1. Although the relative size of the extreme maximum value for each frequency varies, it may be seen that both are predominant at roughly identical frequency portions. In cases of earthquakes of around $M$ = 6-7, vibrations of about 0.3 Hz do not appear very prominently, and vibrations of about 0.5 to 1 Hz are predominant.

When taking into account also that the frequencies of predominant vibrations at this observation site determined from microtremor observations are at relatively low levels such as 0.23 to 0.33 Hz, 0.5 to 0.79 Hz, 0.9 to 1.1 Hz, and 1.3 to 1.4 Hz as previously mentioned, it may be considered that the vibrations predominant in the acceleration record and the strain waveforms during earthquake are vibrations of the ground. When strain records and acceleration records are compared, that the sizes of strain and acceleration are not directly related can be seen from the records of the two in Fig. 1, and rather, the spectrum of strain is similar to the form of the spectrum of displacement converted from the spectrum of acceleration. Also, it may be seen that when strain records are viewed from an overall standpoint there is geometrically great similarity. This is especially distinct in cases of earthquakes of comparatively large magnitudes (indicating magnitudes of about 6 or higher).

Fig. 7 indicates the strains produced in the tunnel in the axial direction and due to bending deformation calculated from strain records of the right and left walls. The strains due to axial-direction deformation had vibration components of long periods, and those due to bending deformation were vibrations of relatively equal periods. Power spectra regarding these are also given in the figure. As for the sizes of strains due to axial-direction deformations, they were approximately quadruple the strains due to bending deformation, and it is necessary to pay attention to the fact that the width of the tunnel is 13 m. Further, regarding the phase differentials between recorded waveforms for measurement points 205 m apart, there were practically no cases of axial-direction deformations, with only slight amounts seen to occur in cases of bending deformation.

3.2.2 Kinuura Port Tunnel Kinuura Port Underwater Tunnel which was opened in 1973 has a submerged tunnel section of a length of 480 m comprised of 6 elements of reinforced concrete box cross sections of height of 7.13 m and width of 15.6 m. The soil conditions differ somewhat for the two sides, with down to -5 m from the ground surface being considerably soft fill, and below -18 m consisting of diluvial sand-gravel and sand layers, but at the intermediate silty clay, the negative side was a hard clay layer of N-value 9 to 13 and the other side a soft clay layer. Observations are being made by the Port and Harbor Research Institute of the Ministry of Transport, and the instruments used for observations are 19 accelerometers at vertical shafts and submerged elements, one displacement meter at the middle of the submerged tunnel, and strain meters in couples right and left at three cross sections for a total of six, and four reinforcing bars stress transducers each at the submerged elements and vertical shafts.

Fig. 8 gives the acceleration records in the direction perpendicular to the tunnel axis obtained at the ground surface and the land tunnel parts in case of an earthquake of epicentral distance of 185 km, depth of 60 km and $M = 5.8$. Further, from the records of accelerometers and reinforcing bar stress transducers, it was judged that the submerged tunnel does not behave uniformly as a whole, but shows complex behaviors in connection with the vibration properties of the surrounding ground.

For earthquakes of magnitudes of 5.3 and 4.9 and epicentral distances of 30 km and 50 km, respectively, short-period components were predominant and it was found that the ground and the submerged tunnel did not show behavior as one.

3.3 Vibration Model Experiments In investigating the behavior during earthquake of this type of tunnel the authors conducted model experiments with the objectives of grasping principle-wise the behaviors of the ground and the tunnel which are basic and the interactions thereof.

The experiment generally carried out consists of making a three-dimensional model of a fairly broad area on a shaking table using a material of low Young's modulus in which the tunnel model is buried, and applying vibrations. It appears there is no other way of showing in an experimentally measurable range that self-vibrations of surface layer ground are predominant in a strong earthquake. As for experiments in the elastic range, it is easier by this method to improve reproduceability and accuracy of the experiments, and this method is rather of advantage for the objective.

Fig. 9 shows the case of a model vibration experiment conducted by the authors, the model being 2.2 m in length and 0.8 m in width. The material for the ground was gelatin, while the tunnel was made of silicone rubber. The so-called bedrock was made horizontal, and of the length of 2.2 m, the two end portions had surface layer ground which was thick and after passing sloped sections the middle had a uniformly thin surface layer ground. This model, because of the limitations in performance of the shaking table, was subjected to sinusoidal vibrations in the one direction of horizontal (either axial direction or direction orthogonal to axis). Since the model tunnel was made of silicone rubber and there is no suitable gage for dynamically measuring strains of the model tunnel available at present, measurement of displacement was substituted.

The fundamental matters clarified by the model experiments may be summarized as follows:

- When grounds having differing self-vibrations are adjacent, the range in which there is interaction is comparatively small and effect is limited to the adjoining area and its vicinity. However, in case of high-order vibrations the influence is seen over a relatively wide area.

- The tunnel vibrates at the frequency of the vibrations of the ground and deforms in correspondence with deformation of the ground. Consequently, the tunnel may be considered as a massless beam connected to the ground.

- A submerged tunnel shows bending deformation and expansion deformation.

- Shaft and ventilation tower portions show rocking motions.

Considered together with phenomena observed in similar experiments carried out separately, the following were also clarified:

- When subjected to vibrations at waveforms of real earthquakes low-order natural vibrations are seen to be extremely predominant in vibrations of the surface layer ground.

- When two kinds of ground having greatly differing natural frequencies adjoin each other through a sloped section, each ground vibrates with its own natural vibration, the vibrating states vary at the slope, and a large section force is produced in the tunnel at this part.

- In relation to the gradient of the slope, intermediate vibrations between the natural vibrations of the grounds at the two sides are seen to be predominant, and there are cases when phases become divergent along the axial line.

- Since displacement of ground directly related to displacement of the tunnel is displacement of the ground at the tunnel location, the distribution of displacement of the ground in the direction of depth must also be considered.

- Since the stiffness of the tunnel against deformation in the axial direction of the tunnel is extremely great compared with that of the ground in which it is buried, when the wave length of the displacement of the ground measured along the axial line is relatively short, it is difficult for the tunnel to deform in accordance with deformation of the ground. Consequently, the behavior of the tunnel is determined by the distribution of dynamic characteristics of the ground on the axial line of the tunnel for a relatively long section. Accordingly, when there are local variations in the state of vibration of the ground, the movement of the tunnel will not necessarily be the same as for the ground in some cases.

- With respect to a direction perpendicular to the tunnel axis, since the tunnel is more easily deformed than in the above case, the deformation of the ground is more easily followed.

- Since shaft and ventilation tower portions generally have great rigidities against bending deformation, they vibrate in accordance with the distribution of displacement of the ground in the direction of depth and rocking vibrations are produced.

- By adopting a joining method allowing movement at the joints of shafts and ventilation towers with the tunnel it will be possible to alleviate large local stresses produced at the joints.

Besides experiments of this type, the authors have conducted vibration experiments burying tubular bodies in actual ground. These experiments, when seen from the standpoint of similarity, may be said to comprise vibration tests of the actual tubular bodies buried. In these experiments, long steel pipes or vinyl pipes of relatively large diameters were buried near the ground surface, and vibrations were produced by a special S-wave generating apparatus or by explosions and impact, and displacements of the pipes and ground, accelerations, and strains were measured. As a result, it was learned that the tubular bodies often vibrated in the same manner as the ground. In these experiments, there were cases when vibrations of the tubular bodies were induced, although very slightly, by impact.

## 4. INTERACTION OF GROUND AND TUNNEL

Regarding the interaction between the ground and tunnel, it was learned from earthquake observations and experimental studies that the behavior of a tunnel during earthquake can be considered as that of a beam (or a pipe) of which mass can be neglected connected to the ground by a spring — not necessarily a linear spring. When the shear deformation of the tunnel is ignored the following equations hold true for deformations of the beam.

