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Mechanism of seismic strain in buried pipelines based on field observations and model experiments

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ABSTRACT: Investigations of pipeline damage caused by the past earthquakes in Japan suggested that non-uniformity of superficial ground condition has a close correlation with the extent of damage. In order to verify the relationship between the non-uniformity and the deformation in the ground, data obtained through earthquake observations at four sites and experiments on two dynamically similar models of ground-pipe system were reexamined by using a parameter which was defined as the non-uniformity index so that it could properly reflect the mechanism of strain due to non-uniform ground condition. A positive correlation was proved between the non-uniformity and the strain in the pipeline and the non-uniformity index was found to be useful to estimate damage susceptibility of pipelines.

1 INTRODUCTION

Deformation in an underground pipeline is caused by so-called horizontally incoherent ground motion. The most extreme incoherence of ground motion may be represented by fault movements and landslides, but they are not very common causes of seismic damage to pipelines especially in Japan where most big cities are located on relatively soft tertiary or alluvial deposits which do not show remarkable fault activities.

As one of the causes of this incoherent ground motion, Newmark (1967) proposed a strain in the ground associated with a horizontally propagating earthquake wave. However, this idea of strain due to propagating wave contains a self-contradiction: if a pipeline should undergo failure, the strain in the ground should necessarily be greater than its elastic limit. This implies that such a wave that causes failure to a pipeline cannot propagate any longer as an elastic wave.

On the other hand, investigations of damage to water and gas distribution systems during major earthquakes in Japan suggested that the degree of complexity or non-uniformity of superficial ground structure has a strong correlation with the damage ratio (e.g. Katayama 1976, Nishio 1981).

Studies of pipeline's seismic behavior based on earthquake observations (Nishio et al.1980, Tsukamoto et al.1984, Nishio and Tsukamoto 1985) and model experiments (Nishio et al.1983) have pointed out that the non-uniform movement of non-uniform surface soil layer in response to S-waves which are almost vertically incident to the surface layers produces strains in the ground in the horizontal direction which could cause failure to pipelines depending on the degree of non-uniformity of the surface soil layer.

In the present study, an index — non-uniformity index — is introduced for characterizing the surface soil layer in terms of non-uniform seismic behavior, and the relationship between the non-uniformity index and the probable maximum strain in a buried pipeline is discussed on the basis of the data obtained during the earthquake observations and model experiments by Nishio et al. (1980) and others.

2 MODELS FOR MECHANISM OF SEISMIC STRAIN IN BURIED PIPELINE

Roughly speaking, two kinds of mechanism of seismic strain in the ground is considered. One is strain due to delay in phase in the axial direction associated with a horizontally propagating wave.

If the wave is expressed approximately by a propagating sinusoidal ground motion, then, the axial strain in the ground is expressed by using acceleration amplitude A, wave velocity V and period of vibration T as

$$\varepsilon = \frac{T}{2\pi} \cdot \frac{A}{V} \tag{1}$$

(Note that the word "axial" means "in the direction of pipeline axis" in this paper)

The velocity of a horizontally propagating wave (so-called surface wave) such as Rayleigh Wave or Love Wave is at least greater than 1 km/s (of the same order of magnitude as the S-wave velocity in the uppermost part of earth's crust). The period T of such surface waves to be observed on earthquake records is one or two seconds to several seconds in general. The maximum seismic acceleration is exhibited during the main shock by S-wave rather than surface wave provided the origin of earthquake is not very distant, therefore, it is hardly expected that a surface wave can produce a great acceleration as intense as 300 gal (gal ≡ cm/s^2). Taking into account the above fact, the possible maximum strain due to surface wave propagation is estimated to be about 1000 μ (μ ≡ 10^{-6} m/m) which is exactly of the same order of magnitude as the yield strain of rocks. This fact is likely to suggest that an elastic wave such as Rayleigh Wave and Love Wave can only produce an elastic strain in the ground; this implies that a surface wave can hardly be a cause of failure of the ground therefore of a pipeline buried in it. More detailed discussions in this regard have been made by Nishio and Satake (1983).

Another model of strain generation mechanism employs a horizontally non-uniform structure of surface soil deposit to which an S-wave is incident upward. This "non-uniformity" means that the stratification condition of the surface soil deposit varies from place to place along the axis of a pipeline. This variation of ground condition gives rise to a variation of seismic response of surface layer along the pipeline causing axial strain in the ground (therefore in the pipeline). This strain in the ground can be defined by the following equation.

$$\varepsilon = \lim_{\Delta x \to 0} \frac{u(x + \Delta x) - u(x)}{\Delta x} \tag{2}$$

where u(x) is the magnitude of response displacement (in the axial direction) of the ground at a particular instant and Δx is distance between two points on the ground along the pipeline. The magnitude of response of the ground primarily depends on the natural period of the surface layer, therefore, the magnitude of strain is considered to depend on the degree of variation of natural period per unit distance along the axis of pipeline.

In this model, the magnitude of strain has no limit (such as elastic limit) because upwardly incident S-wave does not have to propagate further so that the energy of the S-wave can be throughly consumed to stimulate the surface layer until the failure occurs in the ground, although a part of the energy is reflected at the surface layer and transmitted downward into the deeper layers. Of course, whether failure occurs or not will depend not only on the degree of non-uniformity but also on overall natural period of surface layer and the frequency characteristics (spectrum) as well as the intensity of the S-wave.

The effect of the above two kinds of mechanism has been discussed by Tsukamoto et al.(1984) on the basis of earthquake observation on a pipeline which had been buried in a typically non-uniform ground; the site for this observation will be cited as Site 4 in the following chapters. They identified the effect of both surface wave and non-uniform ground structure on the axial strain in the pipeline by means of frequency band analysis of the obtained records. As a result, predominance of the effect of non-uniformity of ground structure over the effect of surface wave has been concluded.

Besides the earthquake observation cited above, Nishio et al.(1980) carried out earthquake observations on buried pipelines at three other sites. Experiments on dynamically similar models simulating the existing ground in which gas distribution pipelines sustained heavy damage during a big earthquake in 1978 were also carried out (Nishio et al.1983). In the following chapters, the data obtained during these observations and experiments will be reevaluated from the viewpoint of relationship between the non-uniformity of surface soil layer and the strain in the pipeline.

For this purpose, an index will be introduced for characterizing the non-uniformity of ground structure; it is defined on the basis of conventional average response spectra of a single-degree-of-freedom system.

3 NON-UNIFORMITY INDEX OF GROUND

3.1 Definition of non-uniformity index

The seismic strain in a surface soil layer in the axial direction can naturally be defined as a change in or gradient of horizontal seismic displacement as has been defined by Eq.(2). However, it seems quite difficult to predict a possible value of gradient of displacement in an actual soil layer which shows varying geological structure from place to place.

