

**EARTHQUAKE RESISTANT DESIGN
OF
SUBMERGED TUNNELS
AND
AN EXAMPLE OF ITS APPLICATION**

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FOREWARD

Researches and investigations on earthquake resistance of submerged tunnels have been conducted since 1968 in Public Works Research Institute, Ministry of Construction. Public Works Research Institute entrusted making earthquake resistant design specifications of submerged tunnels to Japan Society of Civil Engineers in 1971. In response to the entrust, a subcommittee on earthquake resistant design of submerged tunnels was organized in Japan Society of Civil Engineers in 1971, and through surveys and studies of the available research works for earthquakes, earthquake ground motions, dynamic characteristics of submerged tunnels in subsurface ground, Specifications for Earthquake Resistant Design of Submerged Tunnels (Version of 1975) was completed in 1975.

The present publication presents first the summary of earthquake resistant design calculations of submerged tunnel prescribed in the specifications. Then, a numerical example to assist in the interpretation of specifications is presented for the proposed Tokyo Bay Crossing Highway Tunnel.

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I. EARTHQUAKE RESISTANT DESIGN

1. General

In making earthquake resistant design for submerged tunnels, stability of the tunnel shall be checked by the seismic coefficient method and the seismic deformation method for the individual parts of the tunnel and by the dynamic analysis for the total structural system including effects exercised by topography and geology at proposed tunnel sites.

Further, it is necessary to ensure safety of the tunnels by establishing safety equipments which are necessary for the tunnel in earthquakes and by executing preserving operation and preserving inspection of the tunnel.

An example of the above-mentioned system of earthquake resistant design is shown in a form of a flow chart in Fig. 1. In this figure, the term "planning conditions" means traffic utilization conditions and the conditions of traffic lane composition and of the approximate route. The term "design conditions" means the conditions of earthquakes, the ground and the tunnel which are related to the structural design, but does not include numerical values such as dimensions which are necessary for design calculations. The term "design data" means numerical values such as dimensions which are necessary for the design and are to be determined by the design conditions.

2. Basic Principles for Earthquake Resistant Design

This section indicates a basic principle for the earthquake resistant design of submerged tunnels. As mentioned in "1. General," the submerged tunnel is a structure subjected to various kinds of special conditions, and its design requires particular consideration for earthquake resistance as follows:

- (1) In selecting routes and determining lengths of the tunnel and positions of its ventilation towers at design stage, it is recommendable to carry out thorough examinations of the topography and geology of the sites as well as the overall structural system and to avoid extremely soft ground, an area that is liable to cause ground failure such as landslides, and portions where discontinuities in topography and geology exist. It is also recommended to avoid discontinuities in the structure itself.
- (2) In making earthquake resistant design of the submerged structure, consideration shall be given to either the displacement of ground or the design seismic coefficient in earthquakes; and in case of the ventilation tower and other appurtenant structures, consider-

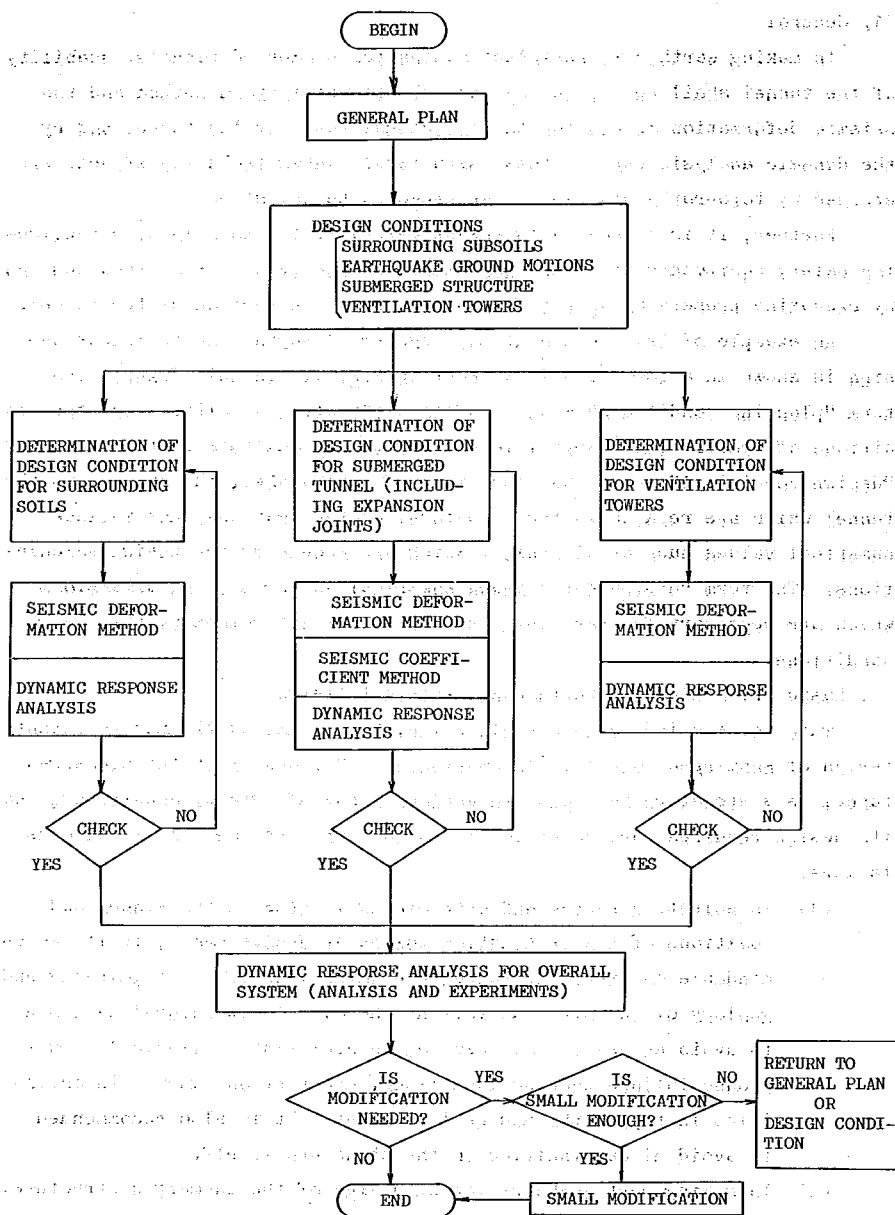


Fig. 1 Flow Chart for Seismic Design

ation shall be given to the design seismic coefficient. In addition to the designs of the above-mentioned parts of the tunnel, it is also necessary to make design and examination of the total structural system based on its dynamic analysis.

(3) In designing the portions which have considerable structural discontinuities such as joints between elements and joints between the tunnel and the ventilation towers (or approaches), examination shall be given in respect of influences and effects on earthquake resistance, particularly for their waterproofing abilities before and after earthquakes caused by the joints.

(4) To ensure seismic safety of the submerged tunnel, provisions shall be made for preservation and countermeasures in earthquakes -- in addition to structural design -- and consideration shall be given both to machinery and electrical equipments necessary for the preservation and countermeasures and to control systems for properly operating such machinery and equipments.

3. Loads and Conditions in Earthquake Resistant Design

3.1 General

(1) In making an earthquake resistant design, the following loadings in addition to the effects of earthquakes shall be taken into consideration. The kinds of loads to be employed shall be selected properly.

- a) Dead loads
- b) Earth pressures
- c) Hydrostatic pressures
- d) Buoyance or uplifts
- e) Live loads
- f) Effects of consolidations and settlements of subsoils
- g) Effects of temperature change
- h) Effect of shrinkage of concrete due to humidity
- i) Other loads (tsunami, wave force, sunken ship and forsaken anchor)

(2) For the effects of earthquakes, consider the following:

- a) Displacements of subsoils or structures in earthquakes
- b) Inertia forces arising from the dead weight of structure
- c) Earth pressures in earthquakes
- d) Hydrodynamic pressures in earthquakes

(3) Combination of loads

For combining loadings in earthquakes, consider the loads in Items a) to g) of (1) in general and consider also Items h) and i) depending upon the condition.

3.2 Ground Displacement during Earthquakes

(1) The displacement of the ground surface where the submerged structure is buried shall be determined in accordance with the provisions in "4.2.1 Ground Displacement in Earthquake Resistant Design." The ground displacement to be employed in the design of the submerged structure shall be the ground displacement at the level of the longitudinal axis of the submerged structure.

(2) Planes where the displacement of ground occurs shall be horizontal and vertical planes which include the longitudinal axis of the submerged structure.

There is no need of treating the submerged structure as being excited by the ground and causing resonance with it in earthquakes. The tunnel moves according to the motion of the ground. Therefore, if it is possible to determine the deformed state of the natural ground in earthquakes, the tunnel can be treated as a rod which is connected to the ground by means of springs. The term "longitudinal axis" of the submerged structure means the central line in the height and the width of the element.

When the submerged tunnel is buried shallow near the ground surface, the bottom plane of the tunnel is positioned at a depth of several to ten meters from the ground surface. Therefore, the displacement of the ground at each position of the tunnel differs from that on the ground surface. In this section, it is stipulated that displacement at the position of the longitudinal axis may be employed (refer to Fig. 2).

In general, it is desirable that planes where displacement of the ground occurs shall be all the planes that include the point under consideration, but in the design of the submerged tunnel, they are stipulated to be horizontal and vertical planes.

3.3 Inertia Forces

(1) Inertia forces due to earthquakes can be obtained by

multiplying the dead weight of

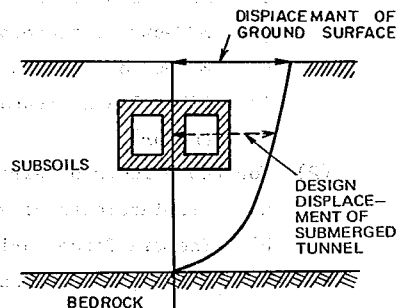


Fig. 2 Design Ground Displacement

Structure and soil mass by the design seismic coefficient which is stipulated in "4.2.3 Design Seismic Coefficient in Seismic Coefficient Method."

- (2) The position on which inertia forces act shall be the position of the center of gravity of the dead weight, and the direction of the inertia forces shall, in principle, be two horizontal directions and one vertical direction.

Designs which are made by using inertia forces include the stability calculation of the sliding of ground, design of ventilation tower, design of approach and design of appurtenant installation. Beside the above, it is allowed in these Specifications that the cross section of the submerged structure can be designed by using inertia forces.

Since appurtenant facilities installed inside the tunnel and the ventilation tower are liable to have large inertia forces, it is necessary to increase the design seismic coefficient which is stipulated in "4.2.3 Design Seismic Coefficient in Seismic Coefficient Method". In such a case, the extra factor shall be determined according to each situation with an upper limit of two times, and more or less two times shall be adopted. In case of the tunnel which is used for vehicle traffic, no inertia forces arising from the weight of live loads requires to be considered. The "two horizontal directions" mean, in ordinary cases, the axial direction and the direction perpendicular to the axis.

3.4 Earth Pressures in Earthquakes

- (1) Horizontal earth pressures in earthquakes shall be determined by Mononobe and Okabe's earth pressure formula.

- (2) Overburden pressures on the upper plane of the submerged tunnel shall be determined by multiplying the weight of overburden soils by $(1 \pm k_v)$, where k_v is the vertical design seismic coefficient.

3.5 Hydrodynamic Pressures in Earthquakes

- (1) Hydrodynamic pressures in earthquakes which are applied to walls shall be determined in accordance with provisions in Revised Design Standard of Dam (Japan National Committee on Large Dams, 1971).

- (2) Hydrodynamic pressures in earthquakes which are applied to columns shall be determined in accordance with provisions in Specifications for Earthquake Resistant Design of Honshu-Shikoku Bridges (Japan Society of Civil Engineers, 1967).

The hydrodynamic pressures during earthquakes shall be taken into

consideration in the design when the ventilation towers are constructed in the water.

3.6 Soil Layers Where Shear Strength is Neglected in Earthquake Resistant Design

In earthquake resistant analyses of ventilation towers and other structures, the shear strength of soil layers stipulated in Items (1) and (2) below shall be neglected.

(1) Sandy soil Layer

The sandy soil layer which has been judged to be liable to cause liquefaction.

(2) Soft Cohesive Soil Layer and Silty Soil Layer

The soft cohesive soil layer which has been judged to be liable to cause sudden changed in properties in earthquakes.

In general, submerged tunnel is often constructed in the soft soil layer. Therefore, if the soil layer which is stipulated in this section lies at the proposed tunnel site, it is necessary to take such proper countermeasures as replacement or improvement of soils. In case of a ventilation tower, however, loads are transmitted to the baserock directly or indirectly. Even if there is a soil layer which is liable to become unstable in earthquakes at a part of the surrounding ground of the ventilation tower, such a soil layer will little affect the stability of the structure. It has been stipulated, therefore, that earthquake resistant analysis can be carried out by disregarding the shearing strength of the soil layers stipulated in this section.