Deformation in Axial Direction of Tunnel

$$EA \frac{d^2u}{dx^3} - K_x u = -K_x u_G$$

Deformation in Direction Orthogonal to Tunnel Axis

$$EI \frac{d^4v}{dx^4} + K_y v = K_y v_G$$

where
$A$ : cross-sectional area of tunnel
$E$ : Young's modulus of tunnel material
$I$ : geometrical moment of inertia of tunnel cross section
$K_x$, $K_y$ : spring constants of springs connecting tunnel and ground for displacements in axial direction and direction orthogonal to axis of tunnel.
$u$, $u_G$ : displacements in axial direction of tunnel of tunnel and ground, respectively.
$v$, $v_G$ : displacements in direction orthogonal to tunnel axis of tunnel and ground, respectively.

In order to investigate the response of the tunnel to deformation of the ground, letting $u_G$ and $v_G$ be

$$a \cos \frac{2\pi x}{\lambda}$$

and obtaining the solutions to the above equations, they will respectively be

$$u = \frac{\beta_x^2}{(\frac{2\pi}{\lambda})^2 + \beta_x^2} a \cos \frac{2\pi x}{\lambda}$$

$$v = \frac{\beta x^4}{(\frac{2\pi}{\lambda})^4 + \beta x^2} a \cos \frac{2\pi x}{\lambda}$$

and the axial strains ($\varepsilon_x$) or fiber strains ($\varepsilon_y$) of the tunnel against $u$ and $v$ may be expressed by the following equations, respectively:

$$\varepsilon_x = \frac{du}{dx} = -\frac{\beta_x^2 \cdot \frac{2\pi}{\lambda}}{(\frac{2\pi}{\lambda})^2 + \beta_x^2} a \sin \frac{2\pi}{\lambda} x$$

$$\varepsilon_y = r_0 \frac{d^2 v}{dx^2} = -\frac{\beta_y^4 (\frac{2\pi}{\lambda})^2}{(\frac{2\pi}{\lambda})^4 + \beta^4} \cdot \gamma \cdot a \cos \frac{2\pi}{\lambda} x$$

However,

$$\beta_x^2 = \frac{K_x}{EA}, \quad \beta_y^4 = \frac{K_y}{EI}$$

$r$, $r_0$ : distance measured from neutral axis of tunnel and edge distance

The value of $|\varepsilon_x|$ is a maximum at $\lambda = 2\pi/\beta_x$ and

$$|\varepsilon_x|_{max} = \beta_x/2$$

The value of $|\varepsilon_y|$ indicates a maximum at $\lambda = 2\pi/\beta_y$, and with $r = r_0$, becomes

$$|\varepsilon_y|_{max} = r_0 \beta_y^2/2$$

Fig. 10 indicates the relation between strain in the axial direction of the tunnel and the wave length of the ground for $\beta_x$ and $\beta_y$.

In general, since $\beta_x < \beta_y$, the wave length which indicates the maximum value of strain due to axial-direction deformation is several times the wave length for bending deformation, and therefore, it is seen to be preeminent at the portion where wave length is long compared with the case of bending deformation, and moreover, preeminent at a wave length realm of fairly wide range. From this, in case of vibration having an amplitude spectrum which is constant, the spectrum of strain produced at the side wall of the tunnel will have a realm of wave length predominant for the direction of bending deformation which differs from the realm of wave length predominant for axial deformation.

## 5. BASIC THINKING IN EARTHQUAKE-RESISTANT DESIGN

As previously stated, since a submerged tunnel is a structure of a new type which shows behavior during earthquake which differs from that of a structure on land, in order for rational earthquake-resistant design to be made, it is necessary to establish the manner of thinking and method of design based on the behavior. For this purpose, the Japan Society of Civil Engineers organized a committee to study earthquake resistance of submerged tunnels with deliberations commenced in 1971, and in 1975 completed "Specifications for Earthquake Resistant Design of Submerged Tunnels" (hereinafter to be called

"Specifications"). In this, the thinking with regard to design is described from a new viewpoint. A discussion follows below.

5.1 Earthquake for Design It has been clarified that the earthquake resistance of a submerged tunnel is closely related to the ground in which it is buried.

In major earthquakes of the past failures and damage have occurred over wide areas at alluvial ground, and even in medium-scale earthquakes, as seen in the case of the Fukui Earthquake, there was failure of the ground at the epicentral area. And as previously described, it was learned that when the period of the low-order predominant vibration of the ground is 1 sec or longer, strains in the axial direction produced in the tunnel walls during earthquake will not be reduced as much even when epicentral distance is increased, and that rather, it is the magnitude of the earthquake which greatly influences strains. For these reasons, it is necessary to consider earthquakes occurring in a comparatively wide area as earthquakes to be considered for earthquake-resistant design. In the Specifications, it is proposed to estimate the frequency of earthquake occurrence in an area with a radius of 200 km with the construction site as the center based on earthquake records from the beginning of history and using the formula of ISHIMOTO-IIDA. The scales of earthquakes and their number occurring during a given period in the future is to be estimated by this means. The earthquakes and their scales which are frequently used for dynamic analyses of submerged tunnels in the vicinity of Tokyo are great earthquakes of magnitudes of around 8 belonging to the Outer Seismic Zone and earthquakes of magnitudes about 7 occurring at close distances. Further, it is stipulated in the Specifications that earthquake observations are to be carried out in order to know beforehand the natures of ground motions at the tunnel site as a safety measure for the submerged tunnel.

5.2 Stability of Ground The examinations of stability of ground during earthquake presently being made may be broadly divided into examinations of the stability of slopes and examinations of liquefaction of sandy ground. In both cases, the problems are difficult ones where earthquake motion, topography, geology and ground structure are inter-related and many investigations and research works are now in progress in this regard. For a submerged tunnel, even in case of a cohesive soil which does not easily liquefy, the displacement of the ground during earthquake must not be so large that damage is inflicted on the tunnel, and care must be exercised that reduction in bearing power will not be extreme to produce trouble with respect to earthquake resistance.

This problem may be split along the lines of stability of ground in a comparatively wide area at the tunnel site and stability of ground in the immediate surroundings of the tunnel. Care will be required since there will be cases of the measures against earthquake differing according to the above.

In order to examine the earthquake resistance of the structure and stability of ground in relation with the ground and soil properties, it is necessary besides various static and dynamic laboratory tests using samples, for various measurements to be made with boreholes such as speed of seismic waves and velocity of seismic waves, and seismic prospecting to be carried out. The Specifications cite the following as investigations and tests to be implemented:

- Boring and sounding (standard penetration tests)
- Sampling and laboratory tests of samples
- Measurement of seismic wave velocities with boreholes
- Measurement of density of soils

- Microtremor observation

There are times when the values obtained from a plural number of such tests and investigations on the same dynamical quantity will not coincide. This is because differences are produced depending on strain level, method of testing and process of testing. This is especially so with the results of dynamic testing, and in case of evaluation in relation to earthquake resistance there are numerous difficult problems. Although it cannot be said that under the present circumstances a method of evaluation has been firmly established, the information will be of importance when making an engineering judgment of stability.

With regard to stability of ground the sliding plane method is customarily used for slopes. In the Specifications, it is stipulated that even for horizontal ground a horizontal sliding plane is to be assumed in the ground and sliding of the plane evaluated through application of the seismic coefficient method. It is proposed that in certain cases the surface layer should be made equivalent to a shear vibration model having one-degree-of-freedom plastic spring characteristics to make earthquake response calculations for examination of displacement of ground.

Concerning liquefaction, ground consisting mainly of sand of uniform grain size which is not well compacted is considered as being a problem. As methods of examining stability, there are methods from the aspect of stress such as the one in which stress conditions during earthquake are assumed and testing is done reproducing the stress conditions in the sample, and the one in which loads of stationary waveforms and real earthquake waveforms are applied, while there are also methods from the aspects mainly of condition of ground and material such as N-value and grain-size distribution. Studies related to liquefaction are now in active progress and the phenomenon is gradually coming to be clarified, but there is still necessity for examination, and the Specifications take the stand that stability of the ground is to be judged from grain-size distribution, N-value, and maximum acceleration of ground carrying out dynamic tests on soil and grasping the properties of the soil during earthquakes. Depending on the results it may become necessary for foundation improvement, rerouting and structural changes to be made.