In spite of the above difficulty, it is possible to determine the degree of variation of seismic displacement in a particular area by which the ground condition can be related to the possible magnitude of seismic strain.

Very often, the seismic response of a structure is given approximately by a response spectrum which is calculated by assuming that the structure is a single-degree-of-freedom system. A soil deposit can also be assumed as a single-degree-of-freedom system, the natural period(T) of which is given by the equation

$$T = \sum_{i=1}^{n} \frac{4H_i}{V_{si}} \tag{3}$$

where H_i is thickness of i-th layer of the soil deposit and V_{si} is S-wave velocity in the i-th layer (Fig. 1).

Fig. 2 shows an example of acceleration response spectra for diluvial and stiff alluvial subsoils which were developed by Kuribayashi et al.(1972) on the basis of 22 earthquake wave components recorded on diluvial and stiff alluvial subsoils (in this figure, only spectra for a damping constant of h=0.1 are illustrated). Based on the mean values of the above two spectra, a displacement response spectrum is obtained as illustrated in Fig. 2 by using the following equation.

$$S_D = \left(\frac{T}{2\pi}\right)^2 S_A \tag{4}$$

The dotted line in Fig. 2 shows an approximation of the above obtained spectrum by three straight lines which are expressed as functions of T by the following equations.

$$\left.\begin{array}{ll} \text{for } T \leq 0.25, & S_D = 8.47T^{2.41} \\ \text{for } 0.25 < T \leq 0.8, & S_D = 2.37T^{1.49} \\ \text{for } 0.8 < T, & S_D = 2.13T \end{array}\right\} \tag{5}$$

Then, by knowing the distribution of the value of T in a certain site, the variation of displacement response per unit acceleration can be determined.

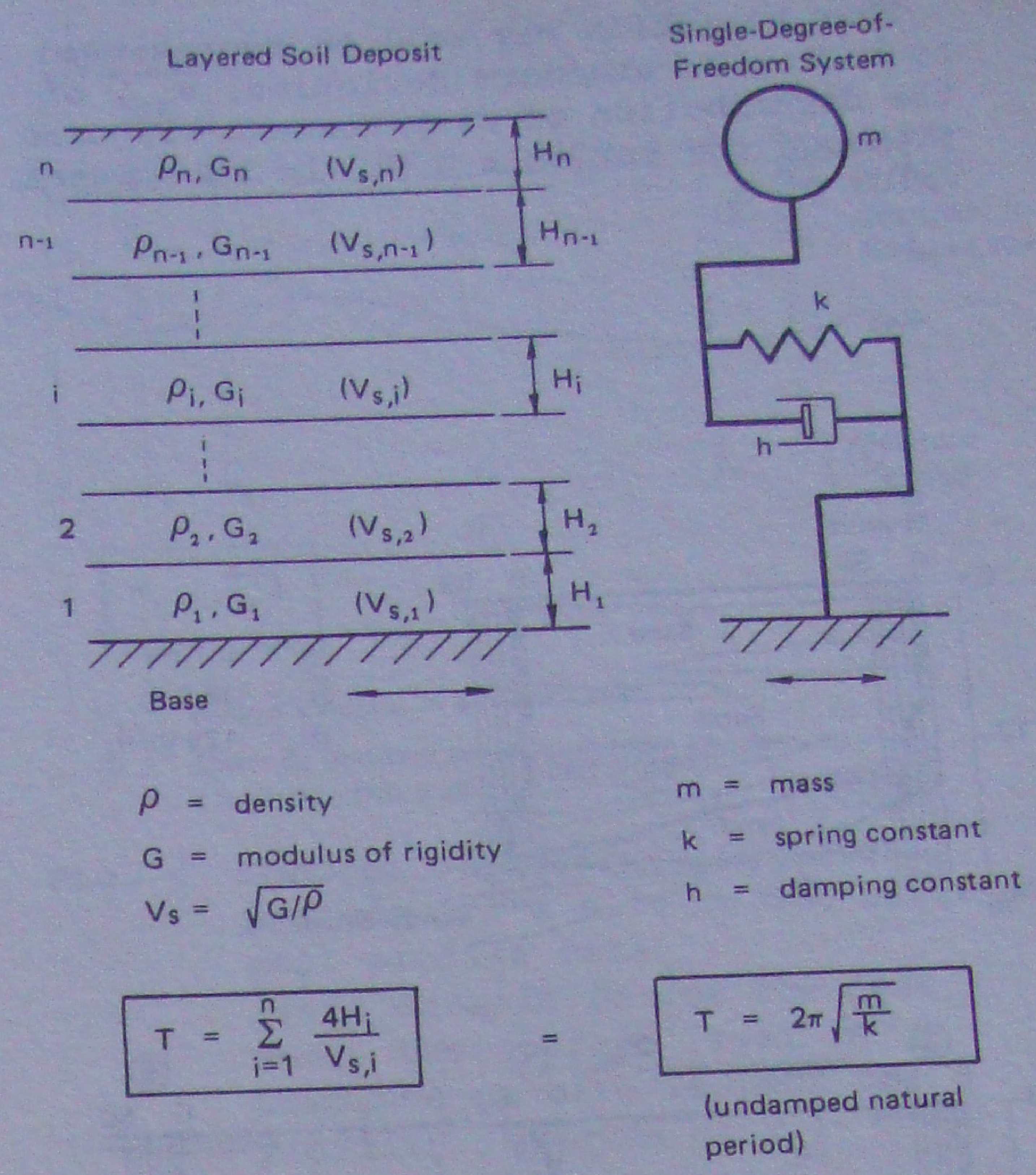


Fig. 1 Layered soil deposit and its equivalent expression with single-degree-of-freedom system

