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# Prediction of Characteristics of Surface Wave for Earthquake Resistant Design

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SYNOPSIS Surface waves are not considered directly in the current earthquake resistant design code of the underground lineal structure, because a method for estimating the surface wave as input motion is not established. A procedure for calculating the expected value of peak ground displacement from bedrock motion is presented in this paper; the bedrock motion is converted to Love wave spectra by the method proposed by the authors, and Love wave spectra is converted to peak ground displacement by the method proposed newly in this paper. Input motions of the underground transmission line is estimated as an example case to compare the axial forces derived by the method and by the current earthquake resistant design code of the underground transmission line. It is confirmed that the structure designed based on the current code is safe against surface waves.

## INTRODUCTION

Recently, structures such as high-rise buildings, large bridges and large tanks, whose natural periods are in the semi-long period (from a few seconds to a little longer than ten seconds), have come to be constracted frequently. It is important to consider surface waves in the aseismic design of these large structures, since the predominant period of the surface wave is closer to the natural period of those structures than that of the body wave.

Tamura et al. (1975) and Oishi et al. (1984) carried out earthquake observations on the underground lineal structures and showed that deformations of the structures are caused by not only body waves but also surface waves. Ieda et al. (1987) pointed out that the dynamic behavior of the structures on the horizontally layered stratum was controlled by surface waves.

It is clear, therefore, that surface waves should be considered in the earthquake resistant design. The method for estimating surface waves as input motion, however, is not still established, hence surface waves are not taken into account in the current design codes directly.

Approaches for calculating input motions for the earthquake resistant design are roughly classified into two groups. The first one is a deterministic method such as a faulting source model. The second one is a probablistic method such as a seismic hazard analysis.

In this paper, a method to calculate the expected value ( so called seismic hazard ) of the velocity response spectra and peak ground displacement of Love wave is presented. The authors (1989) proposed the method to obtain Love wave spectra from the empirical formula of response spectra at the bedrock, which is used to obtain peak ground displacement. The method is applied to the design of the underground lineal structure. Axial forces of the structures calculated by the proposed method are compared with those by the current earthquake resistant design code.

## MAGNIFICATION FACTOR DUE TO LOVE WAVE GENERATED AROUND DIPPING BASEMENT

We previously showed in order to predict the spectral characteristics of Love wave in a plain that the relationship between input motions at the bedrock and Love wave observed at the ground surface was expressed as follows:

$$S_S(T,M,\Delta)=S_B(T,M,\Delta)G_S(T)=S_B(T,M,\Delta)T(T)g_L(T) \tag{1}$$

where T denotes period(sec), M denotes magnitude, $\Delta$ denotes epicentral distance(km), $S_S(T,M,\Delta)$ denotes the response spectrum of Love wave at the ground surface, $S_B(T,M,\Delta)$ denotes the incident motion spectrum at the bedrock, $G_S(T)$ denotes the magnification factor due to Love wave, T(T) denotes the coefficient of influence due to Love wave, $g_L(T)$ denotes the ratio of the displacement amplitude at the ground surface to that at the bedrock due to Love wave.

The ratio $g_L(T)$ is calculated by Haskell's method as shown in equation (2).

$$g_L(T)=U_{ss}(T)/U_{sr}(T)=1/L(1,1) \tag{2}$$

where $U_{ss}(T)$ denotes the displacement response spectra due to Love wave at the ground surface, $U_{sr}(T)$ denotes the displacement response spectra due to Love wave at the bedrock, L(1,1) is a component of the matrix [L] which denotes the matrix for associating displacement and stress due to Love wave at the ground surface with those at the bedrock and is expressed as

$$[L]=[a_{n-1}]\cdots[a_i]\cdots[a_1] \qquad (3)$$

$$[a_i]=\begin{bmatrix}\cos(Q_i) & i\sin(Q_i/G_i)\zeta_i \\ iG_i\zeta_i\sin(Q_i) & \cos(Q_i)\end{bmatrix}$$