One of the methods of determining the stability of cohesive or silty soil layer is to conduct a vibration test, a vibrating tri-axial compression test and a vibrating simple shear test on undisturbed soil samples and to check whether or not the samples develop unstabilizing phenomena such as sudden deformation.

In the Specifications for Earthquake Resistant Design of Highway Bridges (Japan Road Association, January, 1971), it is stipulated that if a soil layer has a uni axial compressive strength of less than 2.0 t/m^2 , the shearing strength of such a soil layer shall be disregarded.

4. Design Earthquake Ground Motions

4.1 General

- (1) In the earthquake resistant design of a submerged tunnel, the displacement of ground in earthquakes or the design seismic coefficient shall be taken into consideration.

(2) For the submerged structure, the seismic deformation method and the seismic coefficient method may be used for the design.

(3) For the ventilation tower and other appurtenant structures, the seismic coefficient method may be used for the design.

The earthquake resistant design of ordinary structures has been made by the seismic coefficient method and the earthquake resistance of such structures has a historical background. Therefore, it is stipulated that for those structures which can be seen in ordinary structures, out of the structural system of the submerged tunnel, earthquake resistant designs shall be made by the seismic coefficient method. However, the behavior of the submerged structure in earthquakes is affected mainly by the deformation and vibration of its surrounding ground in a plane in earthquakes. For this reason, it is stipulated in the Specifications that either the displacement of ground or the seismic coefficient shall be taken into consideration.

The earthquake resistant design for the submerged structure in its longitudinal direction shall be made by using the displacement of ground. However, for the earthquake resistant design of the cross section of the submerged structure, no design method based on displacement has yet been established and, therefore, it is stipulated that the seismic coefficient method shall be used.

In earthquake resistant designs for the ventilation tower and other appurtenant facilities, the seismic coefficient method shall be applied as in previous cases. The seismic coefficient method includes the modified seismic coefficient method considering structural response (applicable to high ventilation towers).

4.2 Design Earthquake Ground Motion

4.2.1 Ground Displacement in Earthquake Resistant Design

Ground displacement to be considered in the earthquake resistant design shall be based on the observed value and determined by taking into consideration the nature of the earthquake ground motion and ground conditions.

In order to obtain ground displacement in earthquakes, any one of the following methods may be employed:

Method by Observation

This is the method to determine the ground displacement on the basis of the results of observation.

Method Using Response Spectral Curve

a) The horizontal ground displacement amplitude on the ground surface can be obtained by the following formula:

$$U_h = \frac{2}{\pi^2} S_v \cdot T \cdot A_{oh} \cdot \nu_1$$

Where U_h : Horizontal ground displacement amplitude on the ground surface (cm)

S_v : Response velocity value per gal of the maximum acceleration at the bedrock (cm/sec/gal). This value can be obtained from Fig. 3 when the natural period T and damping coefficient h of the ground are specified.

T : Fundamental natural period of the subsurface ground (sec)

A_{oh} : Horizontal acceleration on the bedrock surface stipulated in "4.2.2 Bedrock Accelerations on Earthquake Resistant Design." (gal)

ν_1 : Important Factor (Refer to Table 1 below)

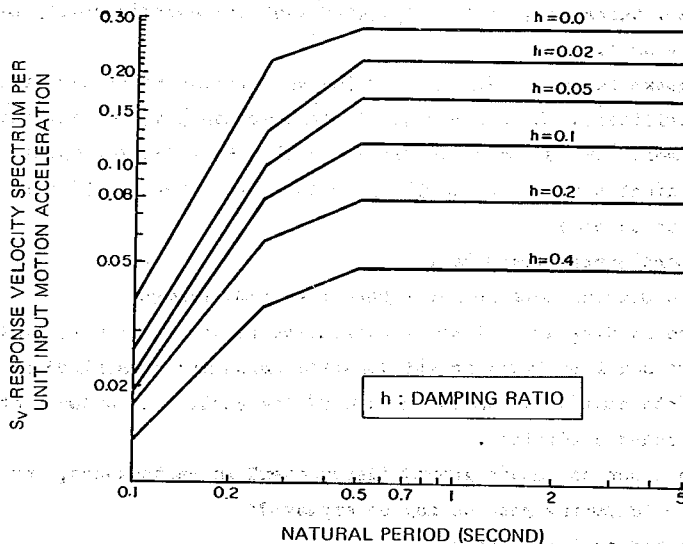
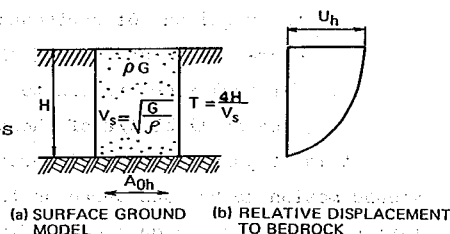


Fig. 3 Response Velocity Per Unit Acceleration (After Public Works Research Institute, Ministry of Construction)

Eq. (1) is a formula for calculating the deformation of ground by means of spectral curves, when bedrock is assumed to underlay homogeneous ground (having a thickness of H) as shown in Fig. 4 and seismic ground motion having a maximum acceleration of A_{oh} is applied to the bedrock. Spectral curves shown in Fig. 3 were obtained on the basis of spectral curves published by the Public Works Research Institute, Ministry of Construction (1970), which are based on seismic records measured on bedrock.

Table 1. Important Factor

Kind	ν_1
Tunnel serving higher public interests	1.0
Others	0.8



In Fig. 3 maximum response velocity values obtained are divided by maximum accelerations of input earthquake ground motions, thereby converting the former into values per gal.

Natural period T may be obtained either by a) method of obtaining the predominant period from micro-tremor observations or b) method of obtaining shear modulus G (or the S-wave velocity V_s) of the ground by means of in-situ tests or indoor tests and then obtaining the natural period, using thickness H according to formula $T = \frac{4H}{V_s}$. In any case, it is recommended to determine the natural period taking into consideration the magnitude of strain that will occur in the ground in earthquakes.

b) Vertical ground displacement amplitude U_v on the ground surface shall be $1/2$ to $1/4$ of U_h .

(3) Method Employing Dynamic Analysis

In this method, the ground displacements are estimated according to dynamic analysis.

(4) Method Employing Equivalent Sinusoidal wave Spectra

In this method, deformations of the submerged structure are calculated on the assumption that sinusoidal wave motions propagate through the ground along the submerged structure. Amplitudes of the sinusoidal wave motions under consideration are given for various periods (they are called the "equivalent sinusoidal wave spectra"); and sweeping the period, the deformation of the submerged structure is repeatedly calculated until the

maximum deformation is obtained. The equivalent sinusoidal spectra may be obtained on the basis of strong motion earthquake records.

4.2.2 Bedrock Accelerations on Earthquake Resistant Design

- (1) Horizontal acceleration to be considered in respect of the design bedrock surface shall be determined by taking into consideration the magnitude of earthquakes at the proposed tunnel site and the degree of importance of the submerged tunnel.
- (2) Vertical acceleration to be considered on the design bedrock surface shall be $1/2$ of the horizontal acceleration.

It is stipulated that the horizontal acceleration of the earthquake ground motion to be considered on the design bedrock surface shall be determined by taking account of the importance of the submerged tunnel and existing data observed at underground.

The horizontal acceleration on the design bedrock surface can be obtained by the following formula:

$$A_{oh} = \nu_Z \cdot A_o$$

Where A_{oh} : Horizontal acceleration on the design bedrock surface.

ν_Z : Seismic Zone Factor (refer to Fig. 5)

A_o : Standard Bedrock Horizontal Acceleration at bedrock surface (which shall be namely equal to 100 ~ 150 gals).

The vertical acceleration is stipulated to be $1/2$ of the horizontal acceleration by taking into consideration the examples of observations and those of other structures.

4.2.3 Design Seismic Coefficient in Seismic Coefficient Method

- (1) The design horizontal seismic coefficient shall be determined by taking into consideration the magnitude of earthquakes at the proposed site of the submerged tunnel, the kind of ground and the importance of the submerged tunnel.
- (2) The design vertical seismic coefficient shall, as a standard, be $1/2$ of the design horizontal seismic coefficient.

Design seismic coefficients are stipulated to be determined, in principle, based on the investigations on earthquakes and earthquake ground motions and on geology and grounds, and by taking into consideration the topography at the site, ground conditions and the importance of the tunnel.

The design horizontal seismic coefficient in the seismic coefficient method can be obtained by the following method:

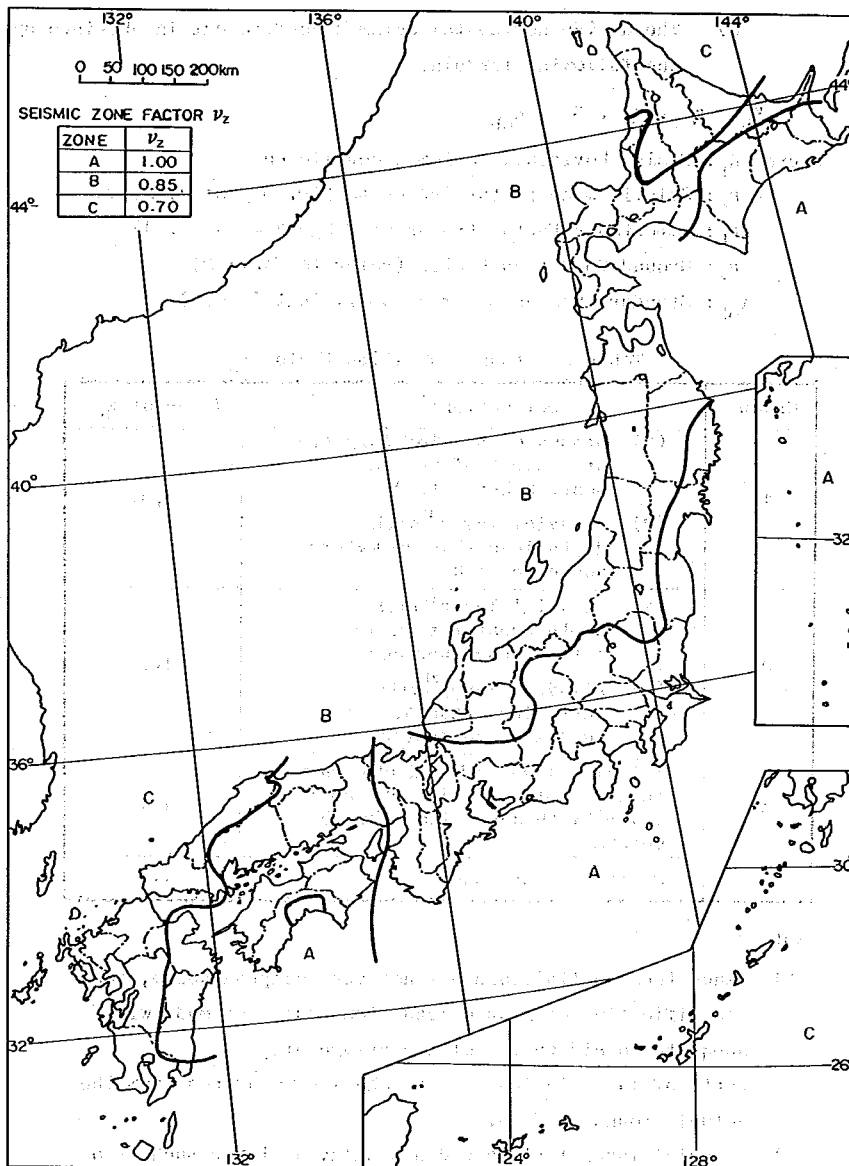


Fig. 5 Seismic Zoning Map

- a) The design horizontal seismic coefficient is obtained by the following formula:

$$K_h = \nu_z \cdot \nu_i \cdot \nu_s \cdot K_{oh}$$

Where K_h : Design horizontal seismic coefficient

ν_z : Seismic Zone Factor (refer to Fig. 3-5 of 4. 2. 2)

ν_i : Importance Factor (refer to Table 1 of 4. 2. 1)

ν_s : Ground Condition Factor (refer to Table 2)

K_{oh} : Standard design seismic coefficient (= 0.2)

Table 2 Ground Condition Factor ν_s

Group	Definitions ¹⁾	Value of ν_s
1	(1) Ground of the Tertiary era or older (defined as bedrock hereafter) (2) Diluvial layer ²⁾ with depth less than 10 meters above bedrock	0.9
2	(1) Diluvial layer ²⁾ with depth greater than 10 meters above bedrock (2) Alluvial layer ³⁾ with depth less than 10 meters above bedrock	1.0
3	Alluvial layer ³⁾ with depth less than 25 meters, which has soft layer ⁴⁾ with depth less than 5 meters	1.1
4	Other than the above	1.2

(Notes)

- 1) Since these definitions are not very comprehensive, the classification of ground conditions shall be made with adequate consideration of the bridge site.
Depth of layer indicated here shall be measured from the actual ground surface.
- 2) Diluvial layer implies a dense alluvial layer such as a dense sandy layer, gravel layer, or cobble layer.
- 3) Alluvial layer implies a new sedimentary layer made by a lands lide.
- 4) Soft layer is defined in Section "3.6 Soil Layer where Shear Strength is Neglected in Earthquake Resistant Design."