The stability during earthquake of soil backfilled around the tunnel is also of importance. Complex stress conditions are produced in the surrounding ground of the tunnel during earthquake. Care must be exercised since large plastic deformation and liquefaction of the surrounding ground will be the causes of instability, uneven settlement and upheaval of the tunnel.

<u>5.3 Basic Concept of Earthquake-Resistant Design</u> As previously mentioned, since a submerged tunnel possesses a number of distinct features, there are areas in the method of earthquake-resistant design which differ from those for structures of other types. The essentials of the basic principles given in the Specifications will therefore be listed below.

- Consideration is given for earthquake resistance of the total structural system including the topography and geology of the construction site.

- In carrying out earthquake-resistant design for the various parts of the tunnel, the displacement of ground during earthquake or the design seismic coefficient is to be used as the basis, while for the total structural system, design and examination based on dynamic analyses are to be performed.

- For design of joints and other parts where variation in rigidity will be prominent, the influences and effects thereof are to be examined.

- For safety measures during earthquake, considerations are to be given that control and operation of various facilities for the safety measures will be carried out with sureness.

Regarding the first point it has already be explained in outline. What should be noted with respect to the second point is that designing is to be done based on displacement of the ground, and that dynamic analyses are to be made for the total structural system. In the past, in earthquake-resistant design of ordinary structures, the basic factors had been the inertia forces of the various structural parts during earthquake, but in the case of a submerged tunnel, the displacement of the ground during earthquake is the basic factor, according to which the concept of design becomes different. Since the measure of design seismic coefficient which considers earthquake force is changed to displacement, it becomes necessary for examinations to be made of the data required and of the relation between acceleration and displacement. Further, as described previously, since a submerged tunnel comprises a structural system where structures of different properties in earthquake response are connected and made continuous, even if each of the structural parts is designed by an established method, a necessity arises for matters concerning connections and behavior as a whole to be studied. The third point has a relation to the second. Not only will the methods of connecting the various structural parts, and types and methods of joining elements greatly influence stress levels produced, but also they will have a relation with functioning of the tunnel, and therefore, it has been stipulated that examinations are to be made with special care. According to an example of analysis, for a submerged tunnel section of length of approximately 1 km, in case free displacement was permitted between the submerged tube part and a vertical shaft, relative displacement of several cm was computed to occur. In regard to the fourth point, it is directed that measures for safety during earthquake are to be implemented in addition to structural design, and that considerations are to be given to planning, structure, equipment and materials so that the safety measures will be actuated without fail during earthquake.

The above signifies that earthquake-resistant design which had been made separately for the various parts due to the characteristics of this structure is to be carried out in unified form.

5.4 Dynamic Analysis Next, an outline will be given with respect to dynamic analysis. Ventilation towers and retaining walls of approaches are designed for earthquake resistance by the conventional seismic coefficient method or the modified seismic coefficient method, and there is much experience regarding their earthquake resistances, whereas tunnels of this type have not experienced major earthquakes. Accordingly, it was decided that dynamic analyses should be made to more accurately grasp dynamic behavior of the structural system including the ground. It is proposed in the Specifications that as dynamic analyses, experimental analyses based on model vibration experiments in the laboratory be carried out in addition to earthquake response calculations. The objective is to grasp in detail and with accuracy, through organic combination of the two analyses, the behaviors during earthquake of the ground and tunnel under three-dimensional and complex ground conditions. For earthquake response analysis there are the method of determining response by a three-dimensional finite element method and the method described below which utilizes models for dynamic analysis, with the latter being generally used.

5.4.1 Models for Dynamic Analysis The authors, with the basic information as described above concerning behaviors of ground and tunnel during earthquake obtained from earthquake observations and model experiments, have proposed dynamic analysis models which are of theoretical nature yet aim for practicality. These models, as indicated in Fig. 11, are divided into numerous segments cut by the surrounding ground of the tunnel and planes perpendicular to the tunnel axis, with each segment replaced by a one-masspoint-spring system equivalent to primary shearing vibration and with these masspoints further connected in the axial direction of the tunnel by springs, for calculating the planar displacement waveform of the ground during earthquake spring-connecting this and the tunnel to determine the deformation of the tunnel. Since the correspondence of this model with high-order vibrations is not adequate, there have been cases where response accelerations have been calculated to be fairly small, but for strains in the axial direction of the tunnel, sufficient accuracy has been obtained as there is little effect of high-order vibrations of the ground. Regarding the effect of high-order vibrations on strain, it is possible for approximate calculations to be made through improvisations of the application method of the model. However, when the state of the ground is extremely complex three-dimensionally, there may be cases arising where this model will not be adequate. On analysis by this model for the previously described vibration model experiments, results which agreed well with those of the experiments were obtained.

5.4.2 Model Vibration Experiments    Gelatin and soil stabilizer of the acrylamide type were used as materials for ground in model experiments, while silicone rubber was used as the material for tunnels.

It is difficult under present circumstances to numerically analyze the earthquake response of a submerged tunnel when it is constructed at ground where topography, soil and ground composition are complex. Model vibration experiments are very effective in such cases. Models used are whole models covering wide areas including tunnels, and partial models for investigating localized behaviors. As materials for models, gelatin gel and acrylamide are used for ground, and silicone rubber materials for tunnels.

## 6. EARTHQUAKE-RESISTANT DESIGN

Since a submerged tunnel is comprised of structural components which show different response behaviors against earthquakes, in earthquake-resistant design the submerged tube portion would be calculated based on displacement of the ground during earthquake (displacement method) while vertical shafts, ventilation towers and retaining walls would have design calculations made by the seismic coefficient method or the modified seismic coefficient method. Needless to say, design and examination based on dynamic analyses must be made for the entire submerged tunnel as previously described. Since the seismic coefficient method and the modified seismic coefficient are already well-known, only special applications will be touched upon, and the discussion here will be chiefly in regard to the displacement method.

6.1 Displacement Method    For computing the section forces produced during earthquake on the structural parts of the tunnel consisting of submerged tube section and approaches, and the earth pressures acting on the tunnel, the distribution of displacements during earthquake of the ground along the tunnel axis must be obtained. With regard to earthquake response of surface layer ground, there have already been many research works carried out with response velocities of ground having natural periods up to several sec having been obtained, and it is considered that in a major earthquake components of low-order natural shearing vibration are predominant with regard to displacement. Therefore, it would be possible to compute the response displacement of the surface layer if the earthquake motion of the bedrock were to be known. However, it is not an easy task to determine how ground displacements will be distributed at the same instant along the axial line of the tunnel. According to the results of earthquake observations, it is seen that vibration components of relatively long periods are propagated at fairly high velocities to the ground surface. It is also known that the submerged tube portion does not respond well to wave motions of short wave length. Thereupon, using the models for dynamic analysis given by the authors, and with the principal objective of investigating the influence of variations in ground conditions on stresses in tunnels, response calculations were carried out for more than 260 cases under various conditions, and data for designing were obtained. The ground conditions considered for calculations were those indicated in Fig. 12, and the earthquake records of Hachinohe (Off-Tokachi Earthquake, 1968), El Centro Earthquake NS (1940) and Taft Earthquake EW (1952) were input from the bedrock and responses of the tunnels computed. The fundamental shearing vibration periods of the land and sea bed portions, $T_1$ and $T_2$, were made up in various combinations, the gradients and shapes of the sloped sections were varied in many ways, and further, the stiffnesses of the tunnels against deformation and the spring relationships between ground and tunnels were variegated. The response stresses of the tunnels determined from calculations were standardized through the equations below.

$$\sigma_t = \frac{\sigma_t}{D_L + D_S} \ (\mathrm{kg/cm^2/cm})$$

$$\sigma_B = \frac{\sigma_B}{D_L + D_S} \ (\mathrm{kg/cm^2/cm})$$

In these equations, $\sigma_t$ and $\sigma_B$ are the maximum axial strain and maximum fiber strain due to axial-direction deformation and bending deformation, respectively, obtained in response calculations, where $D_L$ and $D_S$ are the response displacements (relative displacements) of land and sea bed parts replaced by one-masspoint-spring systems, respectively.