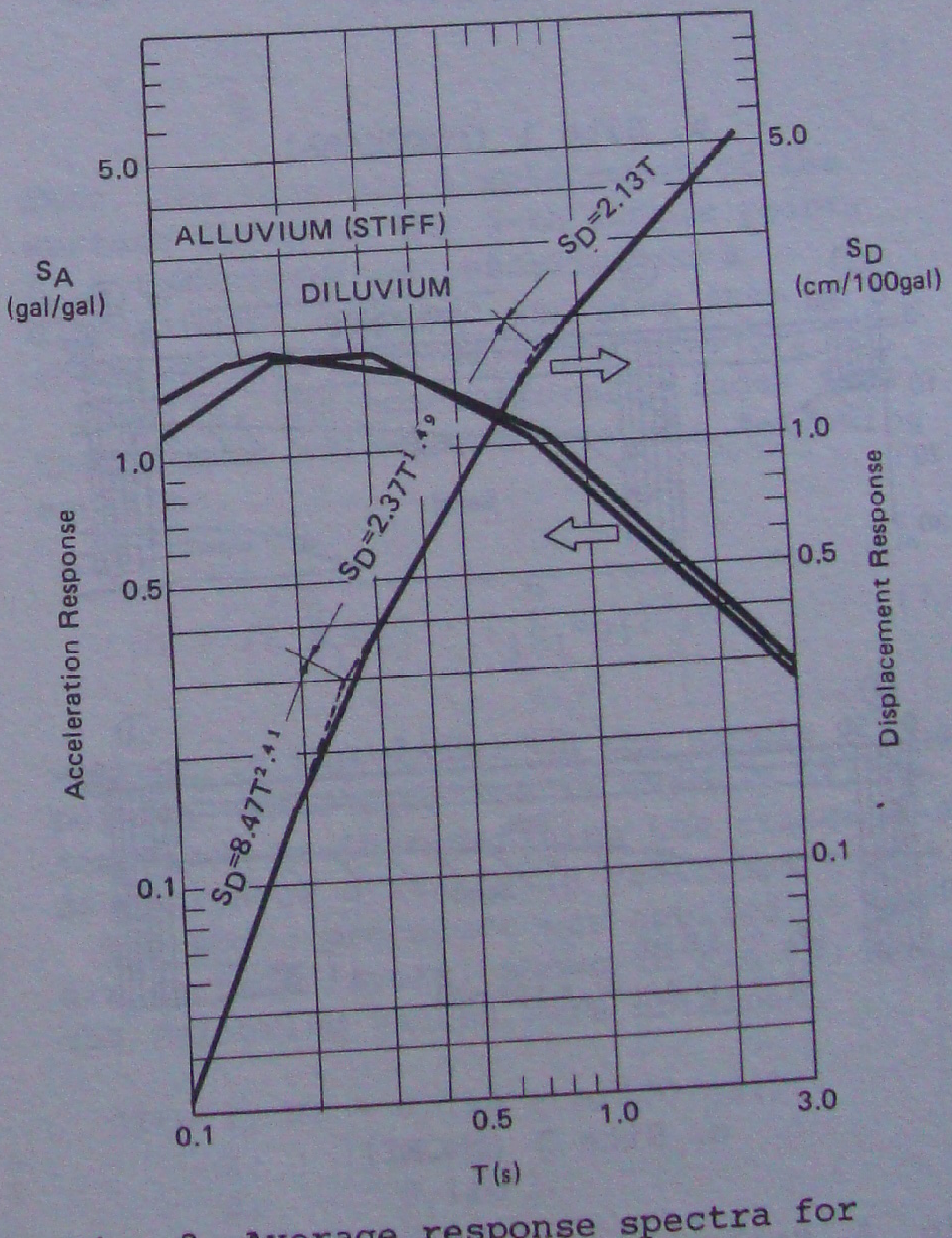
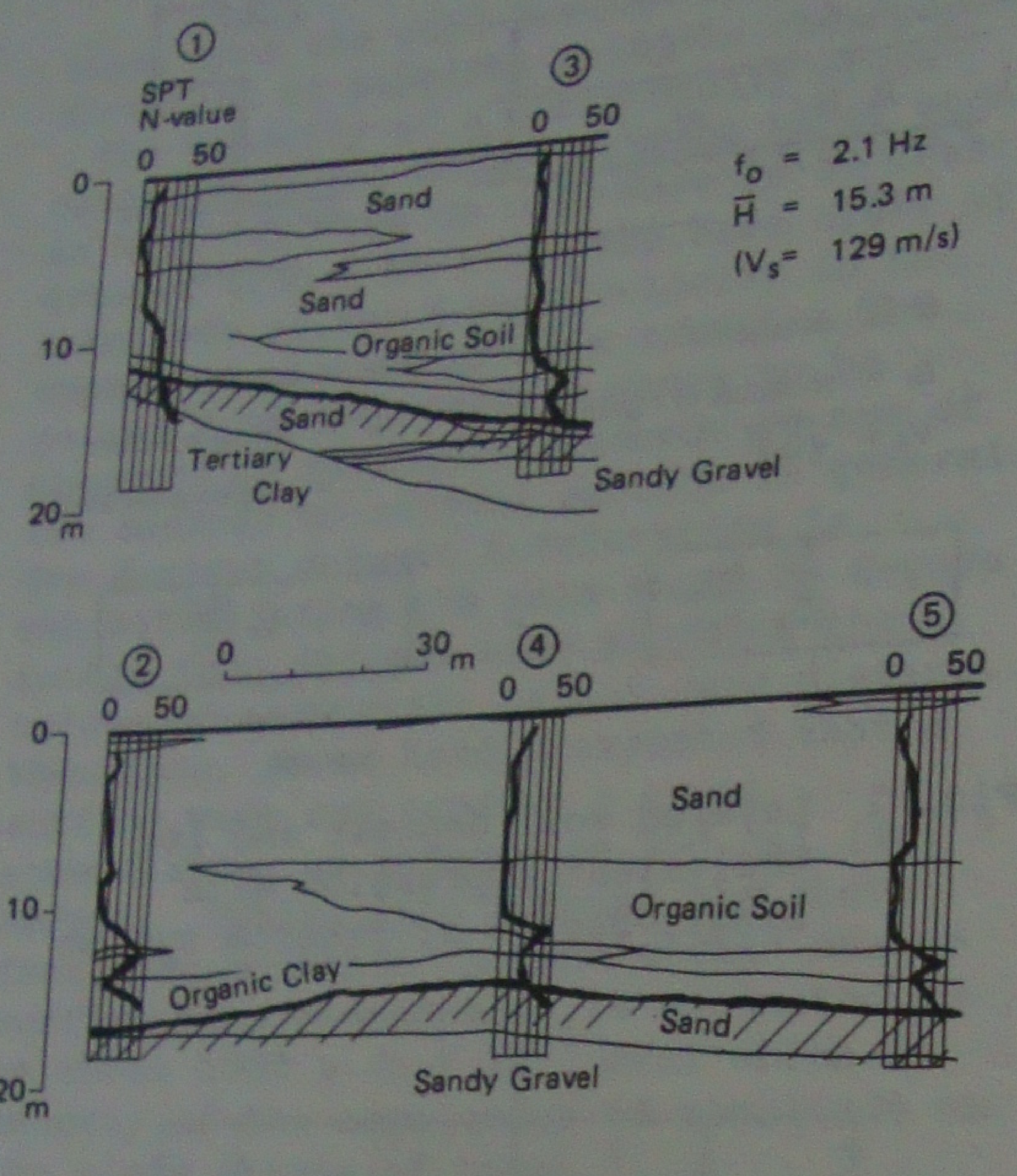
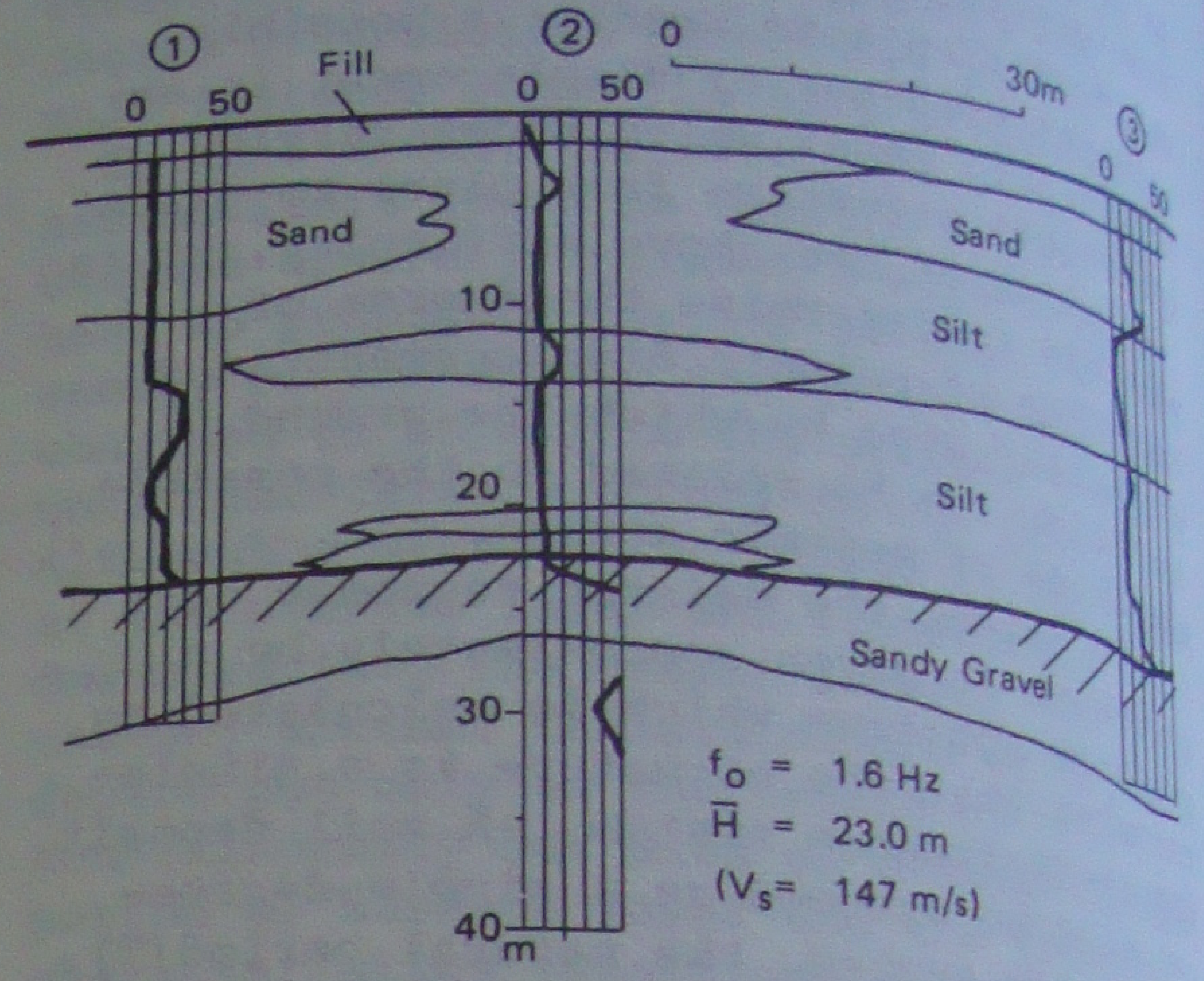