- b) The design seismic coefficient to be used for earthquake resistant analysis of the submerged structure and the approach shall be the value mentioned in Item a) above.
- c) The design seismic coefficient to be used for earthquake resistant analysis of the ventilation tower shall be obtained by multiplying the value of item a) mentioned above by correction coefficient in which response of the ventilation tower is considered. For correction coefficient β , use the value in Fig. 6. Provided that when the natural period of the ventilation tower is less than 0.5 sec, use $\beta = 1.0$.

(2) The design vertical seismic coefficient k_v is stipulated to be $1/2$ of horizontal seismic coefficient k_h , by referring to the existing strong motion earthquake records and other earthquake resistant design standards.

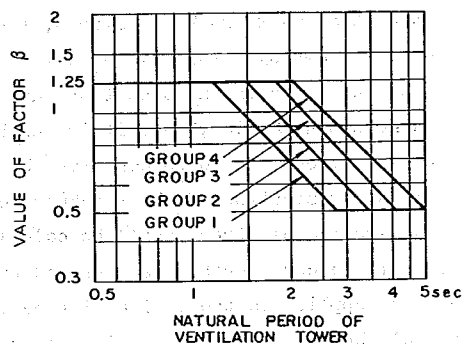


Fig. 6 Factor β

5. Earthquake Resistant Design of Submerged Structures

5.1 General

For the earthquake resistant design of the submerged structure, the seismic deformation method shall be used. For the design of cross section in the transverse direction and for the examination of the stability of sliding of the submerged tunnel, the seismic coefficient method shall be applied.

The submerged tunnel structure, being generally an long and narrow structure and buried under soft ground, is mainly affected by the displacement of the surrounding soil layer in earthquakes. Vibration characteristics of the ground near surface where the tunnel is constructed is affected by the topography, soils, and stratigraphy of the nearby ground. Therefore, it is necessary to design submerged tunnel by taking into consideration the

displacement or deformation of ground. However since sufficient knowledge has not yet been obtained concerning the above-mentioned vibration characteristics, it is stipulated that the displacement of ground in earthquakes shall be treated as a wave or vibration in design.

The procedure stipulated in "5.2 Seismic Deformation Method" is aimed at determining stresses and displacements of the submerged structure along the longitudinal axis assuming the submerged structure has been buried in a homogeneous soil layer.

In the earthquake resistant design of the submerged structure in its cross-sectional direction, it is necessary to examine the thickness of the cross-sectional wall so as to resist against loads in earthquakes and also to examine the stability of the submerged structure against sliding. It is stipulated that in these examinations, the conventional seismic coefficient method may be employed which is used for various civil engineering structures such as the caisson foundation, due to reasons mentioned in "4.2 Design Earthquake Ground Motion," and it is further stipulated that the results of the investigations are to be confirmed by dynamic analysis.

In the examination of the thickness of the cross-sectional wall, first the cross-sectional stress shall be calculated by taking into consideration the inertia forces, earth pressures and water pressures which are conceivable to be applied to the wall during earthquake, and then necessary measures shall be taken for reinforcing the cross section of the submerged structure or increasing the thickness of wall.

The stability against sliding shall be examined by taking into consideration both active and passive earth pressures that are applied to the submerged structure and also shearing resistance forces which act from the adjoining cross sections of the submerged structure.

When foundation structures such as pile foundations are to be used for the submerged structure, it is necessary to examine the submerged structure and the foundations simultaneously paying attention to connecting conditions between the two structures.

What are foreseen in earthquakes beside the above will be such phenomena as floating and dynamic settling. To cope with such phenomena, it will be proper first to take various measures such as the strict selection of soil fill material, improvement of soils and conscientious execution of these works and then to give necessary examination to the crosssectional design of the submerged structure (refer to "8 Stability of Subsoils (Soil fill)").

5.2 Seismic Deformation Method

For the earthquake resistant analysis of the submerged structure, the seismic deformation method (the analysis method based on the displacement of ground in earthquakes) shall be employed.

Deformation taking place in a structure like a submerged tunnel which has larger rigidity but smaller density than the ground is governed by the displacement of soil layers surrounding the tunnel. By taking these properties of the submerged tunnel into consideration, mathematical model of the submerged tunnel to be used in design shall be taken as a rod or a beam on elastic foundation in analysing deformation and stress of the model.

More precise analyses such as earthquake response analyses are recommended for the design of submerged structure taking account of discontinuities of topography, geology and structural joints. Maximum displacement of the ground to be employed in design shall be determined in accordance with provisions in "3.2 Ground Displacement during Earthquakes" and "4.2 Design Earthquake Ground Motion."

5.3 Seismic Coefficient Method

Analysis by the seismic coefficient method shall be made to inertia forces arising from weight of the structure itself and that of soil fill.

Directions and positions of inertia forces and combinations of inertia forces shall, in principle, be determined so that the stresses, strains and deformations of the structure become the maximum.

In the seismic coefficient method, analysis shall be made by taking into consideration inertia forces in earthquakes arising from weight of the structure itself and its contents, the weight of surrounding water and soil fill and weight of the ground.

In making this analysis, it is necessary to grasp phenomena (for instance, an increase in surcharge and sliding due to unbalanced loading) and to examine individual cases. At this time, the directions and positions of inertia forces to be applied and the combinations of inertia forces due to the horizontal seismic coefficient and those due to the vertical seismic coefficient shall, in principle, be determined so that structure will be placed in the worst state in respect of stress or strain.

6. Earthquake Resistant Design of Ventilation Towers

6.1 General

In making earthquake resistant designs for ventilation tower, consideration shall be given to their connections to the submerged structure so that the total structure will become earthquake resistant.

6.2 Earthquake Resistant Design of Ventilation Towers

For the earthquake resistant design of ventilation towers, the seismic coefficient method shall be employed, and the design seismic coefficients shall be determined in accordance with provisions in "4.2.3 Design Seismic Coefficient in Seismic Coefficient Method."

For methods of application and analysis of seismic forces in the earthquake resistant analysis of the ventilation tower, provisions in related specifications shall be applied depending upon the structural types of ventilation tower, and condition of the proposed sites of these structures.

7. Earthquake Resistant Design of Approaches

7.1 General

In making earthquake resistant design of approaches, consideration shall be given to the connection of approaches to the submerged structure and the ventilation towers so that the total structure will become earthquake resistant.

The structural types of approaches that are connected to the submerged structure have variety types such as the tunnel construction by excavation and back-fill process, caisson process and shield process and the open construction by the semi-underground U-shaped construction and retaining-wall construction.

In the earthquake resistant design of these approaches, it is necessary to consider not only the earthquake resistance of the approaches but also the behaviors of the submerged structure to which the approaches are connected and also other structures.

Even if the construction process is different between the approaches and the submerged structure, it is advisable that approaches that are connected to the submerged tunnel should be given the same degree of earthquake resistant analysis as that of the submerged structure, if the approaches have similar structural conditions such as cross-sectional dimensions and rigidity to those of the submerged structure.

7.2 Earthquake Resistant Design of Approaches

The earthquake resistant analysis of the approach may be carried out by other related standards and specifications depending upon the kinds of the respective structures.

8. Stability of Subsoils

8.1 General

The submerged tunnel is usually constructed in soft subsoils; and therefore, in making the earthquake resistant design of the submerged

tunnel, it is necessary to examine the stability of subsoils surrounding the submerged tunnel.

The term "subsoils surrounding the submerged tunnel" here means the following:

- (1) Original ground layer surrounding the submerged tunnel
- (2) Soil-fill surrounding the submerged tunnel

The soil-fill surrounding the submerged tunnel generally consist of soft soils. Therefore, such soils are sometimes liable to develop liquifaction and sliding in earthquakes. In this provision, it is stipulated to examine the stability in earthquakes of subsoils which are within the bound that will affect the submerged structure in earthquakes.

This provision stipulates that the above-mentioned examination shall be carried out in accordance will provisions in "8.2 Stability Analysis of Subsoils" and "8.3 Stability of Soil Fills for Submerged Structures," but if the surrounding soil is considered liable to develop anomaly, it is necessary to examine the effects of this anomaly to be exercised upon the submerged tunnel.

The system of examining the stability of subsoils are shown by a flow chart in Fig. 7.

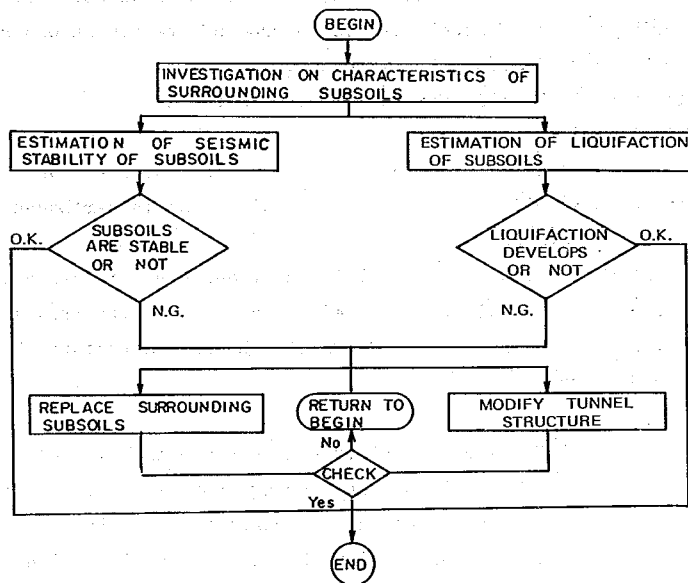


Fig. 7 Flow Chart for Determination of Stability of Soils

8.2 Stability Analysis of Subsoils

The stability analysis of subsoils is carried out by the seismic coefficient method assuming a sliding plane. Further, it shall be confirmed that no harmful effects will occur on the submerged structure by the horizontal ground displacement determined by means of dynamic analysis.

For the stability of subsoils in earthquakes, examples of past earthquake damage constitute good reference materials. For the stability analysis of slopes, the sliding plane method is customarily employed; but regarding the stability of the horizontal ground, no definite method of examination has yet been established. For this reason, the stability analysis of the horizontal ground is carried out by the seismic coefficient method and dynamic analysis, by referring to the examples of past earthquake damage, thereby making it possible to judge the stability of subsoils.

In the seismic coefficient method, the sliding plane is assumed to be a plane in parallel with the bottom plane of the submerged tunnel and seismic force is applied to the subsoil within depth of 10 m from the ground surface by referring to the examples of past earthquake damage and taking actual conditions into consideration. In this examination of the stability, the safety factor of approximately 1.1 shall be allowed.

The surface layer may be replaced by the mathematical model of rigid-plastic shearing vibration model with one degree of freedom in order to estimate the horizontal ground displacement.

8.3 Stability of Soil Fills for Submerged Structures

(1) Liquifaction

The soil to be used for filling at the submerged tunnel should not be the soil that will cause liquifaction in earthquakes.

(2) Stability against Sliding

Stability against sliding in the transverse direction of submerged tunnel shall be examined in accordance with provisions in "5. Earthquake Resistant Design of Submerged Structures."

9. Allowable Stresses

9.1 General

The allowable stresses of materials and increase in allowable stresses in earthquakes shall be determined, considering provisions of related specifications depending upon the kinds and the degree of importance of the structure, and taking into consideration the assumptions in design calculations and the methods of construction and control.

9.2 Allowable Stresses of Concrete

- (1) The allowable stresses of concrete to be used for the submerged tunnel shall conform to the following specifications:

"Standard Specifications of Concrete" by the Japan Society of Civil Engineers.

- (2) The allowable stresses of the concrete placed in the water shall be decided on the basis of the experiments simulating the field conditions as the quality of the concrete depends on the placing methods.

Allowable stresses shall be determined by taking into consideration not only the properties of materials but also the kind and the degree of importance of the structure, assumption in the design calculation and method of construction and control. In the portion of the reinforced concrete structure out of the submerged tunnel, design and construction shall be carried out according to principles specified in the above-mentioned specifications, and allowable stresses shall also conform to stipulations in the same specifications.

