Dynamic Soil Structure Interaction

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Chapter 1 : Introduction

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Preface

Years over a half-century have passed since an investigation of Dynamic Soil-Structure Interaction (SSI) was started, and the SSI has been attracting the researcher's interest up to the present.

Today, many researchers around the world are making their efforts on research and development concerning the SSI, and the efforts will be continued in the future.

This lecture starts from the basic outline of the SSI and comes into phenomena caused by the SSI, and then numerical procedures are explained. Finally, a practical seismic design analysis of structure is presented.

Contents of Lecture Note

Publications for SSI

(1) Richard F.E., J.R. Hall and R.D. Woods: "Vibrations of Soils and Foundations",
Englewood Cliffs, NJ, Prentice-Hall, 1970

(2) Wolf J.P.:"Dynamic Soil Structure Interaction",
Englewood Cliffs, NJ, Prentice-Hall, 1985

(3) Wolf J.P.: "Soil Structure Interaction Analysis in Time Domain",
Englewood Cliffs, NJ, Prentice-Hall, 1988

(4) Wolf J.P.: "Foundation Vibration Analysis using Simple Physical Model",
Englewood Cliffs, NJ, Prentice-Hall, 1994

Reference for Vibration of Soil Strata

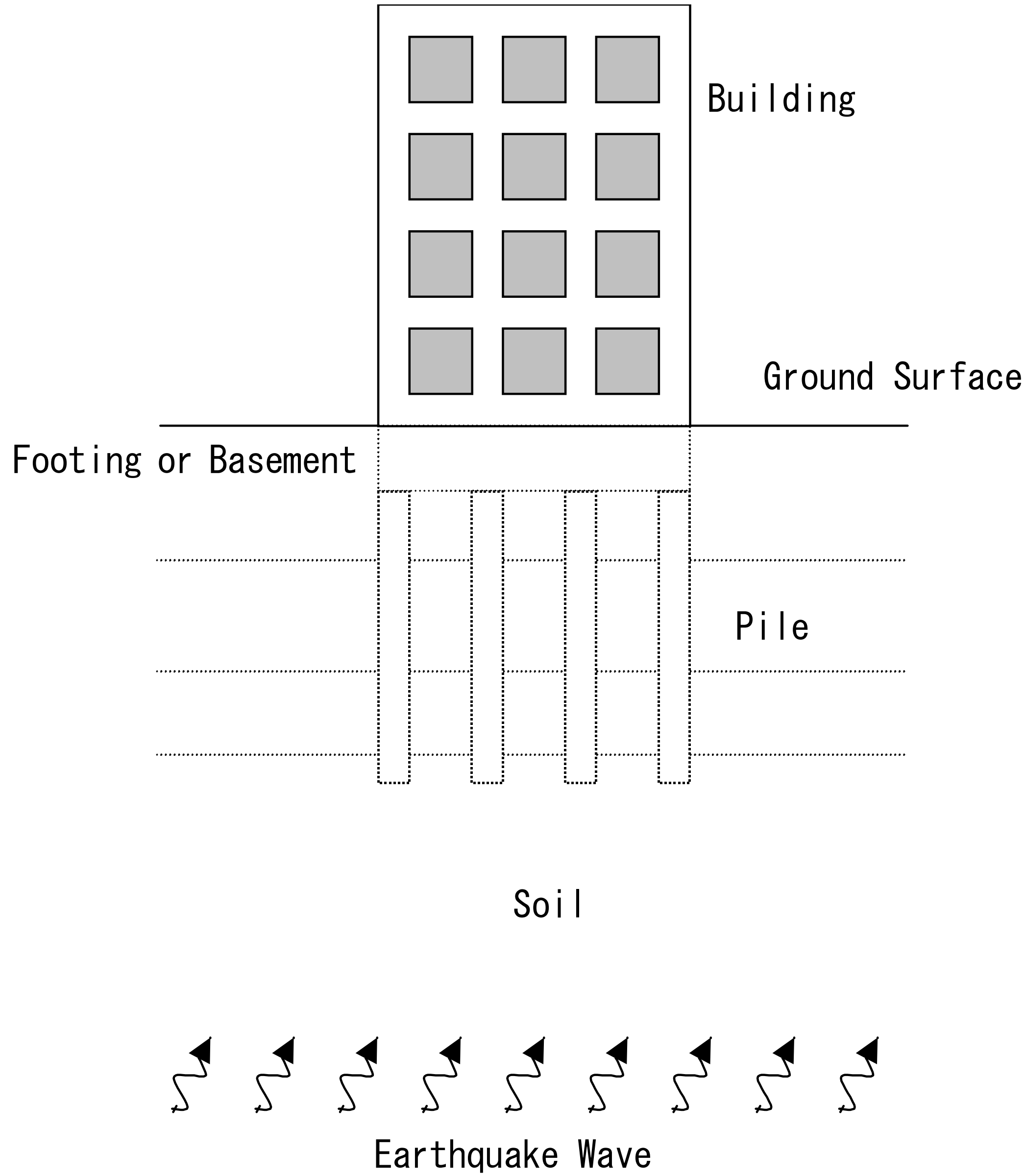
Schnabel P.B., Lysmer J. and Seed H.B.:

"SHAKE A COMPUTER PROGRAM FOR EARTHQUAKE RESPONSE ANALYSIS OF HORIZONTALLY LAYERED SITE", Earthquake Engineering Research Center, No. EERC 72-12, Dec. 1972, College of Engineering, University of California, Berkeley, California

1. Introduction

When an earthquake occurs, the building and the ground vibrate with influencing each other.

This phenomenon is called " Dynamic Soil Structure Interaction", and is recognized as being very important for seismic design of structure.



1.1 Basic Outline of Soil Structure Interaction

1) Role of Foundation

(1) Under normal condition

- Supporting the dead weight and the live load of the building
- Transmitting these loads to the ground.

(2) During an earthquake

- Transmitting the ground motion to the building
- Bearing the building vibrations and transmitting them to the ground.

The ground and the building influence each other through the foundation, and this is called the Dynamic Soil-Structure Interaction (hereafter abbreviated to SSI)

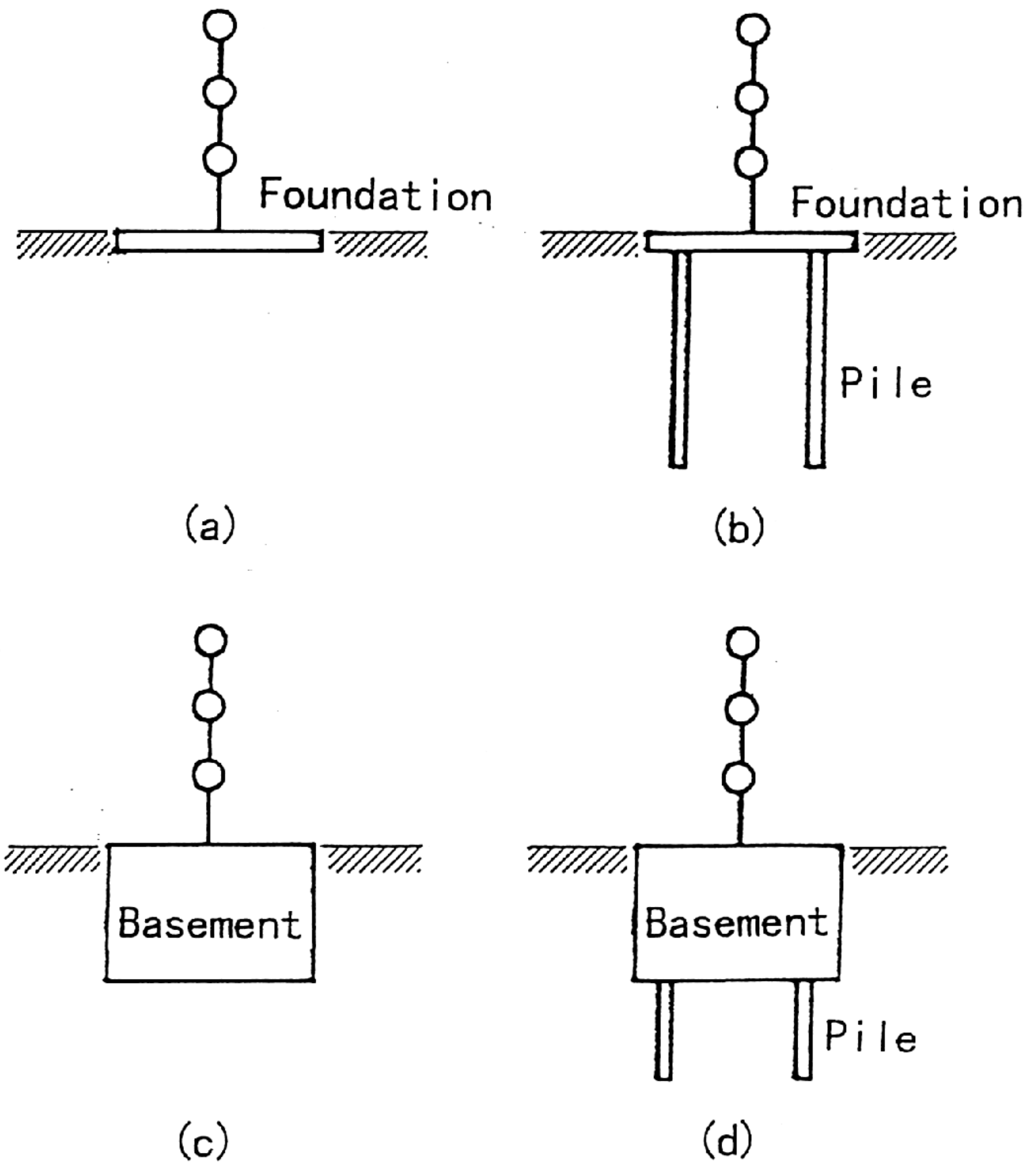
2) Degree of Influence of SSI on Response of Building depends on:

(a) Stiffness of Ground

(b) Dynamic Characteristics of Building itself, that is, Natural Period, Damping Factor

(c) Foundation Types

3) Foundation Type



(a) Spread Foundation

(b) Pile Foundation without Basement

(c) Basement without pile

(d) Basement with piles

The position where the SSI takes place.

(a) Spread Foundation:

through the bottom surface of the foundation

(b) Pile Foundation without Basement:

through the pile foundation

(c) Basement without pile:

not only at the bottom surface,

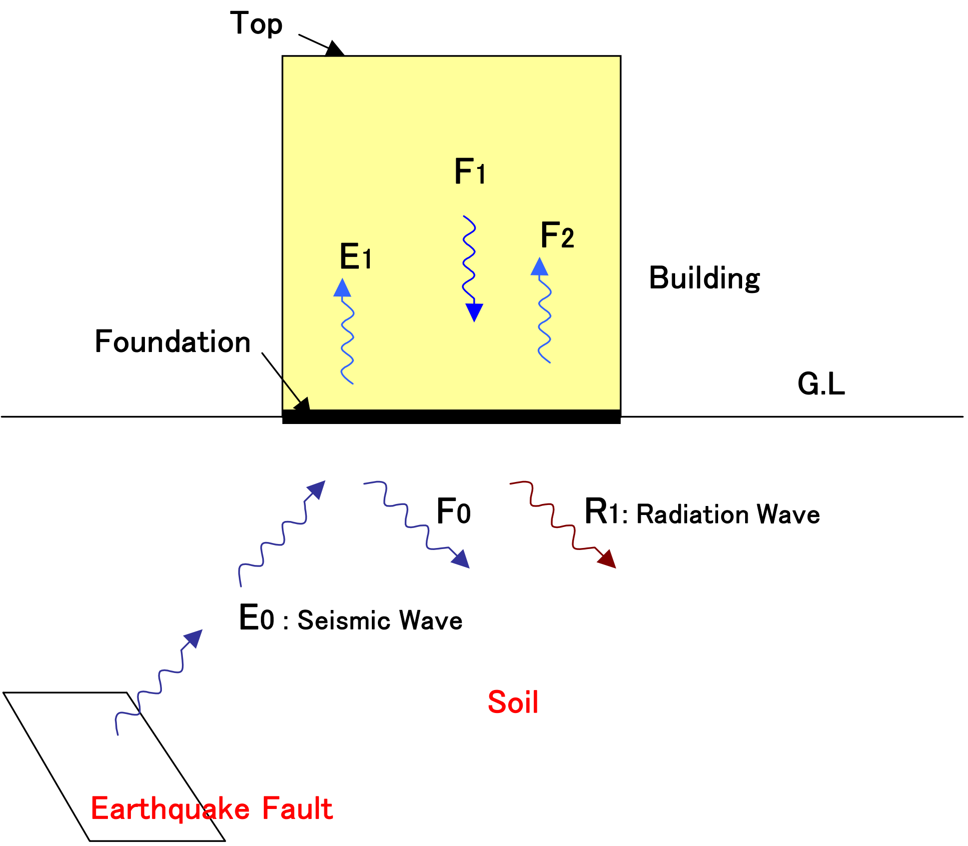
but also on the side wall surface

(d) Basement with piles:

through the basement surface and the piles

The influence of the SSI becomes remarkable and more complicated, as the amount of contact area between the ground and the foundation increases sequentially in the order from (a) to (d).