Fig. 2 Average response spectra for earthquake waves on Diluvial and Alluvial (stiff) sub-soil (after Kuribayashi et al.1972)

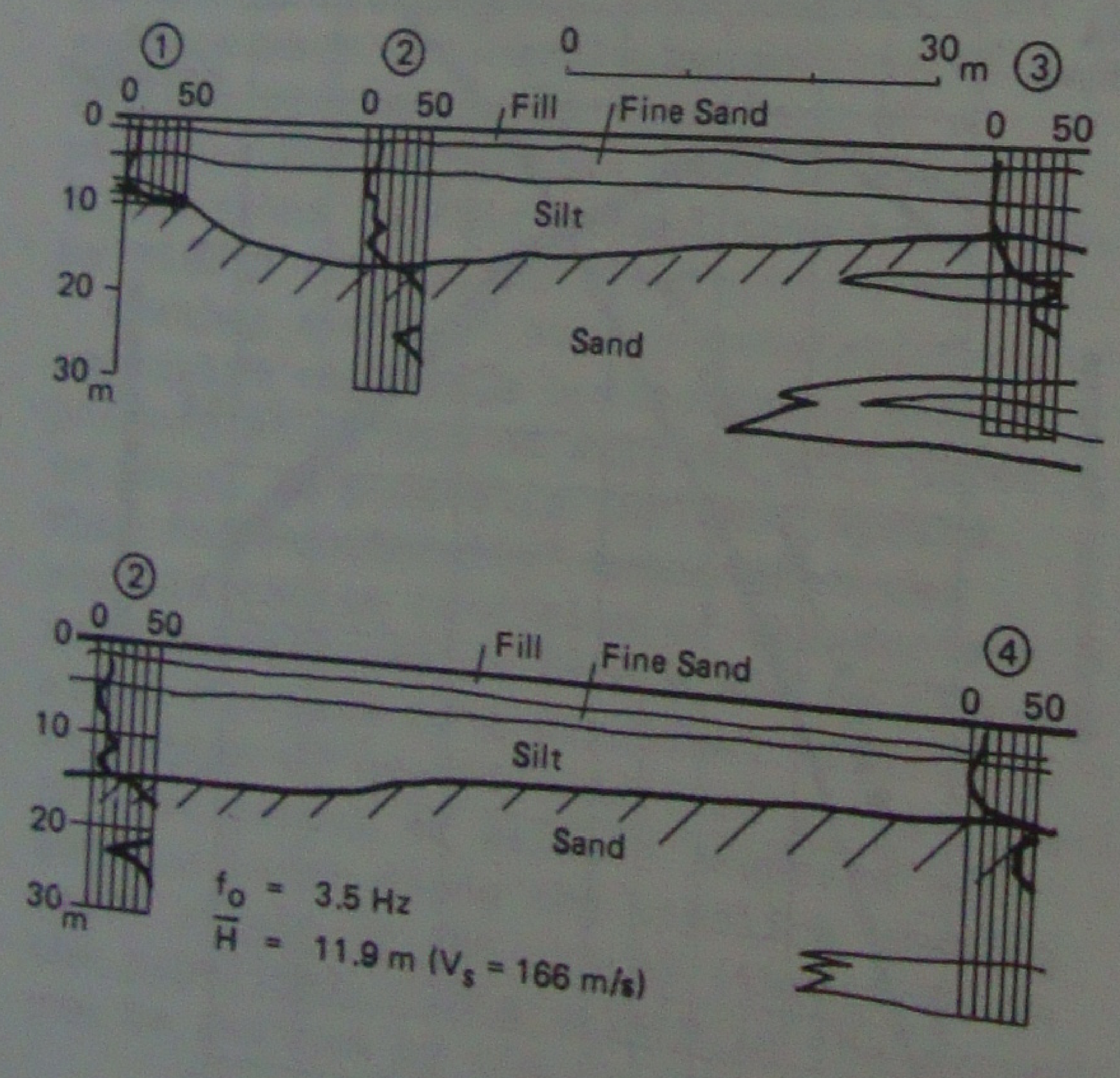
This variation may well be represented by a form of standard deviation, σ_{SD}, of the distribution of displacement response although the variable T or the subsequent value of S_D is not exactly randomly distributed along the horizontal axis of coordinate. In this paper, this standard deviation is defined as the non-uniformity index, NI.