The quality of concrete to be placed in the water greatly depends on the construction condition, and the excellence or inferiority of the construction is generally difficult to judge. In the example shown in the "Specifications for Foundation Design of Highway Bridges (Japan Road Association)," it is stipulated that the allowable stresses of concrete placed in stational water shall have 50% (70% if engineer-in-charge approves) of the allowable stresses of concrete placed in air, and it is also stipulated that no estimate of its strength shall be made for the concrete placed in floating water. Data concerning the quality of concrete placed in the water are still very few and the clarification of the quality has to wait for future investigation. Therefore, when concrete is used for important structures as a submerged tunnel and is placed in the water requiring enough strength, allowable stresses shall be determined on the basis of ample tests and investigations.

9.3 Allowable Stresses of Steel

- (1) The allowable stresses (normal state) of steel to be used for the submerged tunnel shall conform to the following specifications:

- a) Reinforcing Bars

"Standard Specifications of Concrete" by the Japan Society of Civil Engineers.

b) Steel Other than Reinforcing Bars

"Standard Specifications for Highway Bridges (Part of Steel Bridge)" by the Japan Road Association.

- (2) When cracks are of the particularly harmful, allowable tensile stresses (under ordinary condition) of reinforcing bars shall be determined by taking into consideration effects exercised by cracks.

Due to reasons shown in "9.2 Allowable Stresses of Concrete," this provision is stipulated. For steels which act as a single unit with concrete, no reduction in allowable stresses against buckling is required.

The tensile strength of concrete is small and a concrete structure will develop cracks at the place where its tensile stress exceeds a certain limit. In case of reinforced concrete, the tensile strength of concrete is ignored in design analysis and, therefore, cracks on reinforced concrete poses no particular problem for resisting force. However, large cracks may ruin the watertightness of the reinforced concrete or result in rusting of bars. It is necessary, therefore, to impose some restrictions on cracks.

The magnitude of the width of a crack is complicatedly affected by the thickness of reinforcing bars and the depth of cover. As the tensile stress of bars increases, the width of the crack is generally known to become larger. In order to restrict the width of the crack, therefore, it will be effective to restrict the allowable tensile stress of the reinforcing bars. Regarding the allowable width of the crack and the relation formula between the crack width and the stress of the reinforcing bar, many theories have been proposed, and the allowable width of a crack varies considerably with conditions. Generally speaking, the crack width which is allowable from the viewpoint of watertightness is less than 0.1 mm, and that which is allowable from the viewpoint of rust prevention is considered to be about 0.2 mm for members that are always immersed in water and about 0.15 mm for members that are placed near the water surface and severely affected by water conditions.

The relationship between the stress of the reinforcing bar and the width of the crack, according to tests, is mostly within the ranges of 0.05 mm to 0.10 mm at a tensile stress of the reinforcing bar of 1,000 kg/cm², 0.15 to 0.20 mm at 2,000 kg/cm² and 0.2 to 0.3 mm at 3,000 kg/cm². Allowable stresses in the Standard Specifications of Concrete have been stipulated by taking into consideration limits for the crack width allowable from the durability of general members in the ordinary exposing state. It is also stipulated that if the crack is particularly harmful, the allowable

stress shall be reduced.

Submerged tunnels include those which are protected by steel shells at the outside so that concrete will not directly touch water and those which have no such construction. In case of the waterway tunnel, even water-tightness is not particularly required. It is necessary, therefore, to determine the allowable tensile stress of reinforcing bars by taking into consideration the abovementioned characteristics of the structure.

Further, steels which are buried in the concrete and act as a single body with concrete shall be taken for a sort of reinforcing bars and stipulations for reinforcing bars shall be applied to such steels. At present, an allowable stress of reinforcing bars of less than $1,800 \text{ kg/cm}^2$ is used, but this value needs further examination.

9.4 Increase in the Allowable Stresses in Earthquake Resistant Design

(1) When allowable stresses stipulated in "9.2 Allowable Stresses of Concrete" and "9.3 Allowable Stresses of Steel" are to be employed, these values which are applicable to ordinary state can be increased within ranges shown in the following table, depending upon the combinations of loads, in order to obtain allowable stresses in earthquakes:

Table 3 Limit of Increase in Allowable Stresses

Combination of Loads	Increase Percentage
Ordinary load + Earthquake Load	50%
Ordinary load + effects of temperature changes + Shrinkage + Earthquake Load	65%

In this case, for the allowable stresses of reinforcing bars which will be used as reference values, use value stipulated in "9.3 Allowable Stresses of Steel". When methods other than the principles of the Specifications which are stipulated in "9.2 Allowable Stresses of Concrete" and "9.3 Allowable Stresses of Steel" are used in the analysis of the allowable sectional forces of members, allowable stresses or safety factors at ordinary state and in earthquakes shall be separately determined based on test results.

Seismic loads to be taken into consideration for design occur very rarely within the period of the life of the submerged tunnel, and the period of action of these loadings is also short. The values of allowable stresses

have been increased by taking these facts into account. For increase percentages, those in the Standard Specifications of Concrete have been used.

The design of the reinforced concrete structure has been made on the basis of the elasticity theory. Recently it is proposed, in view of the deformation characteristics of concrete, to apply non-elastic design methods such as ultimate strength design methods for critical situations such as earthquakes. It is also proposed that since concrete is not completely without tensile strength, a certain degree of tensile strength may be allowed to the structure in earthquakes. However, since there are only few structures which have been designed based on the above-mentioned design methods, it is stipulated here that if such design methods are to be made, allowable stresses or safety factors can be determined by investigations and tests.

If the allowable stress of a reinforcing bar in ordinary loading conditions is assumed to be $1,400 \text{ kg/cm}^2$, then the allowable stress of the reinforcing bar in earthquakes is $2,100 \text{ kg/cm}^2$ and the strain at this time is 10^{-3} . That is, when displacement of the ground or the submerged tunnel in earthquakes is known beforehand and there is a portion in which strain exceeds the above-mentioned value, it is recommended to make mechanical joints in order to reduce the stresses.

10. Details of Earthquake Resistant Design

10.1 General

In making detailed design of the submerged tunnel, attention shall be paid to earthquake resistance. Especially at the portion of sudden changes in the topography, geology and the structure of the submerged tunnel, severe displacement or deformation is liable to occur in earthquakes, hence the detailed design of the surroundings shall be given thoroughgoing examination.

10.2 Structural Joints

The types and spacing of the structural joints shall be determined by considering the design for normal state and construction and also by examining the earthquake resistance.

In selecting the positions, types and spacing of structural joints in the submerged tunnel, the following points are normally considered; the manufacturing process of tunnel elements at the time of construction, towing and sinking, and uneven settlement and temperature changes of the tunnel after its completion.

For the earthquake resistance of the submerged tunnel, however, con-

struction and spacing of structural joints are important factors. In selecting the structural joints, sufficient examination from the point of view of earthquake resistance is required.

The type of structural joints are broadly classified into the rigid joints in which joints are given rigidity and strength equal to those of the cross section of the tunnel element so that joints can sufficiently withstand deformation and strain in earthquakes and the flexible joints in which joints are given flexibility to absorb deformation in earthquakes. Naturally, joints with intermediate characteristics between the two types mentioned above are conceivable. Hereunder the respective characteristics and points of caution of these types are explained.

Flexible joints - When flexible joints are to be used, displacements and deformations of joint and effects exercised by them upon the entire length of the tunnel vary depending upon the positions of joints and their degree of flexibility. It is desirable that the effects of flexible joints in earthquakes be evaluated by the earthquake response analysis or by experimental model tests.

In designing the joints, the effects of temperature changes and uneven settlement that the submerged structure may develop should be taken into consideration so that joints may maintain the capacity to absorb deformation which will occur in earthquakes.

Since flexible joints have structural characteristics which are different from those of general cross sections, careful examinations are required to prevent joints from becoming weak points of structure.

Rigid Joints - When rigid joints are to be used, it is desirable not to make joints weak in structure.

10.3 Pile Foundation

When a pile foundation is to be used for the submerged tunnel, examination shall be made on the effects of piles exercised upon the behavior of the submerged tunnel in earthquakes.

10.4 Ventilation Tower

In earthquake resistant designs of the ventilation towers, careful attention shall be given to the structures and positions of the ventilation tower. Connections of the ventilation tower to the submerged structure and approaches shall be so arranged that too much cross-sectional forces do not develop in the structure.

II. NUMERICAL EXAMPLE

1. Introduction

This section introduces an earthquake resistant design of proposed Tokyo Bay Crossing Highway Tunnel, as mentioned preceeding section, as a numerical example of "Specifications for Earthquake Resistant Design of Submerged Tunnels".⁴⁾⁵⁾

As shown in Fig. 8, proposed Tokyo Bay Crossing Highway is a highway with a total length of 15 km on central part of Tokyo Bay to connect between Kawasaki City and Kisarazu City.⁵⁾ It consists of a submerged tunnel, bridges and two artificial islands which provide approaches between the submerged tunnel and the bridges.

2. Stability of Surrounding Ground

Ground conditions of the area surrounding proposed tunnel site consist of alluvial layer mainly containing soft cohesive soil. Therefore, stability in earthquakes was examined for the surrounding ground deeper than the bottom plane of the submerged structure, considering the fact that the submerged structure is supported by the soft ground directly below the submerged structure. The ground at the Kawasaki side where soft cohesive soil has developed and distributed was considered in this examination.

The analysis was carried out by using the seismic coefficient method in accordance with provisions in "8.2 Stability Analysis of Subsoils". Since estimated safety factor in this analysis was without satisfaction prescribed, dynamic analysis in accordance with provisions in "8. Stability of Subsoils" was carried out.

Assuming that layer A does not develop sudden change in its shearing strength τ_f from the results of distribution of uni-axial compressive strength q_u corresponding to the depth the shearing strength was estimated as

$$\tau_f = C = 0.15z \text{ t/m}^2$$
 where internal friction angle $\phi = 0^\circ$ and z is depth from the sea-bottom.

2.1 Seismic Coefficient Method

Assuming that seismic forces develop through the sea bottom to a depth of a variable D_m and also assuming a horizontal sliding plane in the ground right beneath the bottom of the submerged tunnel, the safety factor was estimated from the equilibrium of forces in a unit soil mass.

Denoting the seismic force by P_E , shearing force of the bottom by Q_B , the unit weight of soil layer A by γ_t , shearing strength of ground by γ_t and the horizontal seismic coefficient by k_h , safety factor F_s can be ex-

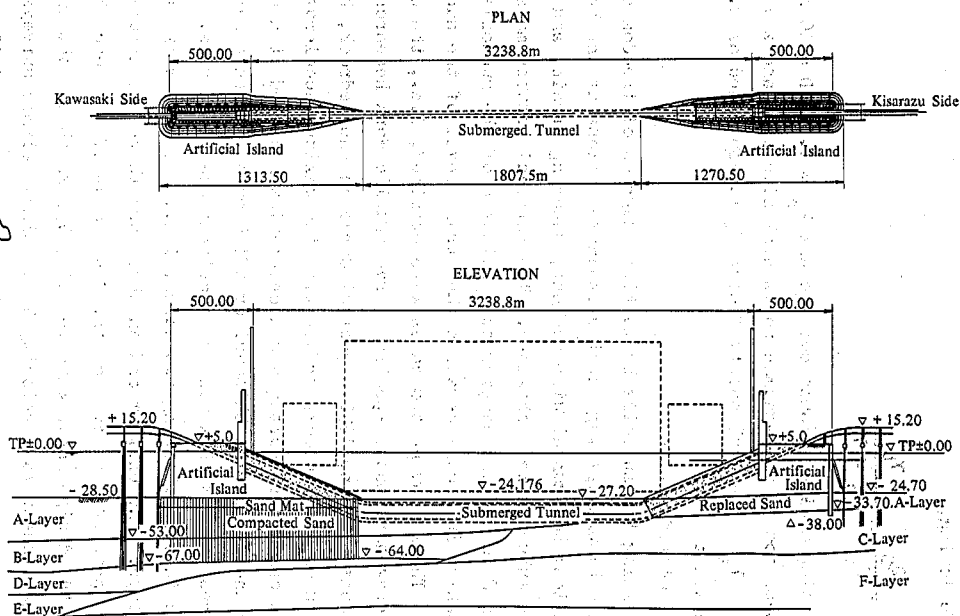
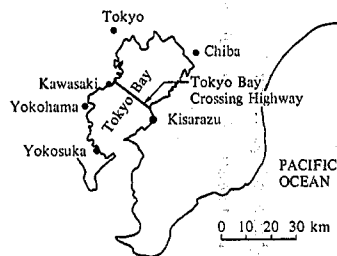


Fig. 8 Proposed Tokyo Bay Crossing Highway

pressed as following,

$$F_S = \frac{Q_B}{P_E} = \frac{\gamma_t}{k_h \cdot D \cdot \gamma_t}$$

Substituting design seismic coefficient $k_h = 0.18$, $D = 10$ m, the depth from the sea-bottom to the assumed horizontal sliding plane $z = 16$ m, unit weight of soil $\gamma_t = 1.4$ t/m³, safety factor F_S was obtained as 0.95 from the equation mentioned above.