Figs. 13 and 14 indicate the relationships between various combinations of $T_1$ and $T_2$, and $\bar{\sigma}_t$ and $\bar{\sigma}_B$. With this model, in case of $T_1 = T_2$, both $\sigma_t$ and $\sigma_B$ will be zero, but considering that grounds of $T_1 = T_2$ do not actually exist, that earthquake wave motion is propagated through the bedrock, and that various wave motions are produced at the ground surface, from a practical standpoint the broken line is taken as the lower limit and only values above this line are taken up.

<u>6.2 Stability of Transverse Cross Section of Submerged Tube Section</u> The force acting on the spring between the submerged tube section and the ground may be calculated by the method proposed by the authors. Although designing has been done for this force to be resisted by passive earth pressure of ground surrounding the tunnel, since there is still room remaining for consideration, it was made permissible in the Specifications for calculations to be made by the seismic coefficient method. With regard to the design seismic coefficient in the seismic coefficient method, this is to be selected taking into account the topographical and geological conditions of the site and importance factor of the tunnel, and referring to the criteria of other related earthquake-resistant design standards.

<u>6.3 Earthquake-Resistant Design of Shafts and Ventilation Tower Sections</u>
Since shafts and ventilation tower sections are considered normally to indicate dynamic behaviors similar to buildings, they are to be designed for earthquake resistance by the seismic coefficient method. In this design,

giving consideration to the fact that the submerged tube section and the approach sections show different dynamic behaviors, it is necessary for attention to be paid to the connections between these sections. It is possible to reduce stresses produced near joints during earthquakes by providing movable joints and sections high in flexibility and expandability in connections with the submerged tube section. In some cases, it is conceivable for shafts and ventilation towers to be built apart from the tunnel to break off the mutual influences of the two. Further, it is necessary for care to be exercised that uneven settlement — uneven settlement of the tunnel section — will not occur, not only during earthquake, but also at all times. In case there are comparatively large displacements of shafts and ventilation towers at underground portions, it will be advisable for dynamic analyses to be made of the structural parts including the submerged tube section.

Fig. 15 indicates the joints adopted at Tokyo Port Tunnel in connecting a shaft end with the submerged tube. The left half is the joint of a shaft with the first submerged element with primary water cutoff by rubber gaskets, and with secondary and tertiary cutoff measures provided. The right half is the joint between the last submerged element and a shaft with the primary water cutoff made by W-shaped rubber seals. By using these methods, the elements can move freely in the axial direction, up and down, right and left, and in rotation.

6.4 Effects of Joints    Flexible joints are used at times in order that joints between elements will have sufficient strength against forces caused by earthquakes and ground settlement after pressure-jointing the elements, and in addition, to reduce the forces produced by these phenomena. Fig. 16 shows the joints adopted for Tokyo Port Tunnel which are provided with shear keys to prevent divergences between elements in the horizontal and vertical directions, while Ω-shaped steel sheets form flexible springs in the axial direction.

By installing suitable joints between tunnel and shaft-ventilation tower sections, and between elements, the flexibility and the expandability of the tunnel are heightened, and as a result section forces of the tunnel can be reduced, but the range in which the effects are felt is determined by the relativity between the rigidity of the tunnel and the rigidity of soil, and is in a comparatively narrow range. Accordingly, it is necessary for studies to be made in the locations of the joints, intervals, and number.

Fig. 17 indicates the results of investigations on the effects of joints in the previously-mentioned analysis model. Case 1 is for no joint, Case 2 is for a single hinge joint, Case 3 is for 2 hinge joints, and Case 4 for when all joints are connected by springs with low spring coefficients. It may be seen that axial forces and bending moments are greatly lowered in Case 4.

6.5 Case of Variation in Dynamic Properties of Ground    When there has been a change in the dynamic properties (natural period, vibration mode, etc.) of the ground along the tunnel axis, it has been clarified by experimental results and analytical results that an extremely large section force is produced in the tunnel at that portion. Fig. 18 is an example of the distribution of response section forces determined for four kinds of earthquake waveforms normalized at maximum acceleration of 100 gal using the previously mentioned vibration model. Although the absolute values of the response quantities may differ, it can be seen that the tendency for a large section force to be produced at the slope is not changed by earthquake. This is the same for the direction of depth also. Therefore, when the submerged tunnel route passes through such a location it is conceivable to aim for reduction in section force by measures such as adopting sections high in flexibility and installation of movable joints as necessary.

6.6 Influence on Tunnel Section Force of Non-Linearity of Stress-Strain Relationship of Soil Surrounding Tunnel Using the models for dynamic analysis previously described, and carrying out response analyses under various conditions and considering the properties of the springs connecting ground and tunnel, in effect, the relation of displacement and force between the surrounding ground of the tunnel and the tunnel considered as being of bi-linear type, the distribution of maximum values of section force will be as indicated in Fig. 19. According to this figure, the coefficient of deformation after yielding of springs does not exert so much influence on section force, but the size of strain at the yield point of the spring has a great effect, and when this value becomes small, it is seen that section force is reduced.

## 7. SAFETY MEASURES DURING EARTHQUAKE

With regard to the position and importance of safety measures during earthquake in earthquake-resistant design of a submerged tunnel, these matters are as described in Chapter 3 and Chapter 5. The safety measures during earthquake may be broadly divided into two kinds, one consisting of what might be called "hardware" facilities, such as evacuation passageways during emergencies, facilities to prevent entrance of water due to tsunamis, and facilities for water cutoff, which must be taken into consideration at the planning and designing stage. The other kind consists of so-called "software-type" facilities such as instrumentation for detection of earthquake motions, communication facilities, drainage facilities and traffic control facilities.

Adequate considerations must be given that these facilities will not lose their functions due to secondary trouble such as inundation, water leakage and uneven settlement of ground at time of earthquake, and considering that this type of tunnel is to be constructed at river beds or sea beds, measures against water leakage and inundation are of particular importance.

Safety measures for tunnels constructed recently will be of reference, while the Specifications require the following as facilities for safety during earthquakes.

- Facilities for detecting, recording and reporting earthquake motion
- Facilities for detecting, recording and reporting tide level and wave height
- Traffic control facilities during and immediately after earthquake
- Facilities for detecting, recording and reporting settlement and leakage
- Evacuation and guidance facilities
- Emergency electric power facilities
- Traffic monitoring facilities
- Drainage facilities and inundation prevention facilities
- Others (strain meter, reinforcing bar stress transducer, stress meter, etc.)

The types and numbers of these facilities would be decided as suited in accordance with the size and importance factor of the submerged tunnel, while depending upon the use of the tunnel, for example, an automobile tunnel, it will of course be necessary to consider facilities to cope with automobile fires.

The Specifications do not clearly stipulate at what level of earthquake these safety facilities should be activated, but do cite "Conduct of Train Operation during Earthquakes" for the Shinkansen lines of the Japanese National Railways as reference. This specifies standards for train operation control, on-ground patrol, in-train patrol, etc., to be carried out on action of earthquake sensors of 40 gal and 80 gal. The Specifications do stipulate that when subjected to earthquakes of seismic intensity 4 or higher, patrols are to be made to check for earthquake effects on the various parts of the submerged tunnel and other abnormalities.