$$Q_i=k\zeta_i d_i$$

$$\zeta_i=\begin{cases}((c_L/V_{Si})^2-1)^{0.5} & c_L>V_{Si} \\ i(1-(c_L/V_{Si})^2)^{0.5} & c_L<V_{Si}\end{cases}$$

where $[a_i]$ denotes the layer matrix at i-th layer of Love wave, $k$, $c_L$, $V_{Si}$, $G_i$, $d_i$ denotes the wave number, the phase velocity of Love wave, the shear wave velocity at i-th layer, the shear modulus, the thickness of i-th layer, respectively, and n-1 denotes the number of layers from the ground surface to the bedrock.

In the procedure to obtain T(T) in equation (1), Love waves are generated by the following two mechanisms which are schematically shown in Fig.1:

1) Transformation from a body wave (SH wave) around the dipping basement; surface wave generates from the incident body wave at the basement by repeatedly reflecting between the dipping layer and the ground surface.
2) Translation of Love wave due to dipping layers; surface wave propagates in rock by passing through dipping layers on the basement.

Therefore, T(T) is obtained from the coefficient of influence due to Love wave which is transformed around the dipping layer from the body wave component of the incident wave at the bedrock, $T_b(T)$, and that which translates around dipping layers from the Love wave component of the incident wave at the bedrock, $T_S(T)$, as follows.

$$T(T) = T_b(T)(1-p(T,M,\Delta))+T_S(T)p(T,M,\Delta) \qquad (4)$$

where $p(T,M,\Delta)$ is the proportion of Love wave in the incident wave at the bedrock. Furthermore, it is confirmed that T(T) which is obtained by substituting $T_b(T)$ and $T_S(T)$ calculated by the FE-BE method and $p(T,M,\Delta)$ chosen adequately to equation (4) is equal to $T_{ob}(T)$ which is obtained from observed earthquake records at a specific site by equation (5).

$$T_{ob}(T)= \frac{S_{SO}(T,h=0\%)}{g_L(T)S_B(T,M,\Delta,h=0\%)} \qquad (5)$$

where $S_{SO}(T,h=0\%)$ denotes a velocity response spectrum of Love wave separated from observed earthquake records by the Kamiyama's method (1987), $S_B(T,M,\Delta,h=0\%)$ denotes the incident wav spectrum at the bedrock by the use of the empirical equation.

As the result of the examination, we showed tha T(T) could be expressed as equation (6) based o the functional shape of $T_{ob}(T)$.

$$T(T) = \frac{\alpha T^{*\beta}}{1+T^{*\beta}} \qquad (6)$$

$$T^* = \frac{T-\gamma}{T_O}$$

where $T_O$ denotes the period which gives Airy phase of Love wave, and $\alpha$, $\beta$, $\gamma$ are parameters. Among three parameters, the value of parameter is always set 2. The rest, $\beta$ and $\gamma$, are estimated on the basis of the surface waves contained in the observed earthquake records; those at the specified site are obtained from $T_{ob}(T)$ by the least squares method.

## SEISMIC HAZARD ESTIMATION FOR SURFACE WAVES

Seismic hazard is an index which expresses the intensity such as peak ground acceleration, peak ground velocity and response spectra etc., and the occurence frequency of a site due to earthquake. Seismic hazards have been evaluate

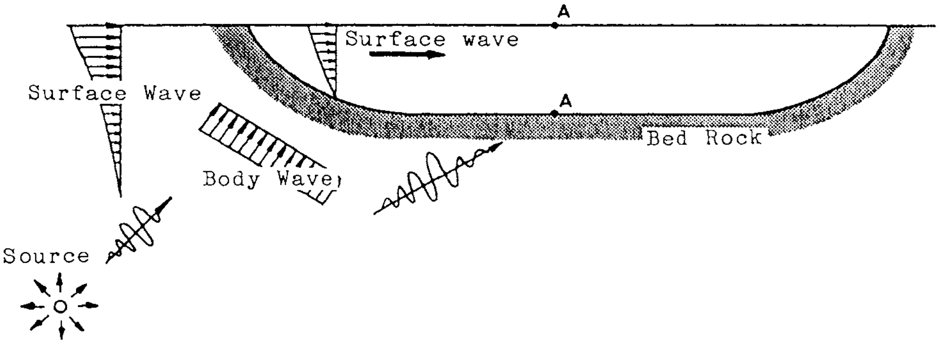


Fig.1 Surface waves generated in the surface layer on bedrock

y some researchers since Kawasumi (1951) and ornell (1968) calculated them by combining eismicity depending on the characteristics of he source mechanism and attenuation properties.