2.2 Dynamic Consideration

By idealizing the subsoils by multiple degrees of freedom shear vibration model and by prescribing input earthquake motions at the bedrock surface, the maximum horizontal displacement, shearing strain, and shearing stress of the subsoils were obtained. The interval between mass points were taken as 2 to 3 m and damping coefficient h of the subsoils was taken as 0.2, by taking into consideration the strain level of the subsoils in earthquakes. The following two cases were examined, i.e., the case in which the averaged response spectral curve (Public Work Research Institute, Ministry of Construction, 1970, Spectral Curve on the bedrock, $h = 0.20$)¹²⁾ was prescribed on the bedrock surface with the maximum acceleration of 150 gals, and the case where earthquake acceleration recorded at a depth of 40 m below the ground surface at Shizunai by off Nemuro Peninsula Earthquake (1973) was prescribed with a maximum accelerations of 45 gals. Analysis was conducted in the following two cases, i.e., one case where the shearing rigidity of layer A is uniform and another case where the shearing rigidity of layer A is proportional with depth. The value of G in each layer was estimated by the design shear wave velocity V_{SD} which was obtained by halving the measured shear wave velocity V_s obtained seismic surveys, by taking account of the levels of shear strain in earthquakes, as follows:

$$G = \frac{\gamma_t}{g} \cdot V_{SD}^2$$

where G : acceleration of gravity

The calculated shear stress of the subsoils is shown in Fig. 9.

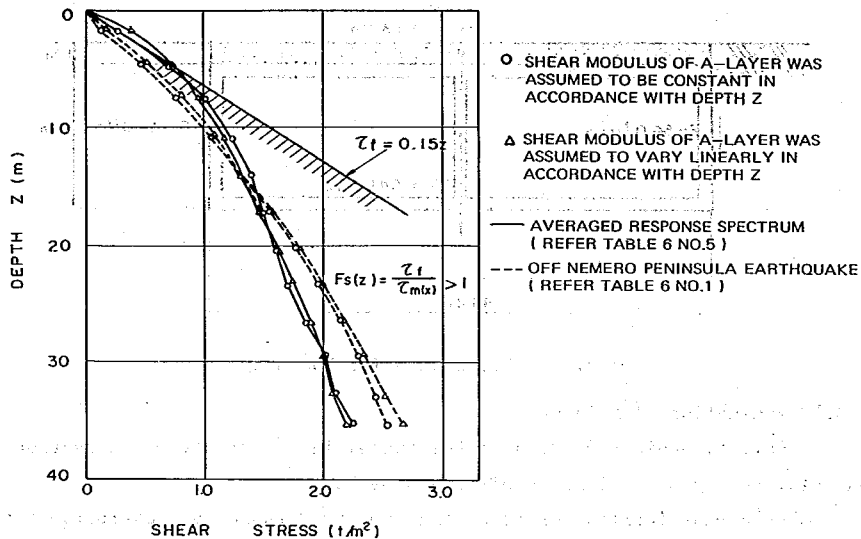


Fig. 9 Distribution of Shear stress induced in Surface Ground

3. Stability of Submerged Structure

3.1 Stability against Buoyancy

Stability against buoyancy of the structure in earthquakes was examined by the seismic coefficient method.

When vertical inertia forces due to vertical seismic coefficient $k_v = 0.11$ acts to the structure in the upward direction as shown in Fig. 10 the safety factor can be obtained as follows:

$$\frac{\text{Buoyant resisting force } W'}{\text{Buoyancy } B_y} = \frac{(W_T + W_S)(1 - k_v) + 2F}{(A_T + A_S)\gamma_w} > 1$$

in which W_T is dead weight of submerged tunnel, W_S is weight of overburdens, A_T is gross sectional area of submerged tunnel, A_S is sectional area of overburdens and F is frictional force acting on side wall.

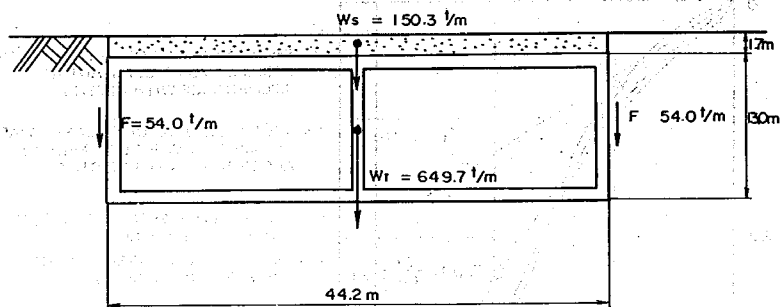


Fig. 10 Resistance for Buoyancy

3.2 Examination of Sliding

Stability against sliding of the tunnel in the transverse direction was examined by the seismic coefficient method.

Considering inertia forces of the submerged tunnel and overburdens and active earth pressure in earthquakes, the safety factor against sliding was evaluated on the assumption that acting forces were resisted by the shearing force of the bottom of the submerged tunnel and passive earth pressure in earthquakes.

The horizontal design seismic coefficient was taken as $k_H = 0.22$ for the tunnel and as $k_H = 0.18$ for the ground in accordance with the provisions in "4 Design Earthquake Ground Motions." The seismic force was applied to the subsoils between the ground surface and 10 m below the ground surface.

Distributions of acting loads and resisting forces thus obtained are shown in Fig. 11. In this figure, W_{Bh} is inertia force applied to the

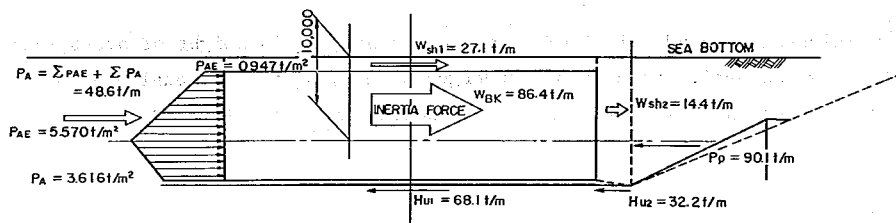


Fig. 11 Examination to Sliding of Submerge Tunnel in Transverse Direction
tunnel, W_{sh1} is inertia force applied to overburden on the tunnel, W_{sh2} is inertia force applied to soil-fill in the passive side, P_A is the total

active earth pressure applied to the tunnel, H_{u1} is the frictional resistance between the tunnel and subsoils, H_{u2} is the frictional resistance between soil-fill and subsoils besides right underneath the structure, and P_p is the total passive earth pressure retained by the total depth of soil-fill as shown in Fig. 11, respectively. The safety against sliding was obtained as

$$F_s = \frac{H_{u1} + H_{u2} + P_p}{W_{Bh} + W_{Bh1} + W_{Bh2}} > 1.0$$

4. Earthquake Resistant Analysis in the Longitudinal Direction

4.1 Design Conditions

The submerged tunnel considered was 3,340 m in length, 44.2 m in width and 13.0 m in height and had a rectangular cross section. Sectional constants used in the analysis of sectional forces in earthquakes are shown in Table 4.

Table 4 Sectional Constants Used in Analysis of Sectional Forces in Earthquakes

Elastic modulus of concrete		E	3.0×10^6 t/m ²
Moment of inertia	Horizontal direction	I_1	43,700 m ⁴
	Vertical direction	I_2	5,150 m ⁴
Sectional area		A	215 m ²
Bending rigidity	Horizontal direction	EI_1	13.11×10^{10} tm ²
	Vertical direction	EI_2	$1,545 \times 10^{10}$ tm ²
Longitudinal rigidity		EA	645×10^8 t
Weight per unit length in longitudinal direction		W	650 t/m

Elements of the submerged tunnel were assumed to be connected each other by rigid joints, and the submerged tunnel and the ventilation towers were assumed to be structurally independent each other.

The bedrock surface was set at a surface 30 to 40 m below the sea bottom based on the results of soil survey and seismic survey.

Young's modulus of the subsoils above the bedrock surface was evaluated by 1/2 of the observed or estimated value of shear wave velocity and unit weight of the subsoils. This is based on the fact that according to observations and experimental tests, rigidity of soils at a shear strain level

of about 10^{-3} is considered to be approximately $1/4$ of that at a shear strain level of about 10^{-6} . Since results of analysis indicated that averaged shear strain induced in the subsoil was approximately 10^{-3} in earthquakes, the shear wave velocity assumed in the analysis was taken as $1/2$ of the shear wave velocity at a shear strain level of about 10^{-6} .

Young's modulus for the subsoils above the bedrock surface evaluated apparently in this way are shown in Table 5.

Table 5 Soil Properties

Grounds	Unit Weight (t/m^3)	Shear wave velocity* to be considered in design (m/sec)	Young's Modulus (t/m^2)
Layer A	1.4	75	2,400
Layer B	1.7	100	5,200
Layer C	1.8	130	9,300
Artificial Asland	2.0	120	9,000
Sand mat	2.0	120	9,000
Compacted Sand	1.7	100	5,200
Replaced Sand	2.0	120	9,000

*) $1/2$ of the observed or estimated value obtained by seismic survey.

4.2 Sectional Forces Calculated by the Seismic Deformation Method

Sectional forces of the tunnel in earthquakes were calculated by using the seismic deformation method. In this calculation, the ground displacements in the longitudinal axis of the tunnel in earthquakes were determined on the assumption that seismic waves propagated in sinusoidal form with a shear wave velocity. Horizontal acceleration considered on the design bedrock surface was taken as 150 gals in accordance with provisions in "4 Design Earthquake Ground Motions."

Sectional forces were calculated for two cases, i.e., when the wave lengths of seismic motions were selected so as to make the sectional forces maximum and when the wave length of seismic motions were assumed to be 4 times of the depth of subsoils above the bedrock surface; and in the latter case, superposing of stresses due to axial force and bending moments were examined. The distribution of the maximum sectional forces calculated

by the seismic deformation method are shown in Fig. 12. In this figure, the results of earthquake response analysis to be mentioned in the next paragraph are also indicated.

4.3 Earthquake Response Analysis

In the earthquake response analysis, sectional forces induced in the tunnel were analysed by assuming that subsoil was modeled by spring-mass system, the submerged tunnel was a rod or a beam system supported elastically by the subsoils and by applying to the bedrock 4 earthquake ground motions shown in Table 6 and the averaged response spectral curve (Public Work Research Institute, Ministry of Construction, 1970, bedrock). The maximum accelerations of the 4 earthquake ground motions were prescribed to be the same maximum accelerations when they were recorded. The maximum acceleration of the averaged response spectral curve was prescribed to be 150 gals.

The same natural period of subsoils, damping coefficient, vibration mode, spring of the subsoils that supported the tunnel as those used in the above mentioned Item 2.2 were used in this calculation.

In the response analysis in the vertical direction, the vertical response amplitude of the ground was assumed to be $1/2$ of the horizontal response amplitude of the ground in the perpendicular direction to the tunnel axis.

The distribution of the maximum sectional forces obtained by the earthquake response analysis are shown in Fig. 13.

5. Earthquake Resistant Analysis of Cross Section

The earthquake resistant analysis of the cross section of the submerged tunnel was conducted by using the seismic coefficient method and by assuming the element per unit length as a frame structure which was supported elastically by the surrounding subsoils. The cross section consequently designed in analysis is shown in Fig. 14.

Inertia forces of the tunnel and overburdens in the horizontal and vertical directions, hydraulic pressure at high tide, active earth pressure in earthquakes, and weight of the cross section of the tunnel were considered to be acting forces for this purpose.

Design seismic coefficients were determined in accordance with the provisions of "4 Design Earthquake Ground Motions," such as horizontal seismic coefficient $k_h = 0.22$ and vertical seismic coefficient $k_v = 0.11$. As for directions of the vertical seismic coefficients, both the cases of upward and downward directions were examined.