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**Table 1 Submerged tunnels in Japan, completed and under construction**

| Name* | Location | Use | Elements | | | | | | Period for construction |
|---|---|---|---|---|---|---|---|---|---|
| | | | Length** (m) | Number | Length (m) | Width (m) | Height (m) | Sectional shape | |
| Aji River Tunnel | Osaka | 2 lane road | 49.2 | 1 | 49.2 | 14.0 | 7.0 | Rectangular | 1935–1944 |
| Haneda Tunnel | Tokyo | 4 lane road | 56 | 1 | 56 | 20.1 | 7.4 | Rectangular | 1963–1964 |
| Haneda Tunnel | Tokyo | 2 track monorail | 56 | 1 | 56 | 10.95 | 7.4 | Rectangular | 1963–1964 |
| Dojima River Tunnel | Osaka | 2 track railway | 70.5 | 2 | 36.0<br>36.5 | 11.00 | 7.18 | Rectangular | 1967–1969 |
| Dotonbori River Tunnel | Osaka | 2 track railway | 24.9 | 1 | 24.9 | 9.65 | 6.96 | Rectangular | 1967–1969 |
| Keiyo-line Haneda Tunnel (Tama River) | Tokyo | 2 track railway | 480 | 6 | 80 | 13.0 | 7.95 | Binocular | 1968–1971 |
| Keiyo-line Haneda Tunnel (Morigasaki) | Tokyo | 2 track railway | 328 | 4 | 82 | 12.74 | 7.99 | Binocular | 1969–1971 |
| Atsumi Power Plant Intake Channel | Aichi Prefecture | Cooling water intake channel for power plant | 36.01 | 1 | 36.01 | 8.4 | 4.0 | Rectangular | 1970 |
| Dokai Bay Tunnel | Kita-kyushu | 2 belt conveyors for iron one and coke | 1363.2 | 18 | 30<br>80.1 | 8.218 | 4.55 | Rectangular | 1970–1072 |
| Kinuura Port Tunnel | Aichi Prefecture | 2 lane road | 480 | 6 | 80 | 15.6 | 7.1 | Rectangular | 1969–1973 |
| Ogishima Tunnel | Kawasaki | 4 lane road | 664.3 | 6 | 110 | 21.6 | 6.9 | Rectangular | 1971–1975 |
| Tokyo Port Tunnel | Tokyo | 6 lane road | 1035 | 9 | 115 | 37.4 | 8.80 | Rectangular | 1969–1975 |
| Sumida River Tunnel | Tokyo | 2 track railway | 201.5 | 3 | 67.5<br>67.0 | 10.30 | 7.80 | Rectangular | 1973–1976 |
| Kawasaki Port Tunnel | Kawasaki | 4 lane road | 840 | 8 | 110<br>100 | 31.00 | 8.54 | Rectangular | 1972–(Under construction) |
| Tokyo Port 2nd Fairway Tunnel | Tokyo | 4 lane road | 744 | 6 | 124 | 28.40 | 8.80 | Rectangular | 1973–(Under construction) |

* Tentative English names
** Lengths submerged structures

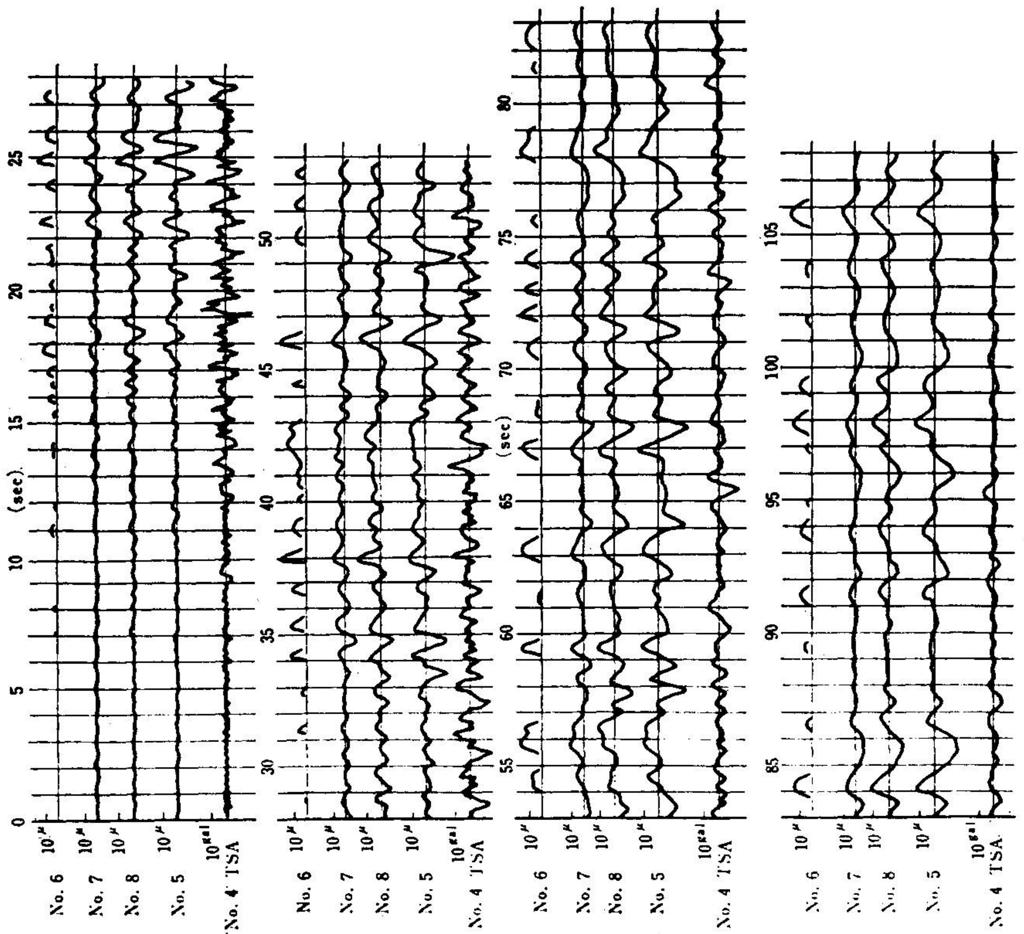


Fig.1 Earthquake records (December 4, 1972)

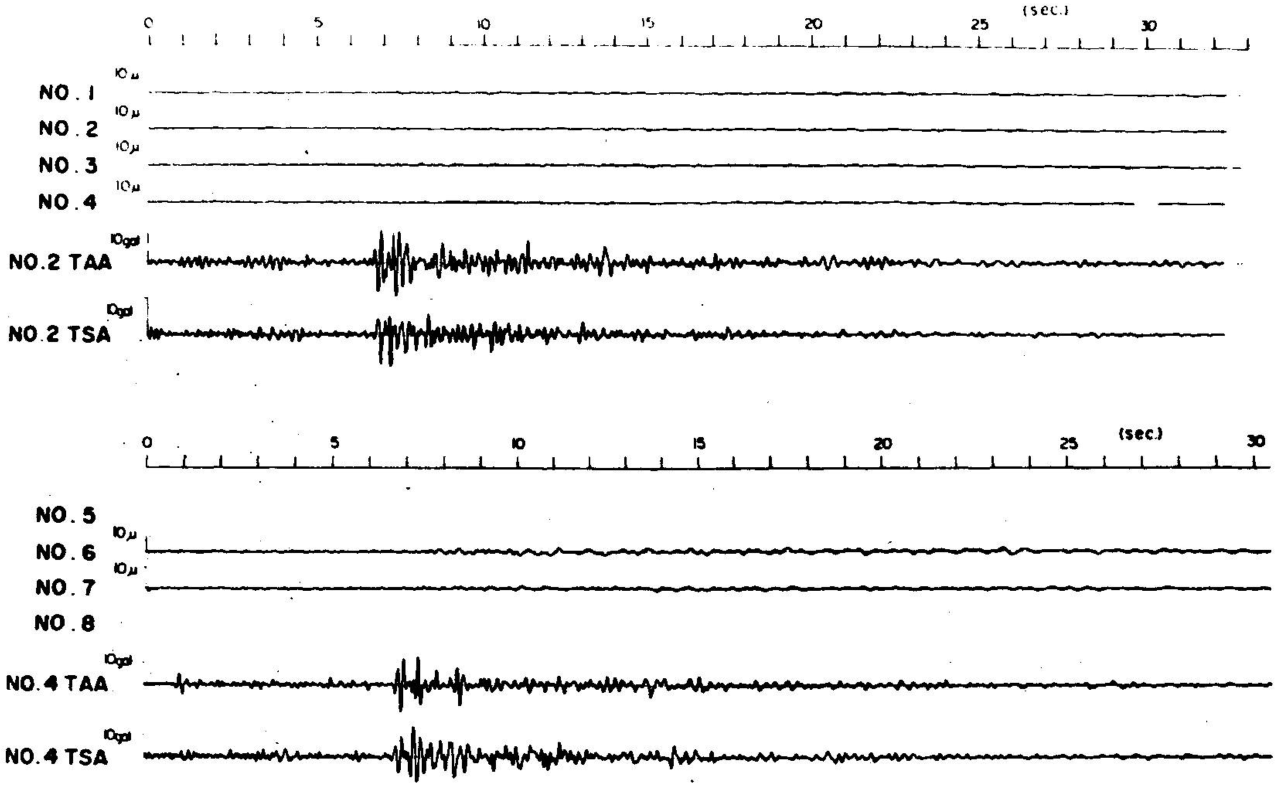


Fig.2 Earthquake records (March 27, 1973)