n this paper, seismic hazard of the surface ave spectra is calculated by the following rocedure.

)The historical catalogue of seismicity is selected, and the available term is chosen.
2)The response spectra at a specific site are calculated by substituting the magnitude and the epicentral distance given by the historical earthquake data to the attenuation equation of Love wave spectra.
3)The historical earthquakes are arranged in the order of decreasing amplitude of the response spectra at each period and the return year of each earthquake is calculated.
4)The response spectrum for a specific return year is calculated by linear interpolation with two adjacent values in a log-log scale figure.

## ESTIMATION OF THE DESIGN INPUT MOTION FOR UNDERGROUND LINEAL STRUCTURES CONSIDERING SURFACE WAVES

Many earthquake resistant design codes employ the seismic deformation method for the design of the underground lineal structures. Since the deformation of the ground due to earthquake is applied to the structures through the spring in this method, it is necessary to obtain ground displacements. The procedure to obtain it from the Love wave spectra is introduced in this section.

Midorikawa and Kobayashi (1979) presented the relation between the value of integrating spectrum and the peak acceleration and velocity of earthquake ground motion. In the same way, the peak ground displacement of Love wave, $U_S$, is calculated by equation (7).

$$U_S=\delta\int_{T1}^{T2} S_S(T,h)dT \qquad (7)$$

where T1 and T2 denote the periods which give an interval of integration of velocity response spectrum due to Love wave, $\delta$ denotes the coefficient depending on the site, which remain unknown. These parameters are determined with