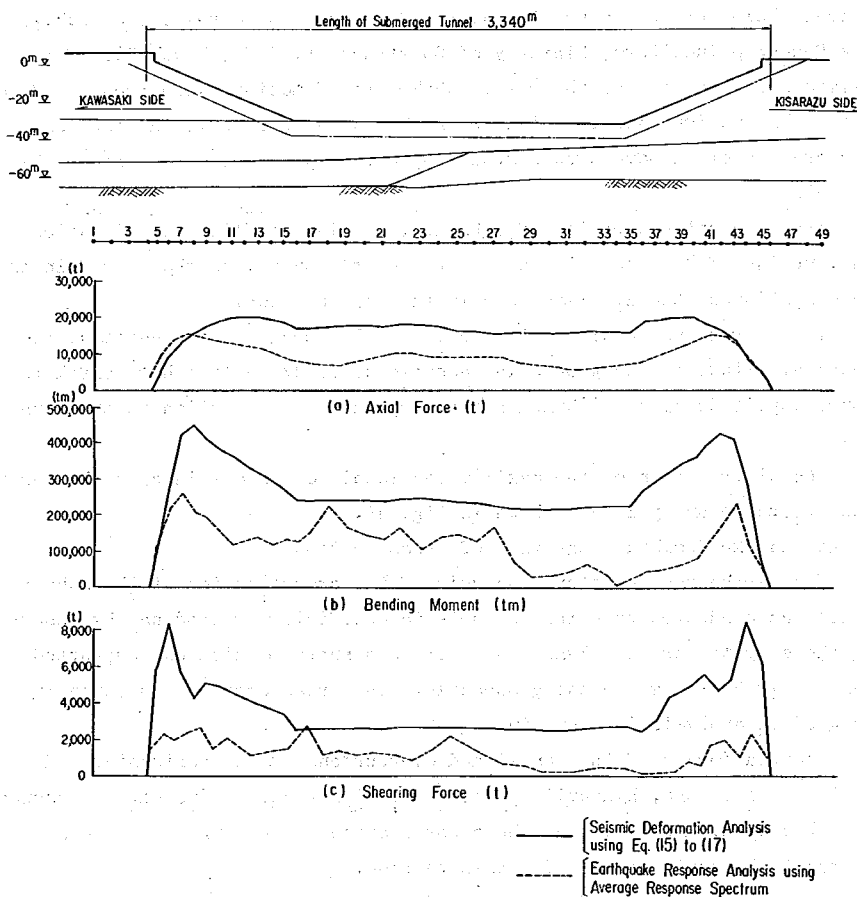


Fig. 12. Distribution of Sectional Forces by Seismic Deformation Analysis and Earthquake Response Analysis

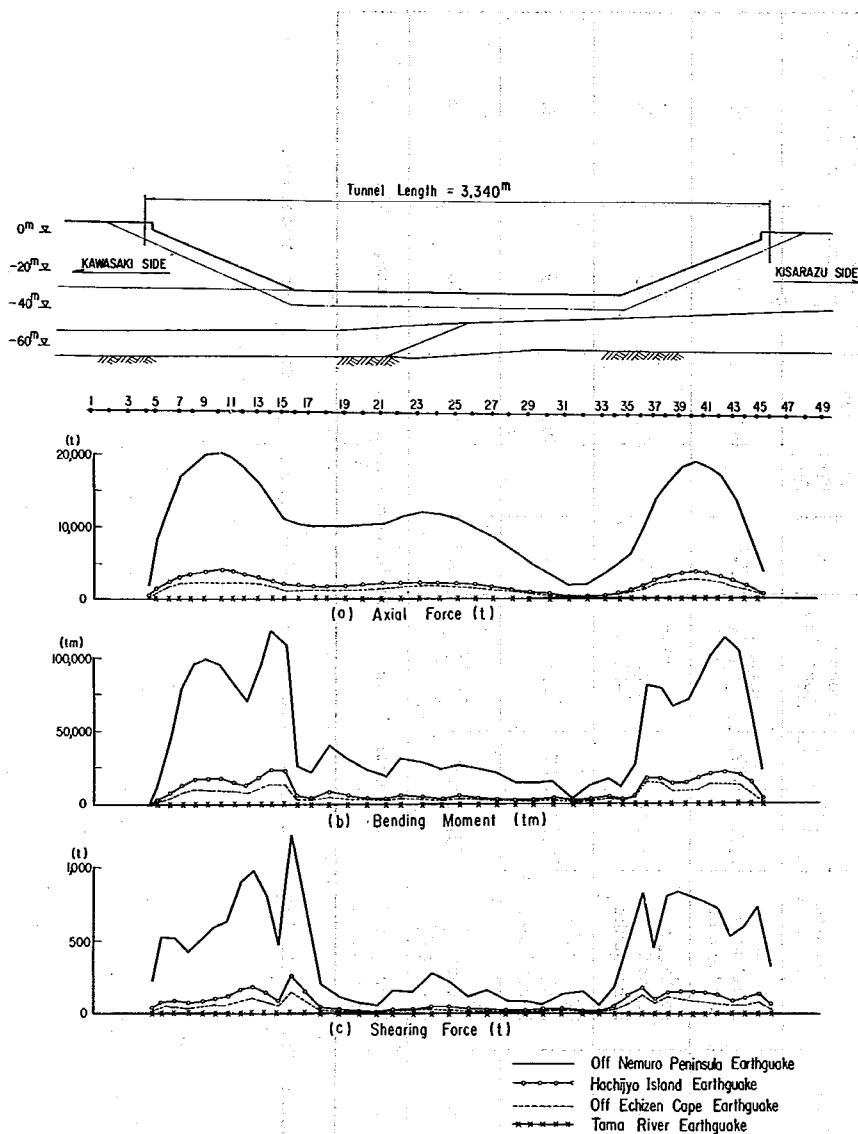


Fig. 13 Distribution of Sectional Forces by Earthquake Response Analysis Using Four Different Earthquake Waves

Table 6 Earthquake Ground Motions

Number	Earthquake	Date	Recorded Location	M	Epicentral Distance (km)	Period of Duration	Max. Acceleration (gals)
1	Off Nemuro Peninsula Earthquake	1973.6.17	Shizunai (-40 m)	7.4	305	12	45
2	Hachijyo Island Earthquake	1972.12.4	Kannonzaki (-80 m)	7.2	275	15	10
3	Off Echizen Earthquake	1963.3.27	Iwaya	6.9	153	9	22
4	Tama River Earthquake	1970.9.30	Kawasaki (-127 m)	4.5	8	10	6
5	Averaged Response Spectral Curve (Public Works Research Institute, 1970, Bedrock, h = 20%)						

Note: Numericals in parenthesis indicate depth where earthquake motion was recorded.

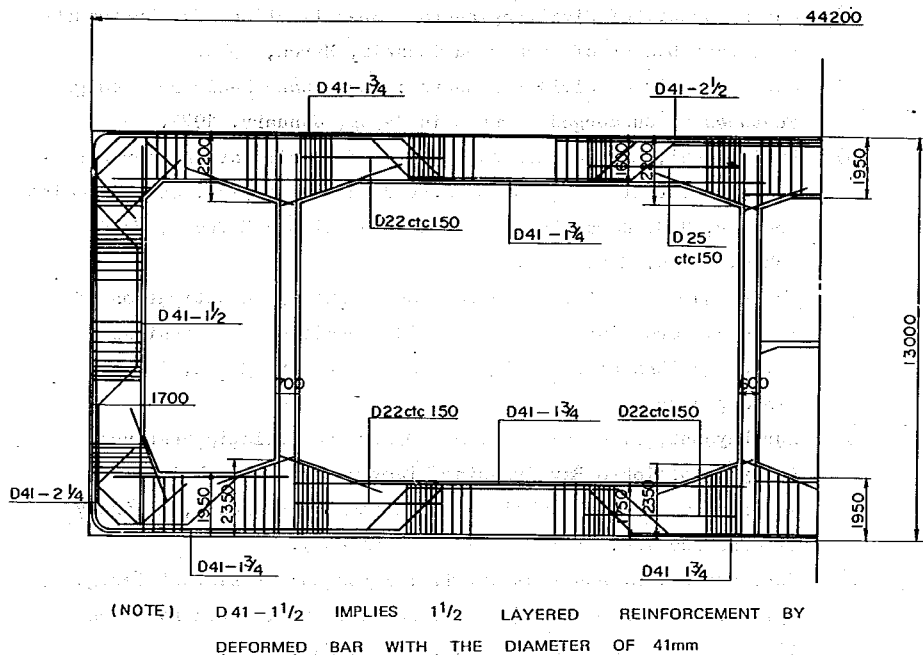


Fig. 14 Reinforcement of Tunnel Section

The elastic spring constants which were connecting the submerged tunnel and the surrounding subsoils were evaluated by the coefficients of subgrade reaction, and following two cases were examined.

- i). $K_H = K_V = 0.1 \text{ kg/cm}^3$ $K_S = 0.05 \text{ kg/cm}^3$
- ii) When K_H , K_V and K_S were assumed to be very small

Where K_H : Coefficient of horizontal subgrade reaction at the side walls of the submerged tunnel (kg/cm^3)

K_V : Coefficient of vertical subgrade reaction at the bottom of submerged tunnel (kg/cm^3)

K_S : Coefficient of shearing subgrade reaction at the bottom of submerged tunnel (kg/cm^3)

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Appendix.

DYNAMIC BEHAVIOIR OF A SUBSURFACE TUBULAR STRUCTURE

INTRODUCTION

Initiation of construction of submerged tunnels is recorded in Boston, U.S.A. in 1893. Since then more than eighty of the submerged tunnels have been constructed in several countries. In early stage of the construction, developments and improvements of the technology and engineering to them were energetically examined and researched by the field engineers who worked in the East Coast of the U.S.A. and the Netherlands.

The construction of the Posy Tunnel completed in 1928 in Oakland, California, U.S.A. is considered as a first trial of tunnels embedded into soft subgrounds at the site in a strong earthquake region.

Submerged tunnels which are relatively long and light structures to the diameter and the unit weight of the subsoil respectively are constructed in soft subsurface layers. In a seismic design, force methods so-called seismic coefficient methods are able to principally be employed, it however is very hard to usually apply them because large scale of the length of the submerged tunnel would produce tremendously large stresses into the structural system and subsoil.

Principles of the design against earthquake motions have been proposed through current researches and applications as follows,

- i) principle due to seismic coefficient methods,
- ii) principle due to earthquake response analyses, and
- iii) principle due to wave propagation analyses.

The principles of i) and iii) above have been oftenly applied to the construction, meanwhile the principle of ii) has not employed yet because of a lack of interpretation to the uniform tunnel embedded in subsoil.

In this paper a new seismic design criteion, seismic deformation analysis, is proposed based on the wave propagation analysis.

SEISMIC DEFORMATION ANALYSIS

According to multi-reflection assumption, subsurface ground motion during earthquakes are attributed primarily to upward propagation of shear waves from underlying base rocks. In such cases the ground motion induced

by a seismic excitation at the base rock are considered to be shear deformation of the subsurface ground.

The subsurface ground has varying dynamic properties in actual spaces, then assuming a simple case of a uniform soil profile as shown in Fig.A-1, amplitude can be estimated as follows,

$$U_h = \frac{4}{\pi} \cdot \frac{T}{2\pi} \cdot S_v \cdot A_{oh} \quad (A-1)$$

where U_h : amplitude of ground displacement (cm)
 T : natural period of subsurface ground (sec.)
 A_{oh} : amplitude of base rock maximum acceleration (gal)
 S_v : normalized velocity response values as shown in Fig.A-2

The values of S are given by average response spectra for rock bases evaluated from observed strong motion accelerations.

Assuming a sinusoidal deformation of the ground as follows,

$$U(x) = U_h \sin \left(\frac{2\pi}{L} x + \varphi \right) \quad (A-2)$$

where L : wave length (cm)
 φ : phase angle (rad.)
 x : variable of the space (cm)

the maximum principal distortion on the horizontal plane γ_{max} can be obtained as follows,

$$\gamma_{max} = \frac{2\pi}{L} U_h \quad (A-3)$$

Applying the distortion to the tunnel structure, sectional forces of the structure are apparently evaluated as follows,

$$P_{ap} = \frac{2\pi \sin \theta \cos \theta}{L} \cdot EA \cdot U_h \quad (A-4)$$

$$M_{ap} = \frac{4\pi^2 \cos^3 \theta}{L^2} \cdot EI \cdot U_h \quad (A-5)$$

$$Q_{ap} = \frac{8\pi^3 \cos^4 \theta}{L^3} \cdot EI \cdot U_h \quad (A-6)$$

where P_{ap} : apparent axial force (kg)
 M_{ap} : apparent bending moment (kg·cm)
 Q_{ap} : apparent shearing force (kg)

- E : Young's modulus of the tunnel structure (kg/cm^2)
 A : sectional area of the principal structure (cm^2)
 I : moment of inertia of the principal structure (cm^4)
 θ : angle between principal distortion axis and the structural axis (rad.)