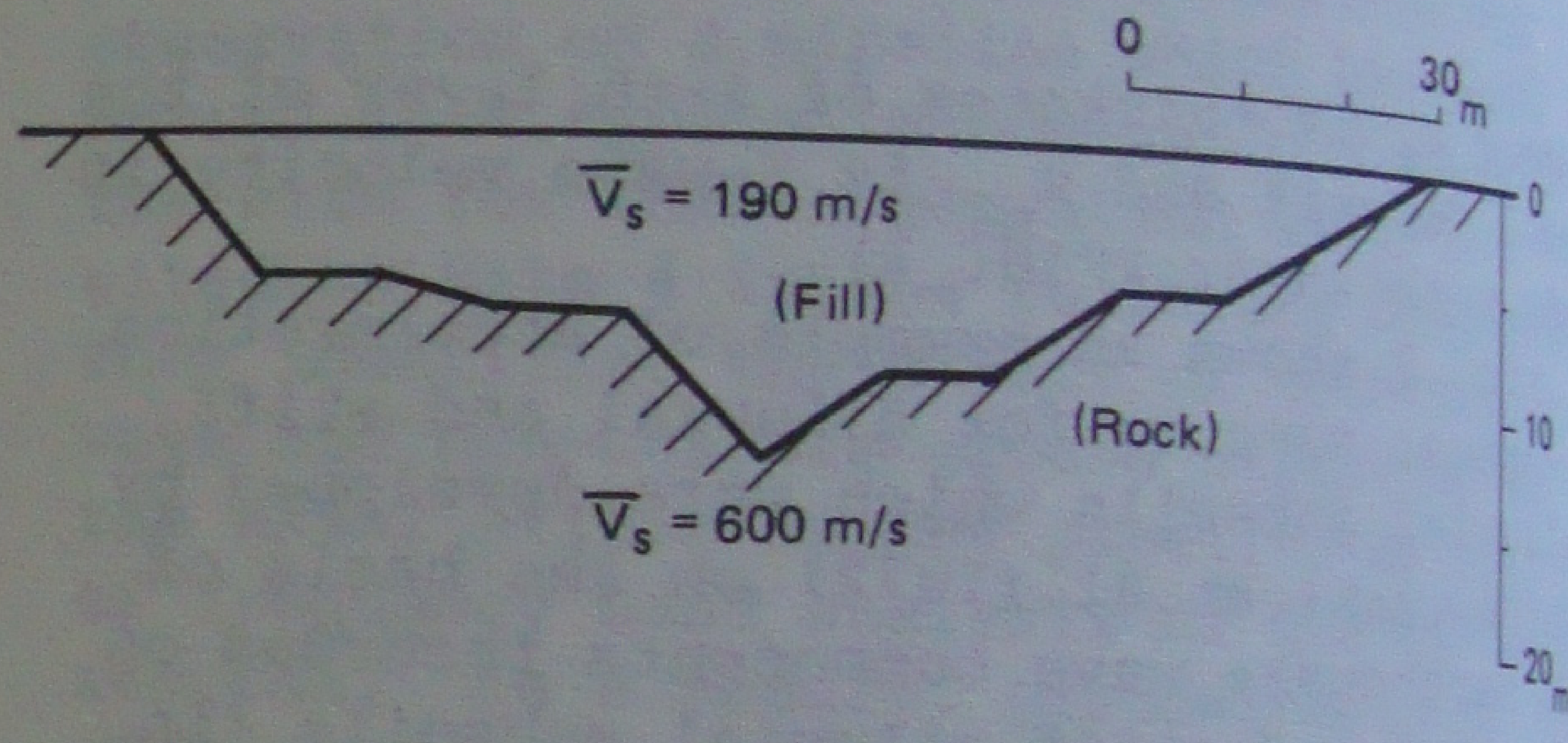
a. Site 1 (YOKOHAMA)



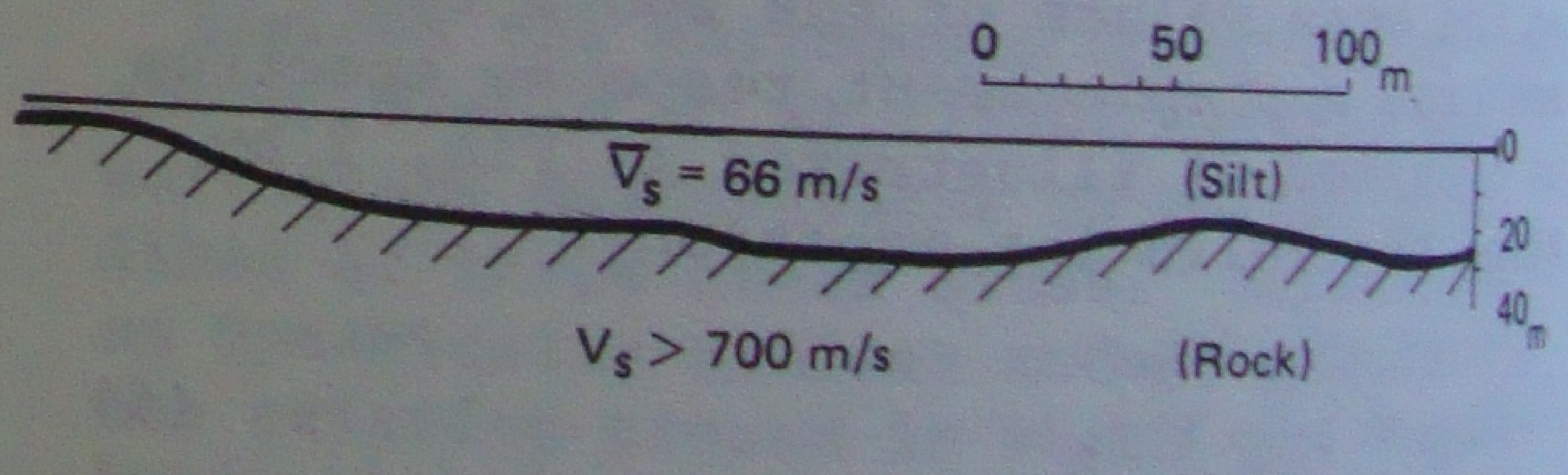
b. Site 2 (SŌKA)