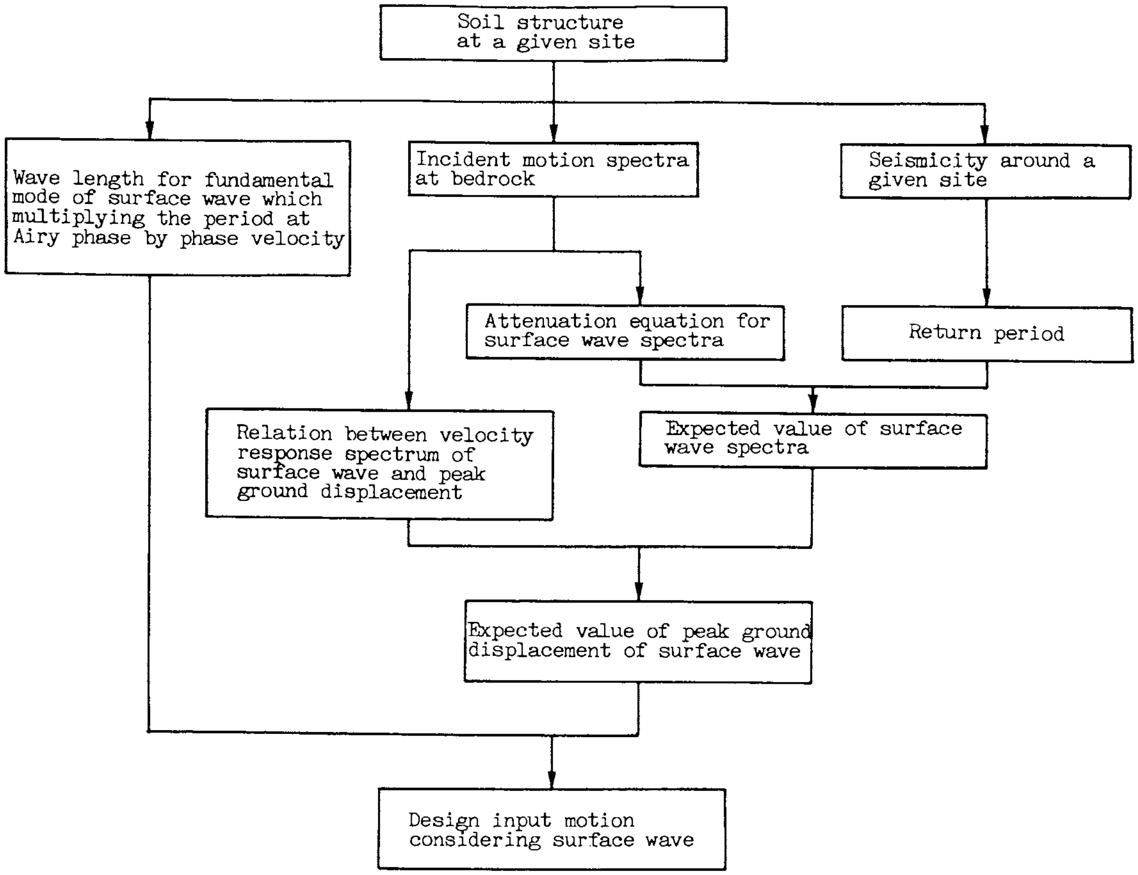


Fig.2 Flow of calculating input motion for aseismic design considering surface wave

the earthquake records observed at the site by the back analysis.

Following two assumptions are employed:

1)Sedimentary layers over the seismic bedrock in which shear wave velocity is higher than or equal to 3000m/s form layered structures.

2)Surface waves propagate as a fundamental mode.

The evidence of the second assumption is reported by several researchers (e.g., Tazime (1957)).

A sinusoidal wave expressed by equation (8) is used as an input motion in current earthquake resistant design codes of the structures.

$$U(x)=U_D \sin\left(\frac{2\pi x}{L_D}\right) \tag{8}$$

where U(x) is an input displacement wave of axial component at point x along the structure, $U_D$ is the peak ground displacement which is calculated assuming that the ground oscillates in shear mode due to vertically propagating body wave, $L_D$ is the wave length of the body wave. Therefore, it is found that the design input motion considering surface waves is obtained by substituting the value of the peak ground displacement due to Love wave, $U_S$, and the value of the wave length of Love wave, $L_S$, to equation (8).

The flow of calculation of the design input motion is shown in Fig.2. At first, the soil structure at a given site and seismic bedrock whose shear wave velocity is about 3000m/s are decided. Next, the wave length of Love wave, $L_S$, is calculated by the product of the period which gives the Airy phase and the phase velocity at the period. The expected value of peak ground displacement due to Love wave for a specific return year is obtained by equation (7). Then, the design input motion considering Love wave is obtained by equation (8).

## DISCUSSIONS

The expected velocity response spectra (h=0%) and peak ground displacement due to Love wave are calculated, for example, at both Hachinohe harbor and Aomori harbor in Japan. The soil structures at both sites are shown in Table 1. The values of parameters at both sites are shown in Table 2. Parameters α, β, γ, $T_0$ were those previously calculated by the authors (1989). The period T1 is fixed because it has been pointed out that the surface wave is predominant at the periods more than 1~2 seconds. The period T2 is chosen on the basis of the correlation between the value of integrating spectrum from the value of T1 to the value of T2 and the peak ground displacement. The relation between the value of integrating spectrum of separated Love wave and the peak ground displacement is shown in Fig.3. Those values are estimated by using earthquake records of 1968 Tokachi-Oki earthquake (No.1), 1978 Miyagiken-Oki earthquake (No.2) and 1983 Nihonkai-Chubu earthquake (No.3) observed at