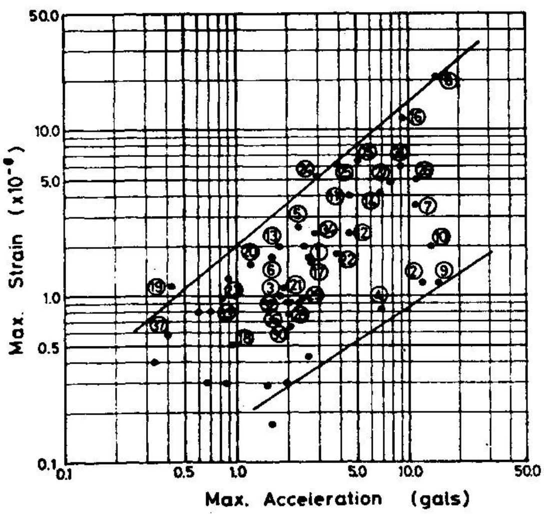


Fig.3 Relation between max.acceleration and max.axial strain at Haneda Tunnel (J.N.R.)

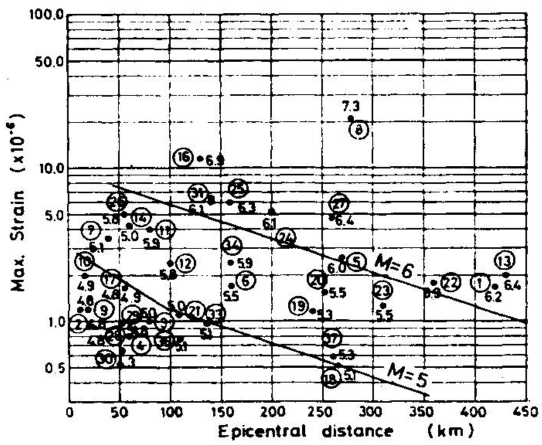


Fig.4 Relation between epicentral distance, magnitude of earthquake and max.axial strain at Haneda Tunnel (J.N.R.)

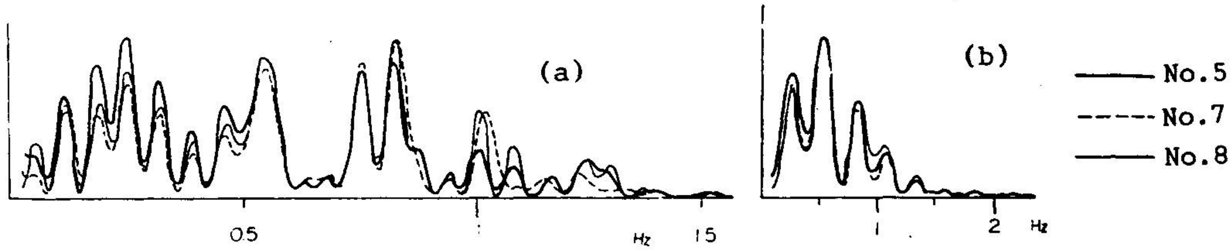


Fig.5 Power spectra of strain records of earthquake (December 4, 1972) at Haneda Tunnel (J.N.R.)

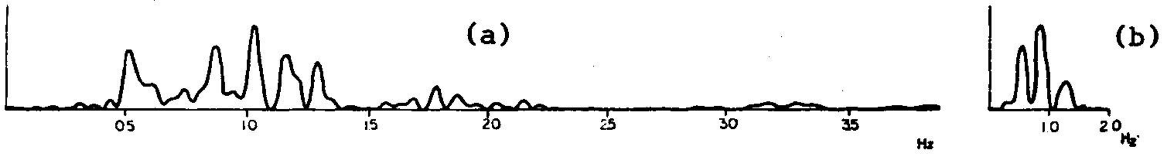


Fig.6 Power spectra of acceleration record (No.4 TSA) of earthquake (December 4, 1972) at Haneda Tunnel (J.N.R.)

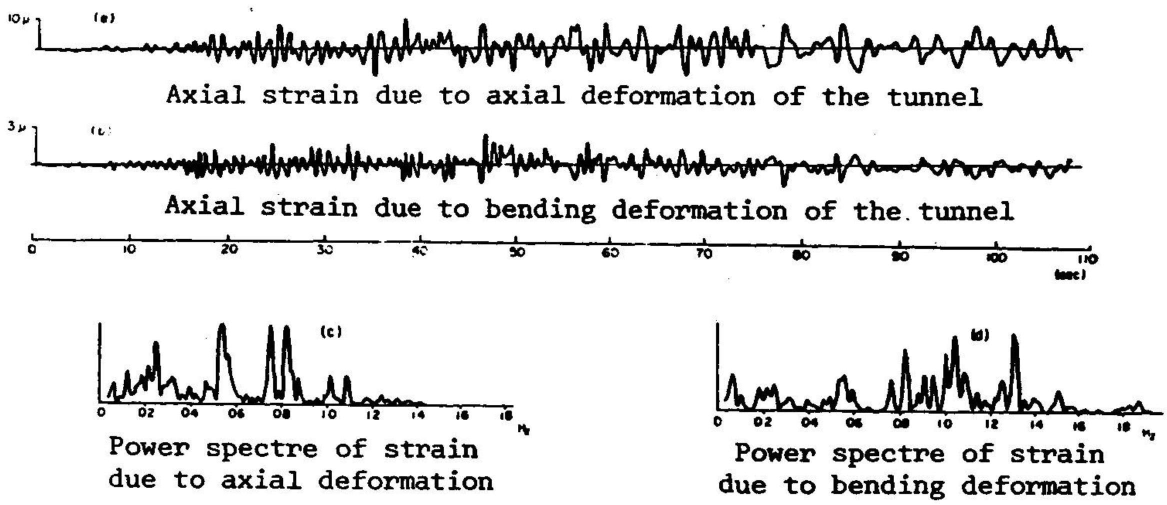


Fig.7 Strain waves generated by axial deformation and bending deformation of tunnel (Haneda Tunnel) during earthquake (December 4, 1972) and their power spectra

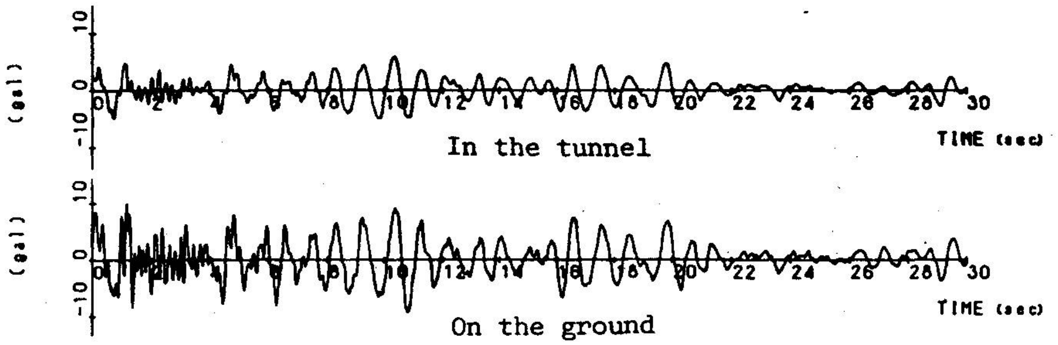


Fig.8 Earthquake records recorded simulteneously on the ground surface and in the tunnel (Kinuura Port Tunnel)