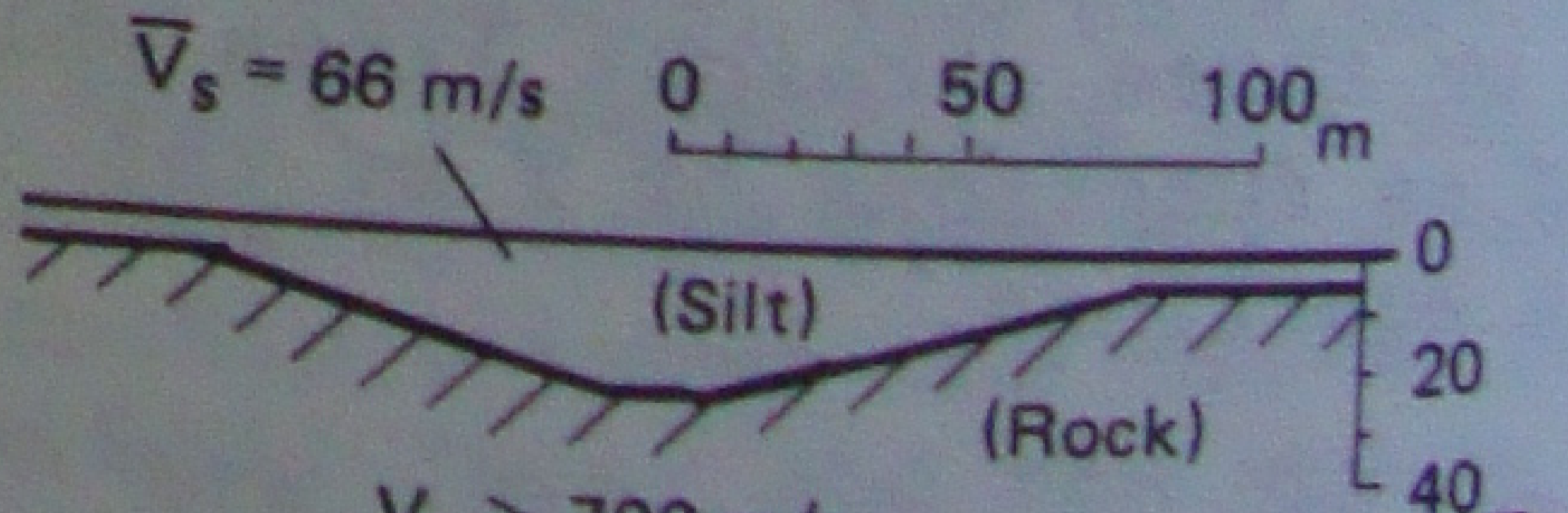
c. Site 3 (ŌMORI)



d. Site 4 (NANKŌ-DAI)



e. Model A (SHIOGAMA)



f. Model B (IDEALIZED)

Fig. 3 Soil profiles and ground conditions for four observation sites and two model grounds (Site 1-3: after Nishio et al.1980, Site 4: Nishio and Tsukamoto 1985, Model A, B: Nishio et al.1983)

3.2 Non-uniformity indices for four observation sites and two model grounds

Earthquake observations on actually buried pipelines have been carried out at four locations by the present author and his colleagues (Nishio et al.1980, Tsukamoto et al.1984, Nishio and Tsukamoto 1985) and model experiments were also conducted by the same investigators (Nishio et al.1983) by considering dynamical similarity to the existing surface soil deposit.

The soil profiles of the four observation sites and the two grounds for model experiments are shown in Fig. 3. Each site can be approximately regarded as consisting of a homogeneous soil deposit having a common modulus of rigidity throughout the deposit since the SPT N-value is very small throughout the entire depth of the deposit and its deviation is also very small. Above all, the ground for Model A showed an extremely low as well as uniform rigidity throughout the surface deposit while its base rock showed a very high rigidity, in contrast. The ground for Model B is not an actually existing one but an imaginary (idealized) one considering abrupt change in the depth of surface deposit; the same rigidity of surface layer as that for Model A ground was given to the Model B ground. The base, or bottom, of each surface layer can be determined at the upper boundary of the shaded areas in Fig. 3 where SPT N-value or shear wave velocity shows distinctly higher value than the upper layer.

The average shear wave velocities in the surface layers of Sites 1-3 were determined from the equation, $Vs = 4f_o\overline{H}$, where f_o is natural frequency based on microtremor measurement and $\overline{H}$ is average depth of the surface layer which is measured on each soil profile in Figs. 3a - 3c. The shear wave velocity for Site 4 was determined by the actual measurement (both PS logging and Rayleigh Wave Technique were used). That for the modeled grounds was also determined by the actual measurement.

Then the non-uniformity index (NI) can be determined by the procedure described below.

First, several sample points are located on the cross section of a surface layer at approximately equal intervals; it is important to take almost the same interval for all the sites so that the non-uniformity could be properly discriminated between different sites; in this case, about 10m for the sampling interval was adopted. Then, the depth of surface layer at each sample point H_j is measured (see Fig. 4). From this value of H_j and the value of V_s already known, the natural period T_j for the j-th sample point is determined by using the equation