Table 1 Soil profiles
(a)Hachinohe harbor

| Depth (m) | Thickness (m) | S-wave Velocity (m/sec) | Density (tf/m$^3$) |
|---|---|---|---|
| 2.0 | 2.0 | 100.0 | 1.8 |
| 4.0 | 2.0 | 160.0 | 1.8 |
| 7.0 | 3.0 | 195.0 | 1.9 |
| 10.0 | 3.0 | 195.0 | 2.0 |
| 12.0 | 2.0 | 380.0 | 2.0 |
| 13.0 | 1.0 | 200.0 | 2.0 |
| 14.0 | 1.0 | 375.0 | 2.0 |
| 17.0 | 3.0 | 375.0 | 1.6 |
| 18.0 | 1.0 | 200.0 | 1.6 |
| 28.0 | 10.0 | 430.0 | 1.6 |
| 36.0 | 8.0 | 200.0 | 1.7 |
| 180.0 | 144.0 | 370.0 | 1.9 |
| 360.0 | 180.0 | 690.0 | 2.0 |
| 380.0 | 20.0 | 1100.0 | 2.1 |
|  |  | 2800.0 | 2.5 |

(b)Aomori harbor

| Depth (m) | Thickness (m) | S-wave Velocity (m/sec) | Density (tf/m$^3$) |
|---|---|---|---|
| 8.0 | 8.0 | 144.0 | 1.8 |
| 14.0 | 6.0 | 173.0 | 1.7 |
| 21.0 | 7.0 | 152.0 | 1.6 |
| 27.0 | 6.0 | 205.0 | 1.6 |
| 34.0 | 7.0 | 260.0 | 1.7 |
| 40.0 | 6.0 | 320.0 | 1.9 |
| 100.0 | 60.0 | 500.0 | 2.0 |
| 270.0 | 170.0 | 900.0 | 2.5 |
| 300.0 | 30.0 | 550.0 | 2.0 |
| 360.0 | 60.0 | 900.0 | 2.5 |
| 600.0 | 240.0 | 650.0 | 2.0 |
|  |  | 1850.0 | 2.7 |

Table 2 Constants

|  | Hachinohe | Aomori |
|---|---|---|
| α | 2.0 |  |
| β | 9.0 |  |
| γ | 0.4 | 0.0 |
| $T_0$ | 2.5 | 2.8 |
| T1 | 1 second |  |
| T2 | 9 second |  |
| δ | 0.02 |  |
| Historical catalogue of seismicity | Usami's catalogue |  |
| The used term of the catalogue | from 1885 to 1982 |  |
| Return years | 50, 75, 100 years |  |

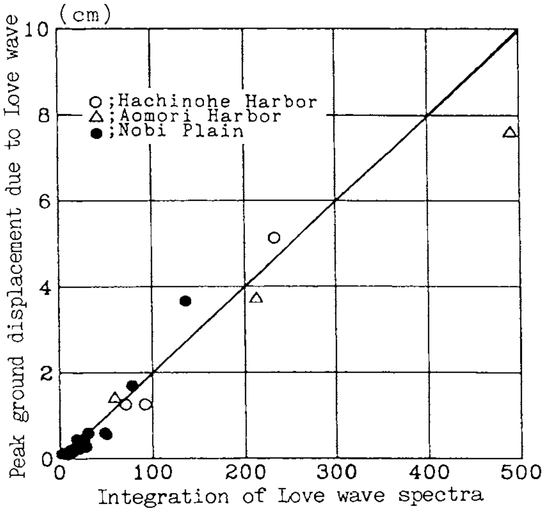


Fig.3 Relation between the integration of Love wave spectra and the peak ground displacement due to Love wave

Hachinohe harbor and Aomori harbor. The relation obtained by Tsuchiyama et al. (1989) is also shown in the same figure. The value of δ, 0.02, gives good agreement at all sites.

The coefficients, T(T), are shown in Fig.4. The ratios of the displacements, $g_L(T)$, are shown in Fig.5. The magnification factors, $G_S(T)$, are shown in Fig.6. The expected values of incident motion spectra at the bedrock by the use of the attenuation equation proposed by Kamiyama (1989), $S_B(T,h=0\%)$, are shown in Fig.7. The expected values of Love wave spectra, $S_S(T,h=0\%)$, are shown in Fig.8. It is seen that the predominant periods agree with the periods which give the Airy phase for both sites and that the maximum values of the spectra are 100∿200 cm/s.