The maximum axial force is derived from Eq. (A-4) in the angle θ of $\pi/4$ rad. and the maximum bending moment and shearing force from Eq. (A-5) and Eq. (A-6) in the angle θ of zero.

The tunnel has larger rigidities than the surrounding subsurface ground, accordingly the behavior of the tunnel structure is not same as that of surrounding subsurface ground.

Assuming the structure as an embedded rod or beam supported on elastic foundations, a reduction effect of deformations of the structure to the surrounding subsurface ground can be found. The reduction factors which give real sectional forces applying to Eqs. (A-4), (A-5) and (A-6) are expressed as follows,

$$\alpha_1 = \frac{1}{1 + \left(\frac{2\pi}{\lambda_1 \ell}\right)^2} \quad \text{for Eq. (A-4)} \quad (\text{A-7})$$

$$\alpha_2 = \frac{1}{1 + \left(\frac{2\pi}{\lambda_2 L}\right)^4} \quad \text{for Eqs. (A-5) and (A-6)} \quad (\text{A-8})$$

where $\ell = \sqrt{2} L$: apparent wave length in the case of $\theta = \pi/4$ rad. (cm),

$$\lambda_1 = \sqrt{K_1/EA} \quad (1/\text{cm})$$

$$\lambda_2 = \sqrt{K_2/EI} \quad (1/\text{cm})$$

K_1 : longitudinal stiffness property of elastic foundation per unit length of principal structure (kg/cm^2)

K_2 : transeverse stiffness property of elastic foundation per unit length of principal structure (kg/cm^2)

Accordingly the real forces are evaluated as follows,

$$P = \alpha_1 \frac{\pi EA}{L} U_h \quad (\text{A-9})$$

$$M = \alpha_2 \frac{4\pi^2 EI}{L^2} U_h \quad (\text{A-10})$$

$$Q = \alpha_2 \frac{8\pi^3 EI}{L^3} U_h \quad (\text{A-11})$$

where P : axial force

M : bending moment

Q : shearing force

From Eqs. (A-9), (A-10) and (A-11) maximum forces are obtained provided the wave lengths are estimated as follows,

$$L_P = \frac{1}{\sqrt{2}} \frac{2\pi}{\lambda_1} \quad (A-12)$$

$$L_M = \frac{2\pi}{\lambda_1} \quad (A-13)$$

$$L_Q = \frac{1}{\sqrt{3}} \frac{2\pi}{\lambda_2} \quad (A-14)$$

where L_P : wave length which makes the axial force of Eq. (A-9)

maximum (cm)

L_M : wave length which makes the bending moment of Eq. (A-10) maximum (cm)

L_Q : wave length which makes the shearing force of Eq. (A-11) maximum (cm)

Consequently the sectional forces of Eqs. (A-9), (A-10) and (A-11) become as follows,

$$P^* = \sqrt{\frac{2}{4}} \sqrt{K_1 \cdot EA} U_h \quad (A-15)$$

$$M^* = \frac{1}{2} \sqrt{K_2 \cdot EI} U_h \quad (A-16)$$

$$Q^* = \frac{\sqrt[4]{3^3}}{4} \sqrt[4]{K_2^3 \cdot EI} U_h \quad (A-17)$$

EARTHQUAKE RESPONSE ANALYSIS⁵⁾

Assuming the subsoil as lumped mass system and the submerged tunnel as elastically supported rod or beam on the ground, the displacement and sectional forces of structure are calculated by the seismic excitation at the base rock.

In the response analysis of ground, it is assumed that the natural frequency of the ground is not affected by the existence of a submerged tunnel. This analysis bases on the ununiformities of the geometry, geology, stratum of the ground, therefore no sectional forces are developed in the tunnel embedded in the uniform subsoils in principle.

NUMERICAL EXAMPLE

The submerged tunnel is assumed to be 3,340m long and rectangular section with 44.2m width and 13m height. These dimensions are determined with reference to the preliminary design of proposed Tokyo Bay Crossing Highway.

The elements of tunnel are treated to be connected rigidly and the tunnel is free from the ventilation tower.

The layer under 30 to 40m from the surface is estimated as the base rock. The rigidities of subsoils are evaluated from the unit weights and the design shear wave velocities which have been taken as one-half of the small amplitude seismic wave velocities.¹⁾⁷⁾ Damping ratio is determined to be 20% by considering the shear strain level during earthquake.⁷⁾

The subsoils consist of two or three layers with different shear wave velocities. For these cases the natural period of these subsoils have been estimated by assuming the subsoils as uniform soil layer with converted shear wave velocities,⁶⁾ that is,

$$T = \frac{4H}{V_{sc}} = \sum_i \frac{4H_i}{V_{si}} \quad (A-18)$$

where, H and V_{sc} are the overall thickness (cm) and converted shear wave velocity of subsoil (cm/sec) respectively. H_i and V_{si} are thickness and design shear wave velocity of the i th layer respectively. The natural periods of the subsoils are about 1.0 to 2.5 seconds.

The stiffness properties between tunnel and subsoil K_1 and K_2 are estimated by considering the tunnel to be rigid rectangular plate on the semi-finite elastic body as follows,

$$K_1 = K_2 = G_s \quad (A-19)$$

where, G_s is the average shear modulus of subsoil evaluated from unit weight and design shear wave velocity.

In the seismic deformation analysis, the base rock acceleration in Eq. (A-1) is taken to be 150 gals. U_h in Eqs. (A-9), (A-10) and (A-11) is taken to be the displacement at the center of gravity of tunnel and this is obtained by the shear deformation mode presented in Fig. A-1.

In this case, combination of axial forces of the structure due to a couple of waves which propagate orthogonally through the x-y plane in Fig. A-3 is treated by root-mean-square principle. The sectional forces near

the both ends of the tunnel are corrected to satisfy the boundary condition that the tunnel is free from the ventilation tower.

In the earthquake response analyses, four different earthquake waves and one average response spectrum as shown in Table A-1 are employed. These four earthquake waves are selected almost for following reasons,

- (1) The soil conditions at the recorded places are similar to those of base rock.
- (2) The earthquake waves to be recorded near the construction site of the tunnel.
- (3) The epicentral distances and magnitudes of earthquakes can be classified into following three categories,
 - (i) large earthquakes with long epicentral distances
Off Nemuro Peninsula Earthquake ($M=7.4$, $D \approx 305$ km)
Hachijyo Island Earthquake ($M=7.2$, $D \approx 275$ km)
 - (ii) medium earthquake with medium epicentral distance
Off Echizen Cape Earthquake ($M=6.9$, $D \approx 153$ km)
 - (iii) small earthquake with short epicentral distance
Tama River Earthquake ($M=4.5$, $D \approx 8$ km)

The maximum base rock accelerations have been taken as same as the recorded maximum accelerations, that is, normalization of maximum accelerations without taking account of the characteristics for the magnitude and epicentral distance is avoided. However the results with normalizing the maximum base rock accelerations to be 150 gals are also obtained to compare the response level of the sectional forces.

In the earthquake response analysis using the average response spectrum, the base rock acceleration is taken to be 150 gals.

The coefficients of response acceleration (per unit acceleration, damping ratio $\zeta=20\%$) for the four earthquake waves and average response spectrum are presented in Fig.A-4.

Numerical Results for the sectional forces developed in the submerged tunnel are shown in Fig.A-5, Fig.A-6 and Table A-2. Fig.A-5 shows the comparisons of distribution of sectional forces estimated by seismic deformation analysis using Eq.(A-15) to Eq. (A-17) and earthquake response analysis using average response spectrum. Fig.A-6 shows the comparisons of distributions of sectional forces estimated by earthquake response analysis using the four different earthquake waves. Table A-2 shows the estimated maximum values from Fig.A-5 and Fig.A-6.

From these numerical results, following inclinations are observed,

- (1) the sectional forces evaluated by the earthquake response analysis are smaller than those evaluated by the seismic deformation analysis,
- (2) in the earthquake response analyses, the sectional forces of tunnel embedded almost uniform subsurface ground become very small.

Next, in order to compare the response levels, the sectional forces with normalized the base rock maximum accelerations to be 150 gals are presented in Table A-3. In Table A-3, two cases of the axial forces evaluated by earthquake response analyses are larger than those estimated by seismic deformation analysis. However the normalization of base rock accelerations to be 150 gals without taking account of magnitudes and epicentral distances corresponds to tremendously large earthquakes which may be considered not to occur. The appropriate treatments for these cases have the necessities for more detailed researches.

NATURAL FREQUENCIES OF SUBSURFACE GROUNDS DUE TO MODEL TESTING

Model vibration tests of submerged tunnel and surrounding subsoils have been conducted.

The model subsoil consists of five layers with different shear moduli and the ratio of shear moduli between the stiffest layer and the softest layer is about 1:13.

The model base rock has been excited by sinusoidal waves with varying frequencies from 0 to 20 Hz (these frequencies correspond to 0 to 4 Hz in the actual ground). The displacement amplification factors for each frequency are obtained by dividing the response displacements at model ground surface by the ones at the base rock. One of the displacement amplification factors is presented in Fig.A-7. The most predominant frequency is about 5.9 Hz.

The natural frequency of this model subsoil estimated by Eq. (A-18) is about 6.8 Hz. Therefore the relative difference with the test's result is about 13% even in this case.

The first natural frequency evaluated from plane strain finite element analysis for cross section of model subsoil is about 5.5 Hz. The relative difference with the test's result is about 8%.

From these results, the accuracy in estimation of natural period mentioned previously is reliable.

CONCLUSIONS

A seismic deformation analysis is proposed and results of earthquake response analysis incorporate it through an application to the longitudinal analysis of a submerged tunnel. From these results it is concluded that,

(1) In the earthquake response analysis of lumped mass system, the sectional forces of the tunnel induced by the large earthquakes with long epicentral distances are larger than those by small earthquake with short epicentral distance, because of the comparatively long natural period of the subsurface ground.

(2) In the earthquake response analysis, no sectional force of the tunnel embedded in the uniform subsurface ground is principally developed, accordingly the same trend is given in the numerical results.

(3) In the seismic deformation analysis, the sectional forces of the tunnel embedded in the uniform subsurface ground can be obtained assuming the appropriate wave length.

(4) The model testing is a useful method for evaluating the dynamic behavior of subsurface ground with geological and geodetic properties.

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7.1.1

The purpose of this report is to provide a summary of the available data on soil moduli and damping factors for dynamic response analysis. The data are presented in the form of graphs and tables, and are intended to be used as a guide for the selection of appropriate values for use in dynamic response analysis. The data are based on a review of the literature and on the results of laboratory and field tests. The data are presented for a wide range of soil types and for a wide range of frequencies and amplitudes of vibration. The data are intended to be used as a guide for the selection of appropriate values for use in dynamic response analysis. The data are presented in the form of graphs and tables, and are intended to be used as a guide for the selection of appropriate values for use in dynamic response analysis.

7.1.2

The purpose of this report is to provide a summary of the available data on soil moduli and damping factors for dynamic response analysis. The data are presented in the form of graphs and tables, and are intended to be used as a guide for the selection of appropriate values for use in dynamic response analysis. The data are based on a review of the literature and on the results of laboratory and field tests. The data are presented for a wide range of soil types and for a wide range of frequencies and amplitudes of vibration. The data are intended to be used as a guide for the selection of appropriate values for use in dynamic response analysis. The data are presented in the form of graphs and tables, and are intended to be used as a guide for the selection of appropriate values for use in dynamic response analysis.