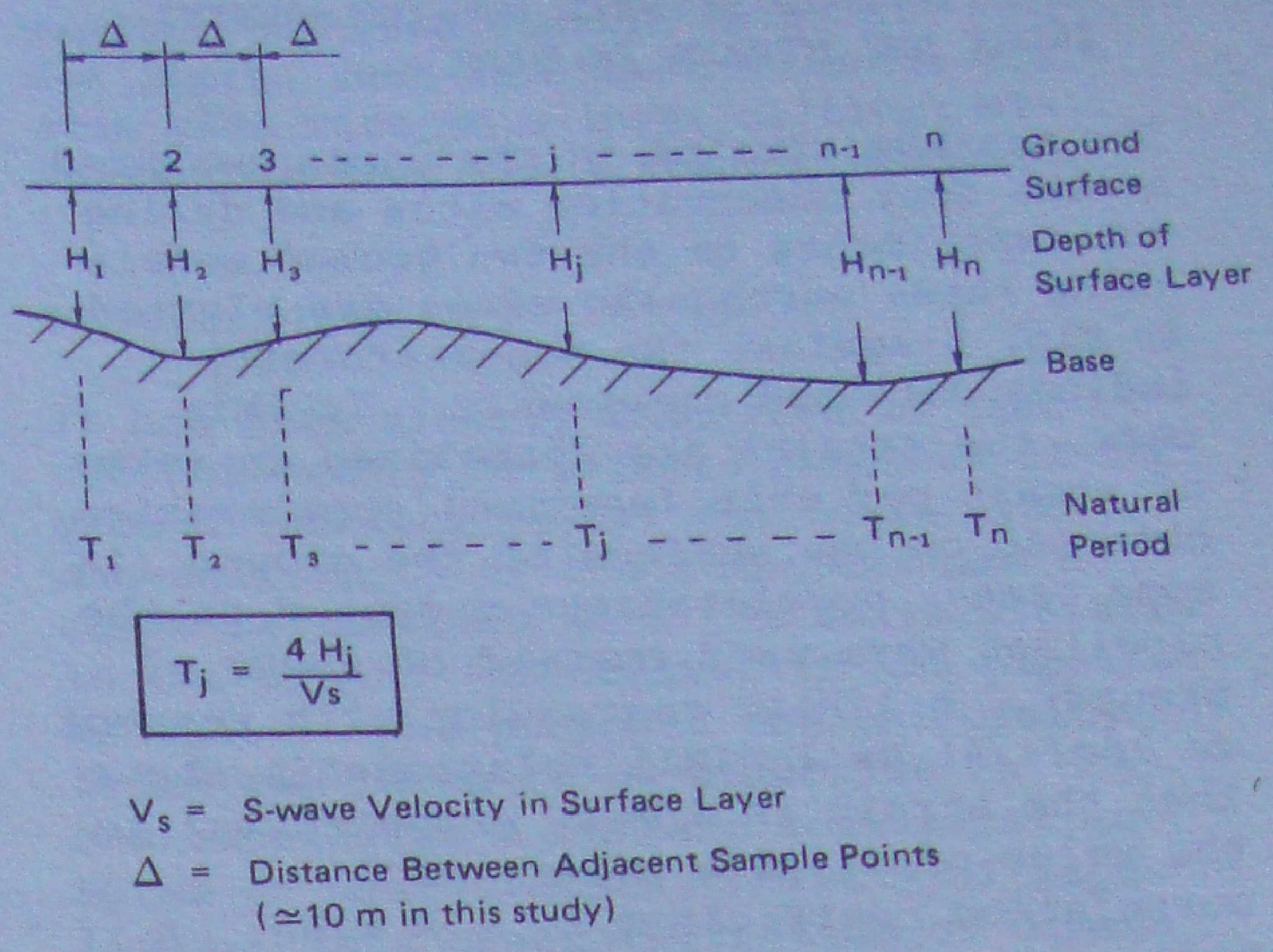


Fig. 4 Concept of determining natural periods for a site on the basis of soil profile data (This example is for the case where the surface layer is homogeneous with respect to rigidity in terms of V_s)

$$T_j = \frac{4H_j}{V_s} \qquad (6)$$

Then, the response displacement of the surface layer at the j-th sample point, S_{Dj}, is determined referring to a displacement response spectrum such as shown in Fig. 2 or given by Eqs.(5).

Finally, the non-uniformity index for the site is calculated from the following equation.

$$NI = \sqrt{n\sum_{j=1}^{n} S_{Dj}^2 - (\sum_{j=1}^{n} S_{Dj})^2}\,/n \qquad (7)$$

where n is the number of the sample points. This equation is exactly of the same form as that defining the standard deviation of a statistic variable.

The above procedure was applied to the six surface layers, shown in Fig. 3, and the following values were obtained.

Site 1, NI = 0.114 [cm/100 gal]
2, 0.031
3, 0.110
4, 0.091
Model A, 1.330
B, 1.242

4 RELATIONSHIP BETWEEN NON-UNIFORMITY INDEX AND STRAIN IN PIPE

The maximum strains in the pipes measured at the four observation sites and during the experiments on the two ground models using three earthquake waves are plotted in Fig. 5 against the non-uniformity indices obtained previously. In this case, the strains are normalized in terms of strain per unit (maximum) acceleration observed on the surface of the ground (in some cases, accelerations measured on the pipelines were used instead of those of ground). A linear regression with respect to log(ε/A) vs log(NI) relationship shows that the strain is almost proportional to the value of NI with a very high correlation coefficient of r = 0.88. A wide scattering of the data implies that seismic response of the surface layer (therefore strain in the pipeline) greatly depends on the frequency characteristics of the incident earthquake wave which greatly varies depending upon focal mechanism, focal intensity, focal depth and distance, properties of earth's crust through which the wave propagates, and so forth, for each earthquake event. In order to take into account this variation of seismicity, a line for a probability of exceedance of 5%, as an example, is indicated with a broken line in Fig. 5.

In spite of the above scatter of the data, a positive correlation between strain and non-uniformity index can be recognized from Fig. 5.