The expected values of the peak ground displacement due to Love wave obtained by equation (7) are shown in Table 3. In this Table, the ground displacements and the wave lengths given by the design code of multi-purpose underground duct (1988), which is one of the current Japanese earthquake resistant design codes for the underground lineal structures, and the peak ground displacements due to Love wave separated from the observed earthquake records are also shown. The peak ground displacements due to Love wave by the proposed method are 1.7∿2.6 times as large as the design values. The peak ground displacements due to Love wave separated from the observed earthquake records are not so different from the values by the proposed method except the case that epicentral distance is longer than 200km. However, wave lengths by the proposed method are 16 times as large as the design values, because the seismic bedrock in the proposed method is deeper than

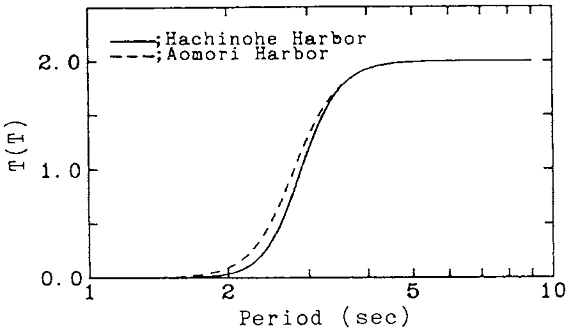


Fig.4 Coefficient of influence due to Love wave, T(T)

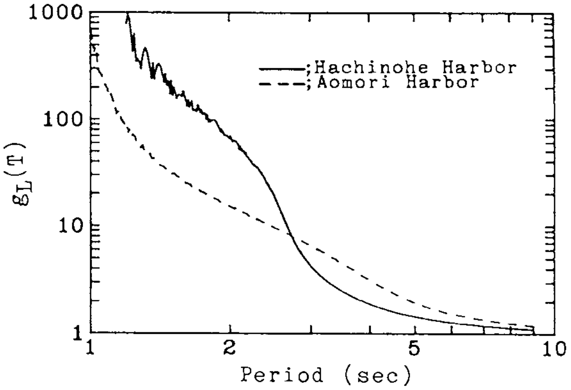


Fig.5 Ratio of the displacement at the ground surface to that at the bedrock due to Love wave, $g_L(T)$

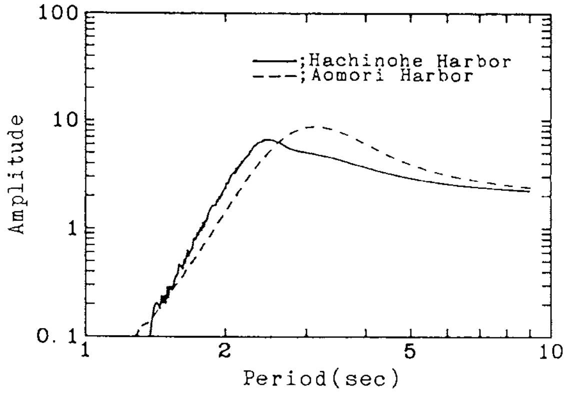
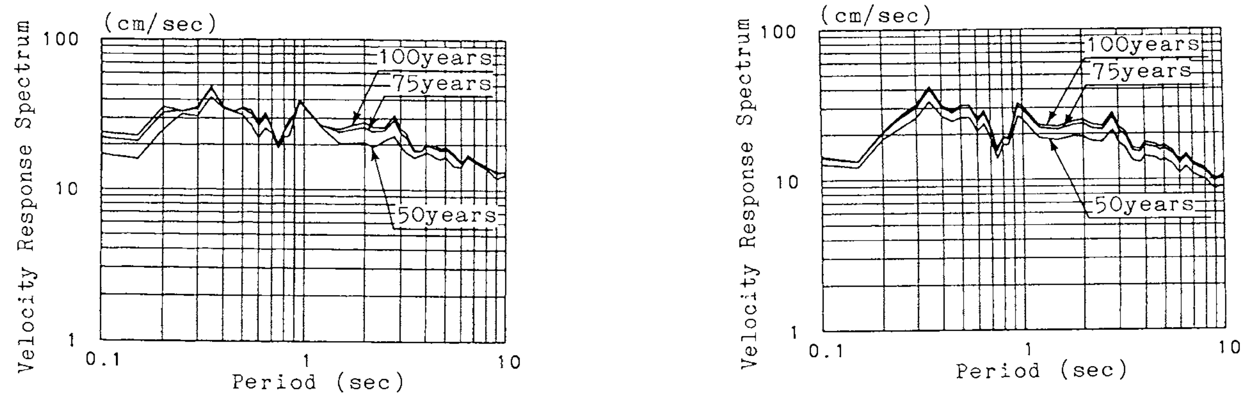