4) Interaction between Ground and Building during Earthquake

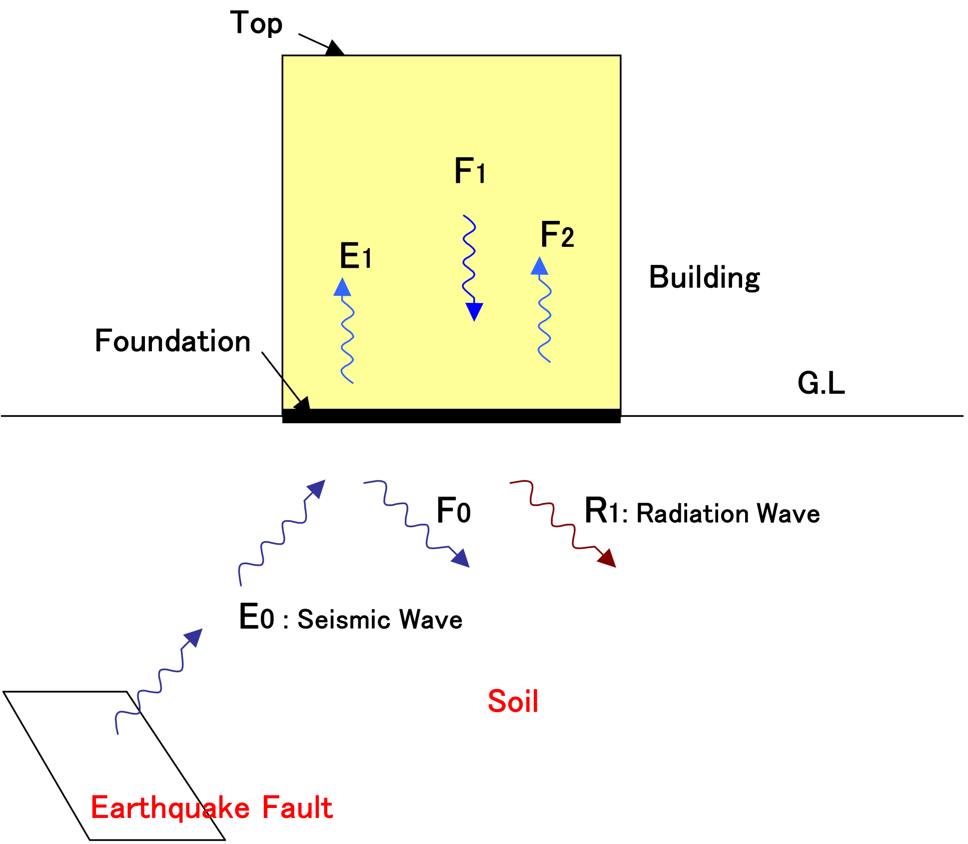


When the seismic wave E_O generated by the earthquake fault reaches the bottom of the foundation, they are divided into two types:

the waves E_1 entering into the building

and the waves F_O being reflected back into the ground.

The wave E_1 are called the transmission waves, while the wave F_O are called the reflection waves.