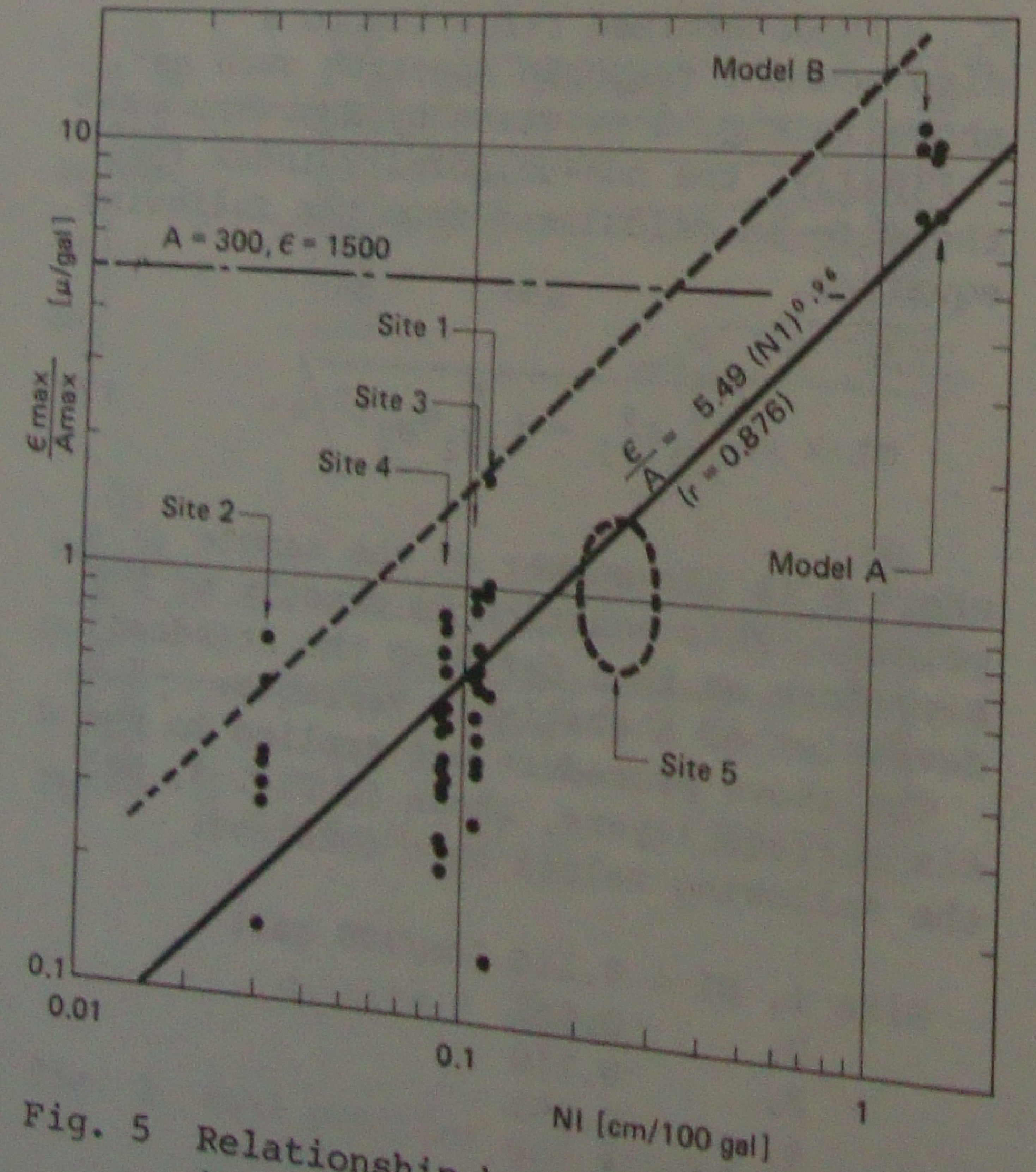


Fig. 5 Relationship between NI and strain in pipeline

5 DISCUSSIONS

5.1 Comparison with the data obtained at another observation site

Although a high correlation between strain and NI-value has been demonstrated in Fig. 5, it is desirable that some more data are added to Fig. 5 so that the certainty about this correlation could be increased. For this purpose, an information being obtained at another observation site (to be called Site 5 in this paper) will be helpful.

The present author and his colleagues have put a new earthquake observation system into operation at Site 5 since April, 1986, and a few earthquake records have been obtained. However, the ground structure at this site is a little complicated and some more soil investigation should be made in order to determine the reliable NI-value for the site.

In spite of the above circumstances, the data could be expected to be centered around the zone indicated with a closed broken line in Fig. 5. This fact will ensure the previously recognized positive correlation between the stress in a buried pipeline and the degree of non-uniformity of a ground which has been defined by the lateral variability of response characteristics of a surface soil layer as the non-uniformity index, NI.

5.2 Comparison with a stochastic approach to seismic strain in ground

The spatial variation of ground motion was discussed by Harada and Shinozuka (1986) on an assumption that horizontal displacement u(x) constitutes a homogeneous, one-dimensional stochastic field with zero mean and a variance σ^2_u, and they showed that the possible maximum strain in the ground is proportional to the quantity σ_u. Moreover, by applying their method to a lateral soil layer which assumes a realistic physical properties as well as dimensions that are stochastically distributed along the horizontal axis(x), they showed that the maximum strain in the ground is mainly controlled by the spatial variability of ground's predominant frequency while the contribution of relative displacement due to propagating wave is not very significant.

It will be naturally understood that both the standard deviation of ground displacement σ_u, which is related to the spatial variation of predominant frequency of ground, and the standard deviation of displacement response σ_{SD} (= NI) based on the laterally varying natural period applied to an average response spectrum are representing the same concept in principle.

A very similar idea has been applied by Nishio (1981) to the invenstigation of the relationship between damage ratio and ground condition for the damage to buried pipelines during a recent disastrous earthquake in Japan. He assumed that the seismic displacement of an arbitrary point on the ground takes a random value according to a normal distribution with a standard deviation σ. The pipeline damage was assumed to occur when the relative displacement between two points on the ground at a certain distance exceed pipeline's ability of absorbing the longitudinal displacement. This relative displacement of ground can also be shown to take the value according to a normal distribution with a standard deviation of $\sqrt{2}\sigma$. Based on this assumption, he could describe very well a positive relationship between ground condition, piping material (or type of fitting) and damage ratio.

All studies that have been related above – namely, studies based on earthquake observations, stochastic theory and damage investigation – are based on almost the same concept of lateral variation in seismic response of surface soil layer. Only this concept will give a good reason to the seismic damage to buried pipelines in apparently non-discontinuous ground observed during the past strong earthquakes in Japan.

5.3 Estimation of damage susceptibility based on NI

Conventional thread jointed steel pipes are known to break at the threaded part when tensile strain at non-threaded part has scarcely reached the yield strain of steel because of a reduced sectional area at the threaded part; the yield strain of common mild steel is less than 1,500 μ. So, ε_{max} = 1,500 can be regarded as a kind of critical strain with respect to seismic damage. This fairly great strain will be caused by a very intense earthquake associated with a great acceleration such as A_{max} = 300 gal. The value of $\varepsilon_{max}/A_{max}$ by assuming the above values is indicated in Fig. 5 with a chain line. The point of intersection of this line and the broken line indicates that the pipeline's susceptibility to damage becomes significant as the NI-value of the ground exceeds a value of about 0.3. If a more intense earthquake ground motion is to be considered, this critical NI-value will be smaller. A less ductile material for piping such as asbestos cement will also give rise to a lower critical NI-value than that for a steel pipeline.

6 CONCLUSIONS

It has been clearly demonstrated that non-uniformity of seismic response of the ground (surface layer) due to lateral non-uniformity of its structure has a close correlation with the seismic strain in the ground (therefore, in the pipeline as well). The proposed non-uniformity index was shown to be effective in characterizing a surface soil layer in terms of damage susceptibility of pipelines. This characterization of damage susceptibility will help to plan the earthquake countermeasure effectively for underground lifeline systems such as water distribution networks, sewage systems and gas distribution networks.

The data which will be obtained at Site 5 where an earthquake observation is presently being carried out are expected to reinforce the above conclusions.

Since earthquake observations are considerably expensive as well as hard to carry out because of the difficulty of finding out suitable locations, numerical simulations on seismic responses of existing surface soil layers and subsequent axial strains in the ground or a pipeline buried in it will be an effective alternative means of verifying further the relationship between the proposed NI-values and the seismic strain in the pipeline.

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