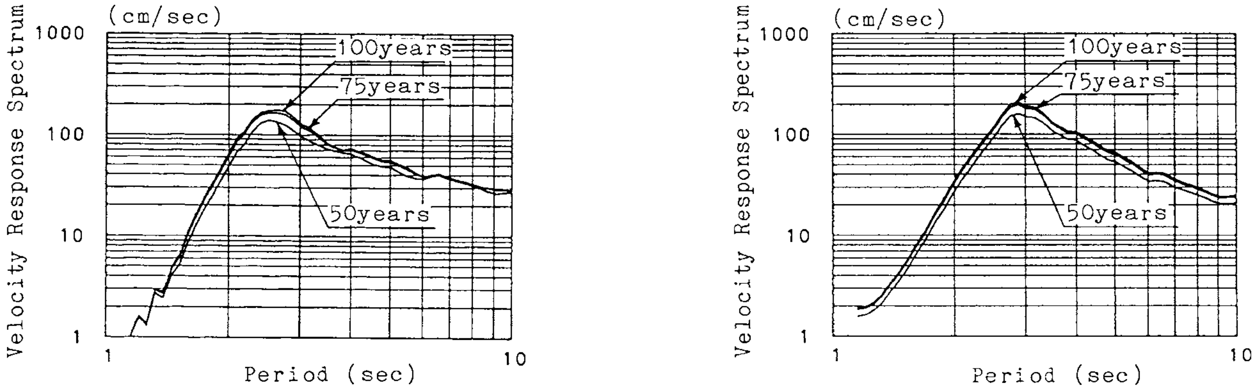
Fig.6 Magnification factor due to Love wave, $G_S(T)$



(a)Hachinohe harbor

(b)Aomori harbor

Fig.7 Expected values of incident motion spectra at bedrock



(a)Hachinohe harbor

(b)Aomori harbor

Fig.8 Expected values of Love wave spectra

Table 3 Comparison between the peak ground displacement and wave length obtained by the proposed method and those obtained by the Japanese earthquake resistant design code for underground lineal structure

| Site | Proposed method | | | | Japanese design code | | Observed records | | |
|---|---|---|---|---|---|---|---|---|---|
| | Displacement (cm) | | | Wave length (m) | Displacement (cm) | Wave length (m) | Displacement (cm) | | |
| | Return year | | | | | | Earthquake No. | | |
| | 50 | 75 | 100 | | | | 1 | 2 | 3 |
| Hachinohe | 7.9 | 9.0 | 9.4 | 3075 | 3.7 | 190 | 5.1 | 1.3 | 1.3 |
| Aomori | 8.2 | 9.7 | 10.2 | 3900 | 4.4 | 250 | 7.6 | 1.4 | 3.8 |

that in the design code and the shear wave velocity of the seismic bedrock in the proposed method is larger than that in the design code. The axial forces by the use of the peak ground displacements and the wave lengths of Love wave shown in Table 3 are compared with those given by the design code. The comparison is based on the ratio, A.R., between axial forces obtained by the proposed method and those by the design code given by following equation:

$$A.R. = \frac{L_D U_S}{L_S U_D} \qquad (9)$$

The ratios by equation (9) are shown in Table 4. Axial forces by the proposed method are much smaller than those given by the design code, since wave lengths obtained by the proposed method are much larger than those obtained by the design code.