Table A-1 Four Earthquake Waves and a Average Response Spectrum

No.	Earthquakes	Recorded Time	¹⁾²⁾ Recorded Place	Magnitude	Epicentral Distance (Km)	Duration (sec)	Recorded Max. Acceleration (gal)	³⁾ Class
1	Off Nemuro Peninsula Earthquake	1973. 6.17	Shizunai(-40m)	7.4	305	12	45	A
2	Hachijyo Island Earthquake	1972.12. 4	Kannonzaki(-80m)	7.2	275	15	10	A
3	Off Echizen Cape Earthquake	1963. 3.27	Iwaya	6.9	153	9	22	B
4	Tama River Earthquake	1970. 9.30	Kawashaki(-127m)	4.5	8	10	6	C
5	Average Response Spectrum							

- Remarks
1. Kannonzaki and Kawasaki are the places near construction site of Submerged Tunnel.
 2. Recorded depth from the ground surface is presented in the parenthesis.
 3. Four earthquake waves are selected due to following three categories.
 Class A: large earthquake with long epicentral distance
 Class B: medium earthquake with medium epicentral distance
 Class C: small earthquake with short epicentral distance

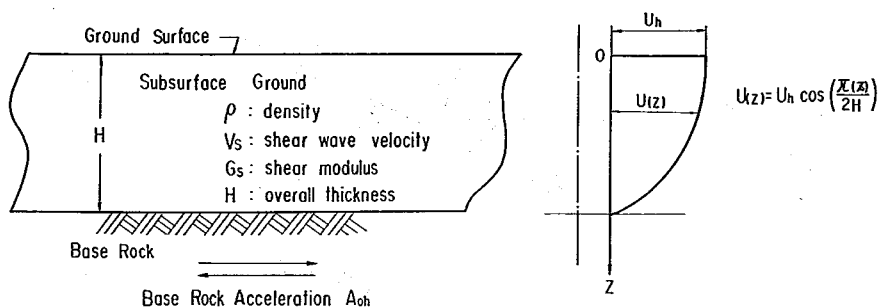
Table A-2 Sectional Forces of Submerged Tunnel

	Earthquake Response Analysis					Seismic Deformation Analysis
Earthquakes	Off Nemuro Peninsula Earthquake	Hachijyo Island Earthquake	Off Echizen Cape Earthquake	Tama River Earthquake	Average Response Spectrum	Average Response Spectrum
Damping Ratio	0.2	0.2	0.2	0.2	0.2	0.2
Maximum Base Rock Acceleration (gal)	45	10	22	6	150	150
Axial Force (t)	19,900	3,750	2,450	180	15,400	20,600
Bending Moment (tm)	119,000	23,800	13,400	1,120	259,600	441,700
Shearing Force (t)	1,230	260	150	10	2,760	8,500

Table A-3 Sectional Forces of Submerged Tunnel

(maximum base rock accelerations are normalized to be 150 gals)

	Earthquake Response Analysis					Seismic Deformation Analysis
Earthquakes	Off Nemuro Peninsula Earthquake	Hachijyo Island Earthquake	Off Echizen Cape Earthquake	Tama River Earthquake	Average Response Spectrum	Average Response Spectrum
Damping Ratio	0.2	0.2	0.2	0.2	0.2	0.2
Maximum Base Rock Acceleration (gal)	150	150	150	150	150	150
Axial Force (t)	66,300	56,300	16,700	4,500	15,400	20,600
Bending Moment (tm)	396,700	357,000	91,400	28,000	259,600	441,700
Shearing Force (t)	4,100	3,900	1,000	250	2,760	8,500



(a) Model of Uniform Shear Deformation System of Subsurface Ground

(b) Shear Deformation Mode of Subsurface Ground

Fig. A-1 Shear Deformation System of Subsurface Ground

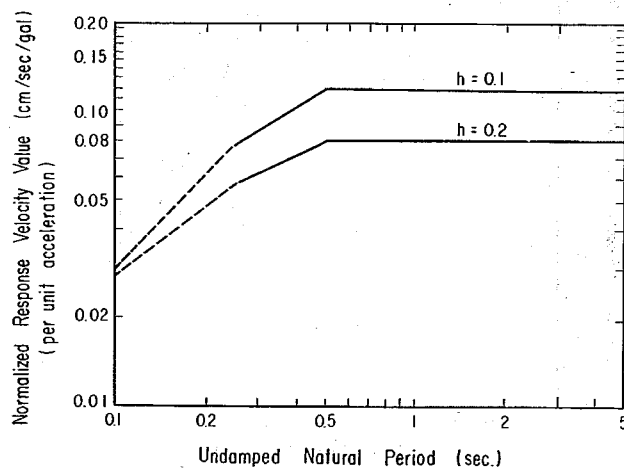


Fig. A-2 Normalized Velocity Response Value S_v

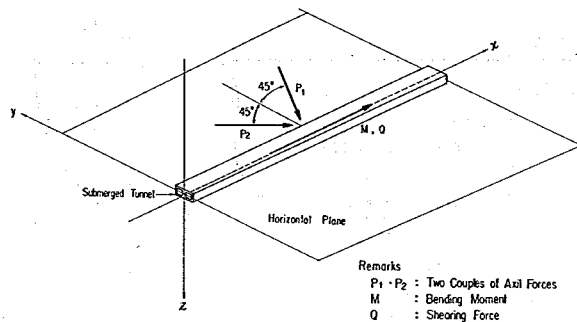


Fig. A-3 Combination of Waves

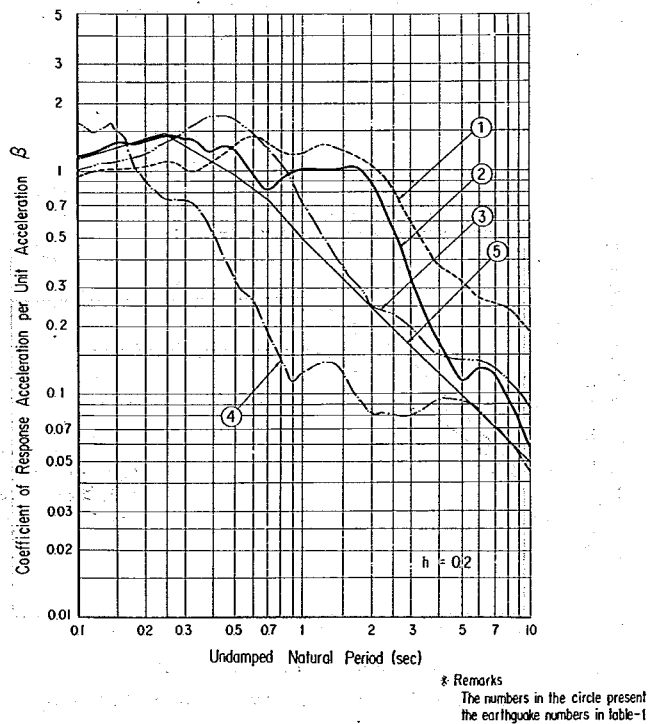


Fig. A-4 Coefficient of Response Acceleration per Unit Acceleration, β

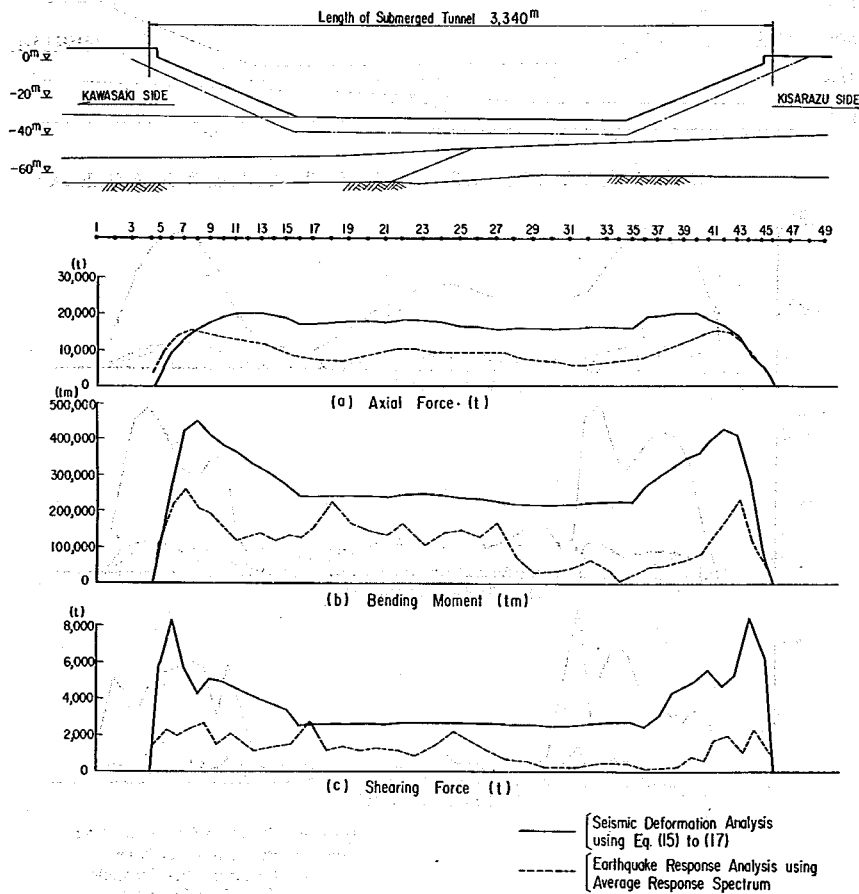


Fig. A-5 Distribution of Sectional Forces by Seismic Deformation Analysis and Earthquake Response Analysis

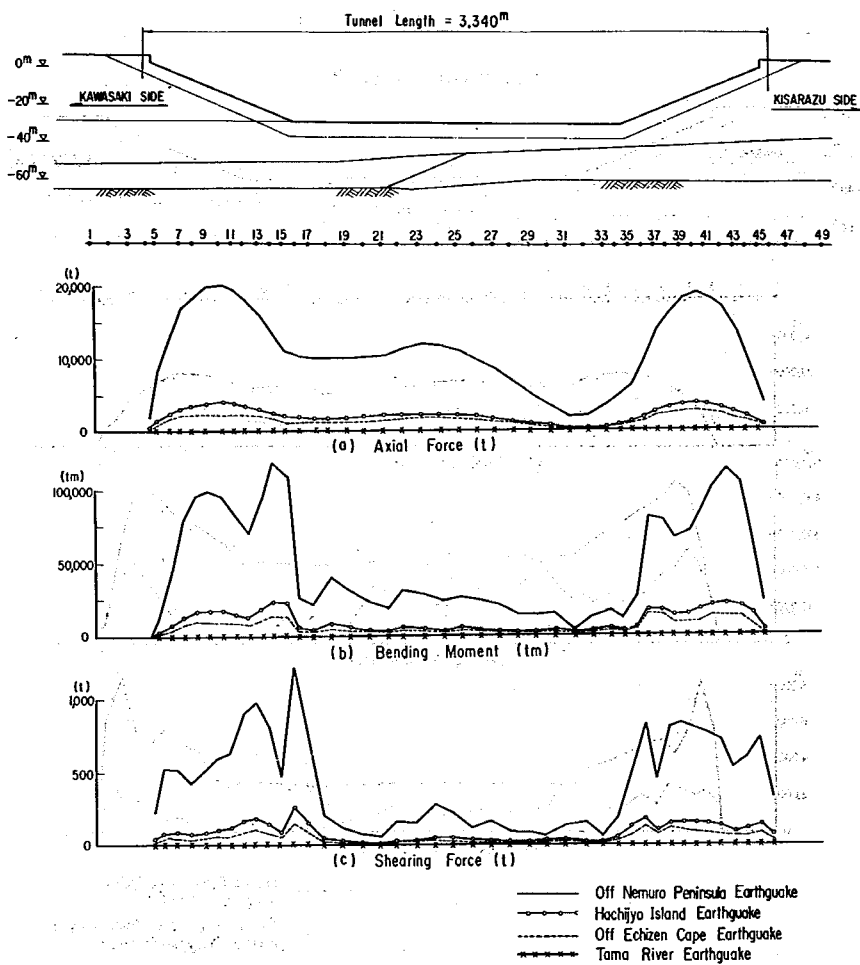


Fig. A-6 Distribution of Sectional Forces by Earthquake Response Analysis Using Four Different Earthquake Waves

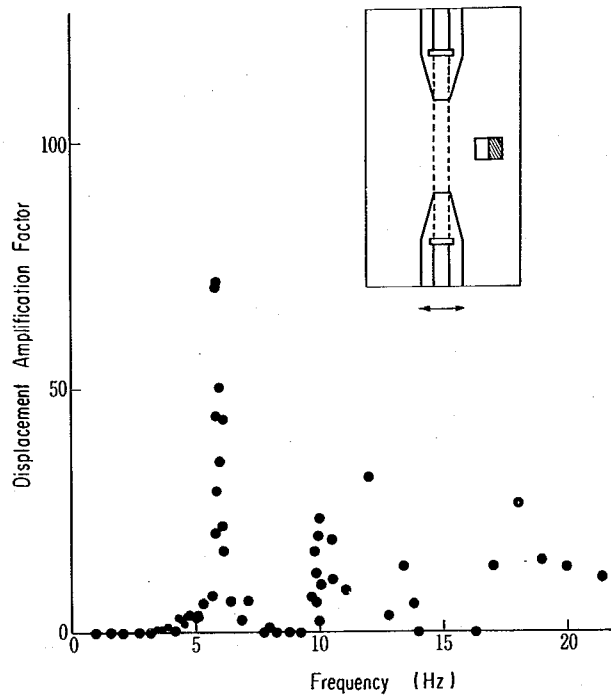


Fig. A-7 Displacement Amplification Factor at the Ground Surface