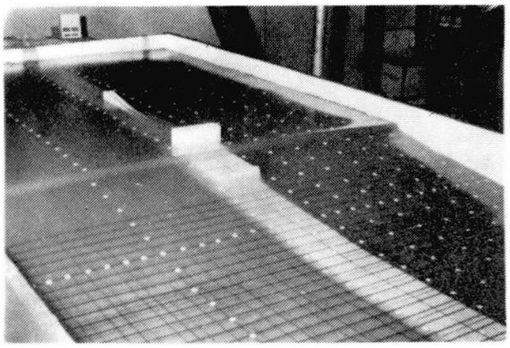

Fig.9 A model of tunnel

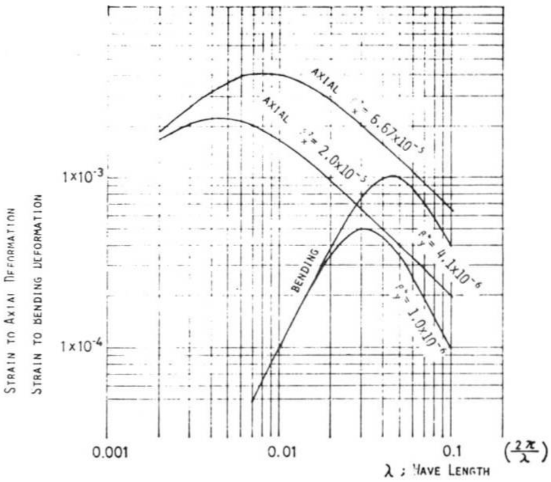


Fig.10 Relation between wave length and axial strain of tunnel

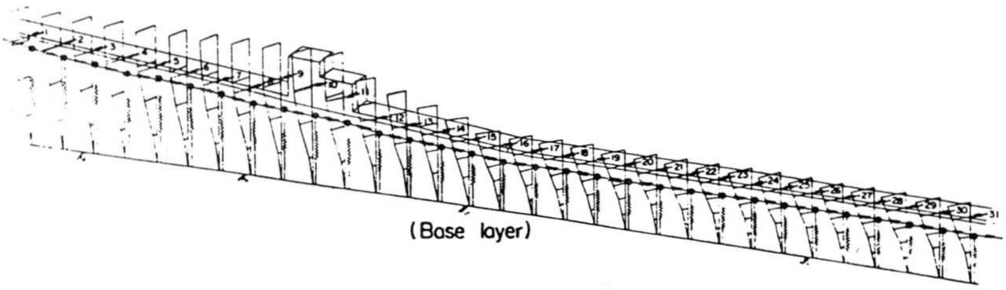


Fig.11 Mathematical model of tunnel

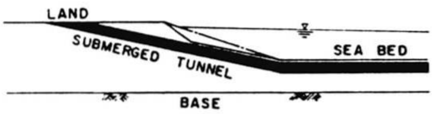


Fig.12 Typical profile of ground and tunnel for analysis

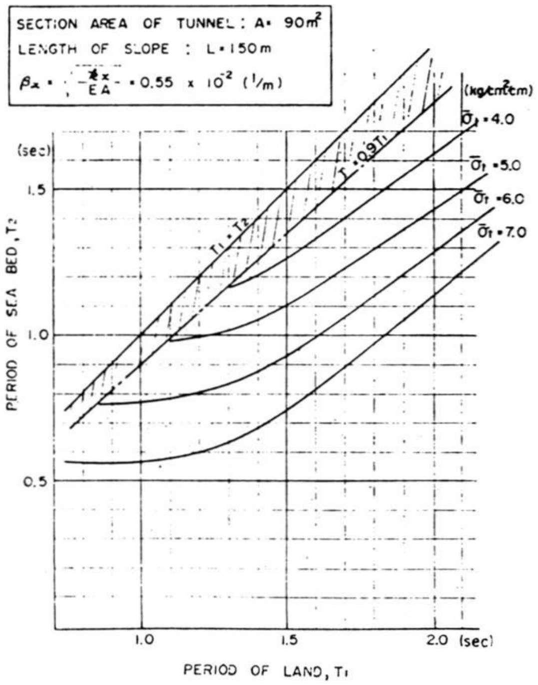


Fig.13 Max. response axial stresses of tunnel normalized by response displacement of ground

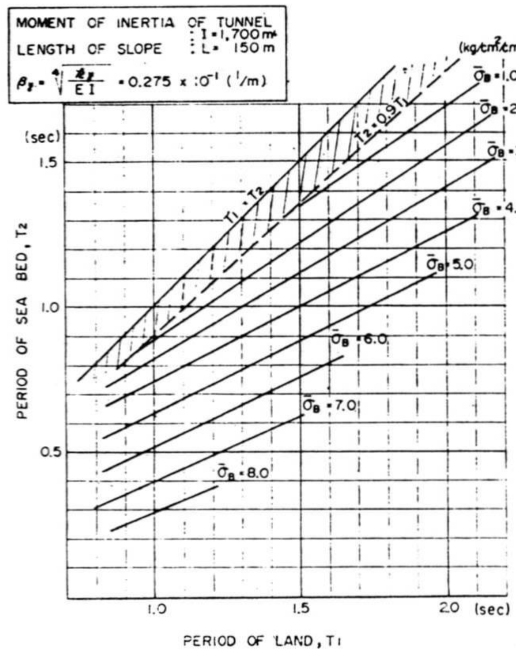


Fig.14 Max. response fiber stresses of tunnel normalized by response displacement of ground

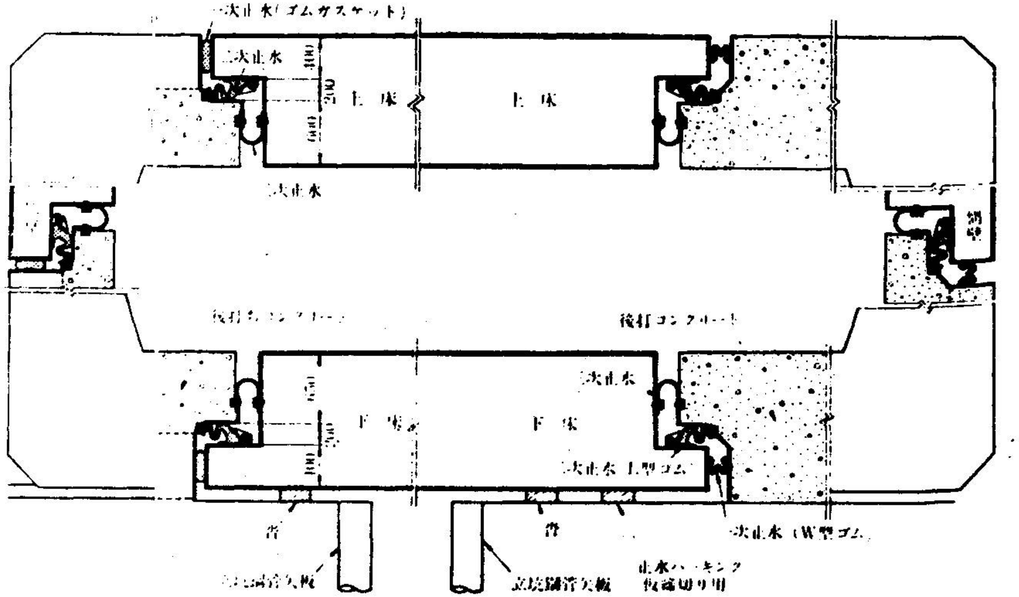

Fig.15 Movable joints connecting vertical shaft and element (Tokyo Port Tunnel)

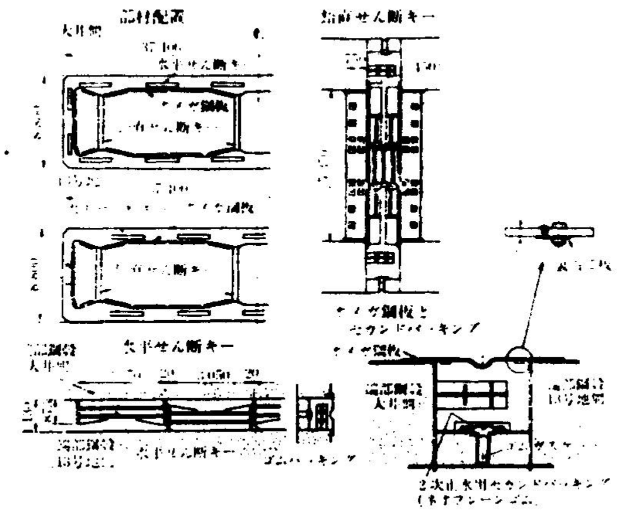

Fig.16 Movable joint connecting elements each other (Tokyo Port Tunnel)