As a next example, the distribution of the expected peak ground displacement at Nobi plain with the return year of 100 years is shown in Fig.9. Equal depth contour line of bedrock at Nobi plain is shown in Fig.10. The deeper the depth of bedrock becomes, the larger the peak ground displacement becomes.

Table 4 Ratios of axial forces

| Site | Ratio of axial forces | | |
|---|---|---|---|
| | 50years | 75years | 100years |
| Hachinohe | 0.13 | 0.15 | 0.16 |
| Aomori | 0.12 | 0.14 | 0.15 |

## CONCLUDING REMARKS

In this paper, the method to calculate the expected Love wave spectra and the expected peak ground displacement due to Love wave by seismic hazard analysis and the method to calculate the design input motion of the underground lineal structure is proposed. Next, the axial forces of the underground lineal structures due to the above input motion are calculated and compared with those obtained by the current Japanese earthquake resistant design code. It is confirmed that the structure designed based on the current code is safe against surface waves.

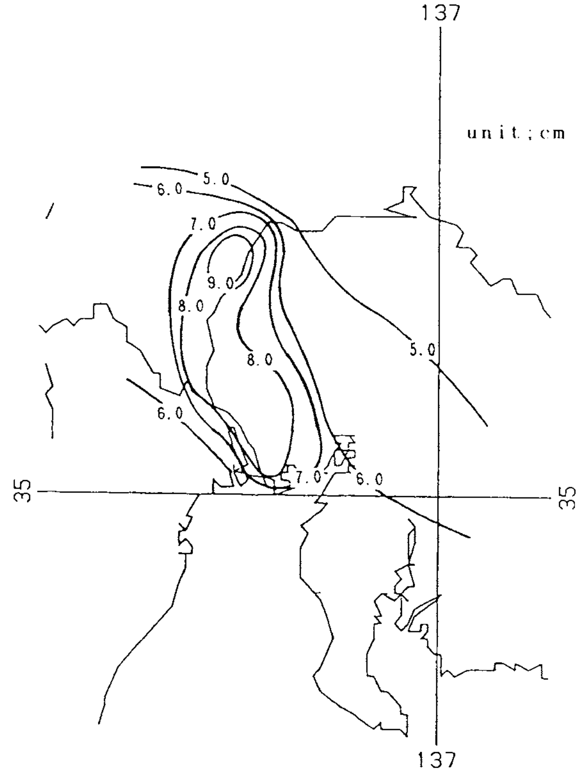


Fig.9 Distribution of the expected peak ground displacement at Nobi plain with the return year of 100 years

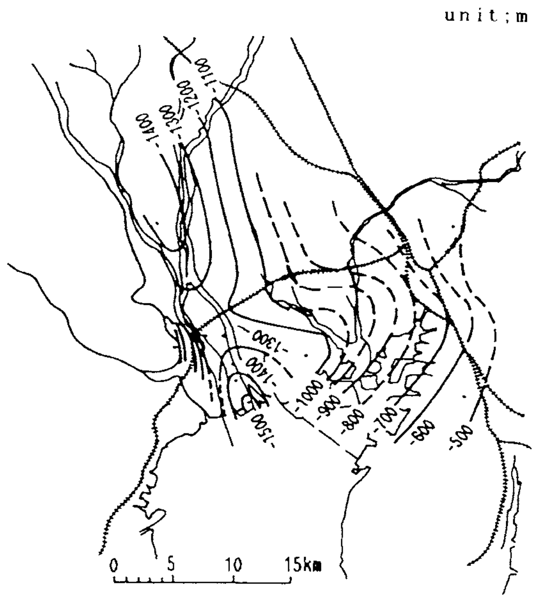


Fig.10 Equal depth contour line of bedrock at Nobi plain

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