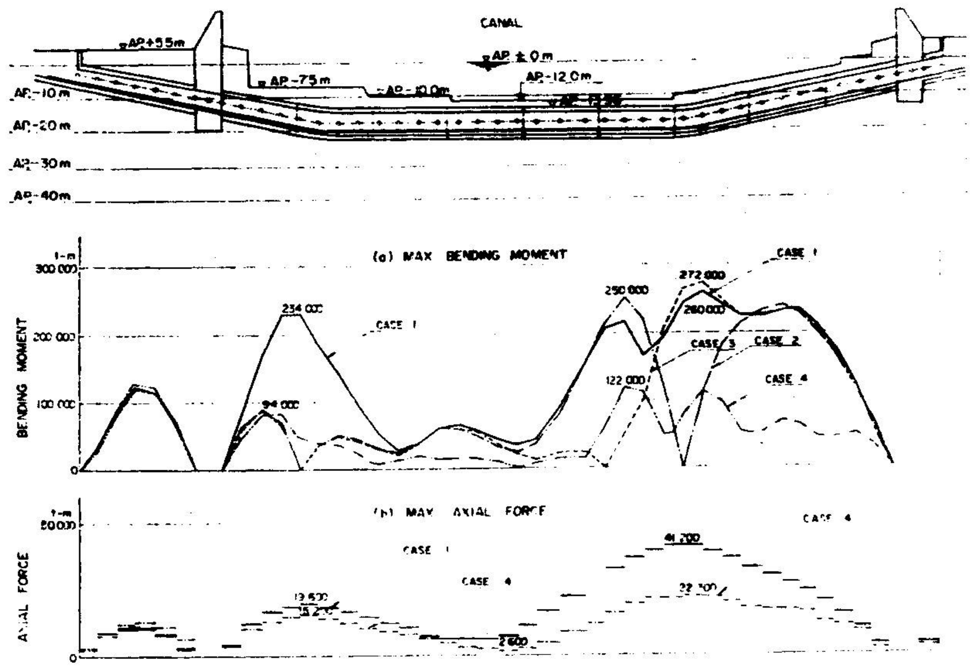


Fig.17 Influence of hinged joint and spring joint on stresses of tunnel (Tokyo Port Tunnel)

Case 1 Rigid connection
Case 2 One himged joint
Case 3.Two hinged joints
Case 4. Spring joints connecting elements

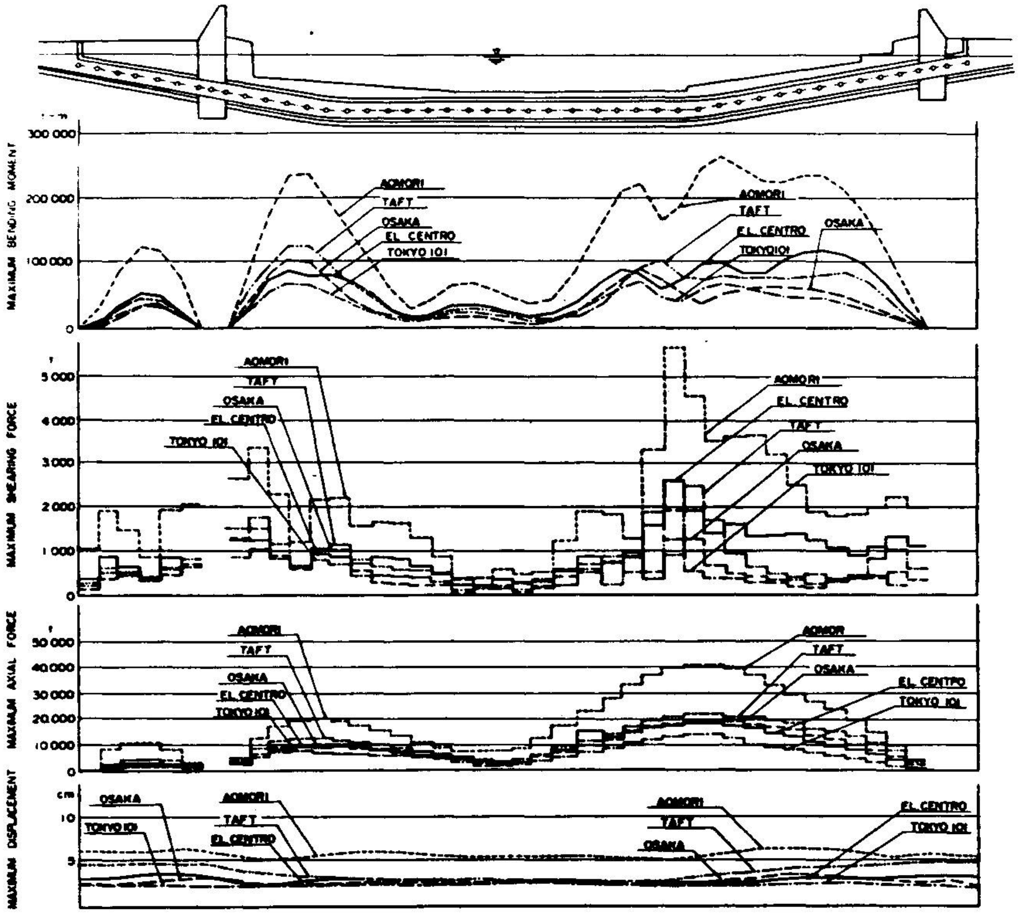


Fig.18 Distribution of response displacement and response cross-sectional force of tunnelto 5 earthquake records which are normalized by max. acceleration of 100 gals (Tokyo Port Tunnel)

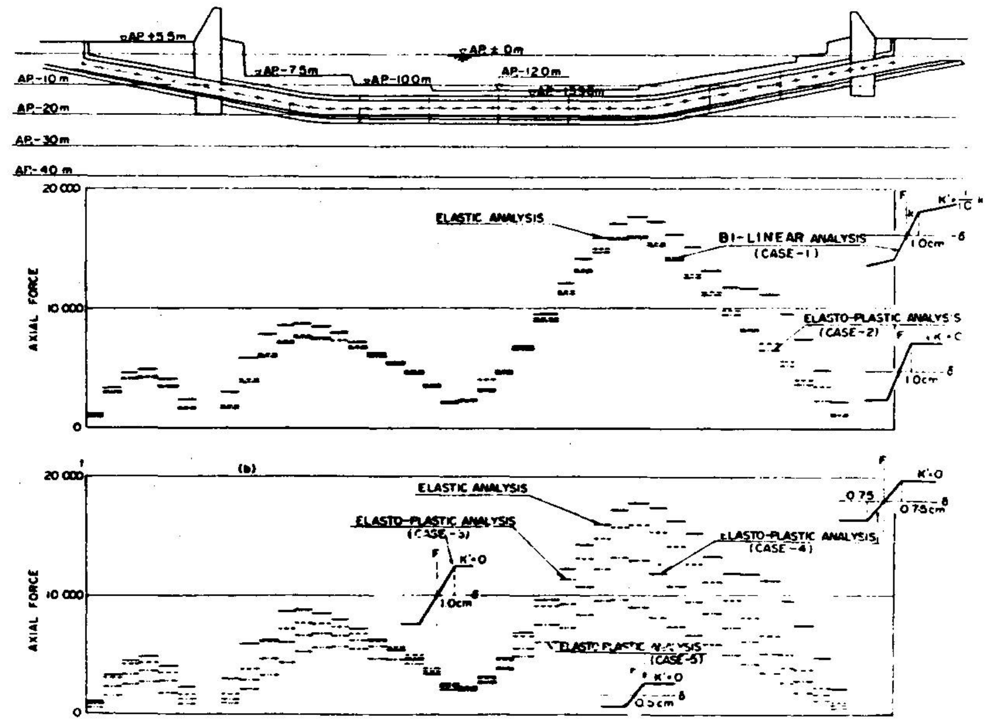


Fig.19 Max. response axial force of tunnel for bi-linear model of spring K which connects tunnel and ground (Tokyo Port Tunnel)

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