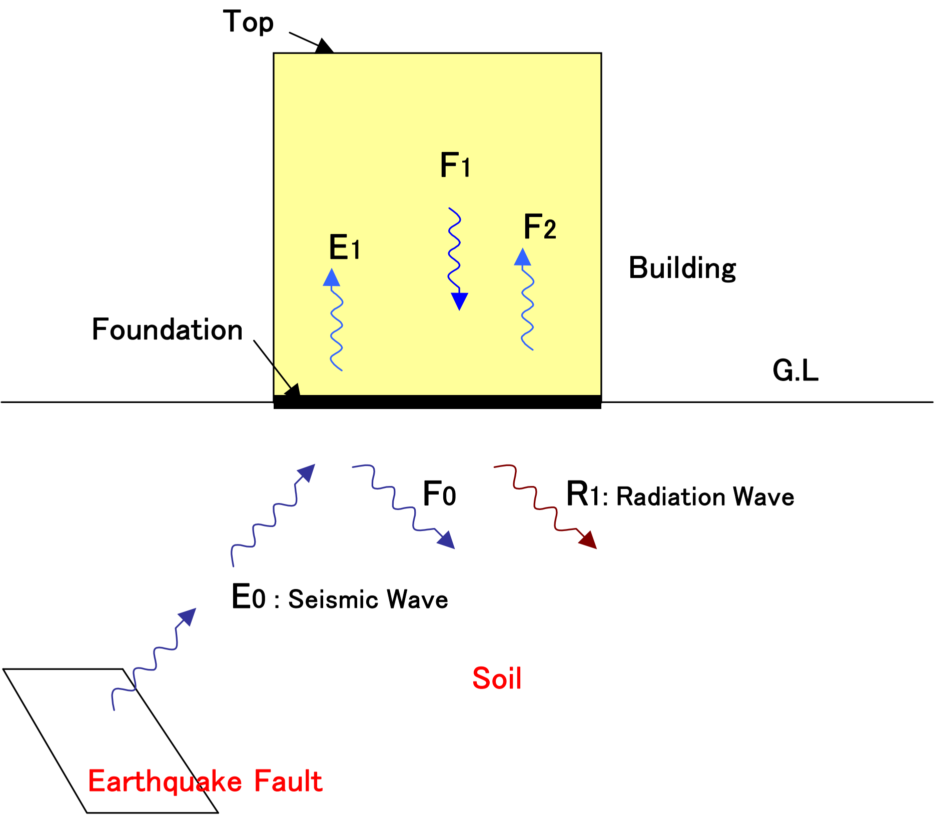


And then, they are reflected at the top and travel back down to the foundation. Here, a crucial phenomenon occurs for consideration of the SSI.

When the waves that are reflected at the top of the building and traveling downwards (*F_1* in this figure) reach the foundation, a part of them is transmitted into the ground, while the rest is reflected back again and once starts to move upwards through the building.

The transmission waves *E_1* entering into the building travel towards the top of the building with subjecting the building to vibration.

The former waves, escaping into the ground, are called " Radiation waves".



When the amount of these radiation waves are small, the seismic waves once transmitted into the building continue to remain in the building, and the building continues to vibrate for a long time.

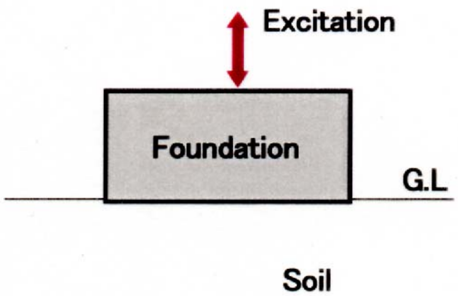
The apparent vibration condition becomes the same that of the small damping of the building.

The damping caused by escape of the seismic waves, which have been transmitted into the building, back into the ground is called " Radiation Damping".

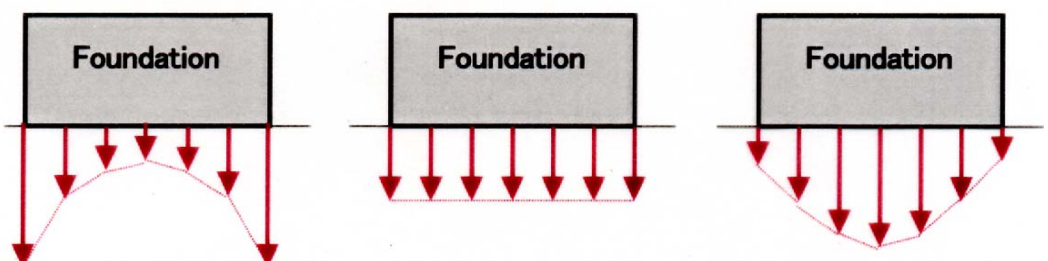
1.2 Radiation Waves

The seismic waves escaping back into the ground are called radiation waves, and these waves cause radiation damping.

When the building foundation is forced to vibrate vertically, a stress called " Contact Earth Pressure" is caused at the boundary between the bottom surface of the foundation and the ground.



The distribution of this contact earth pressure over the bottom surface of the foundation is called " the Contact Earth Pressure Distribution".



(a) Rigid (boussinesq)

(b) Uniform

(c) Parabolic

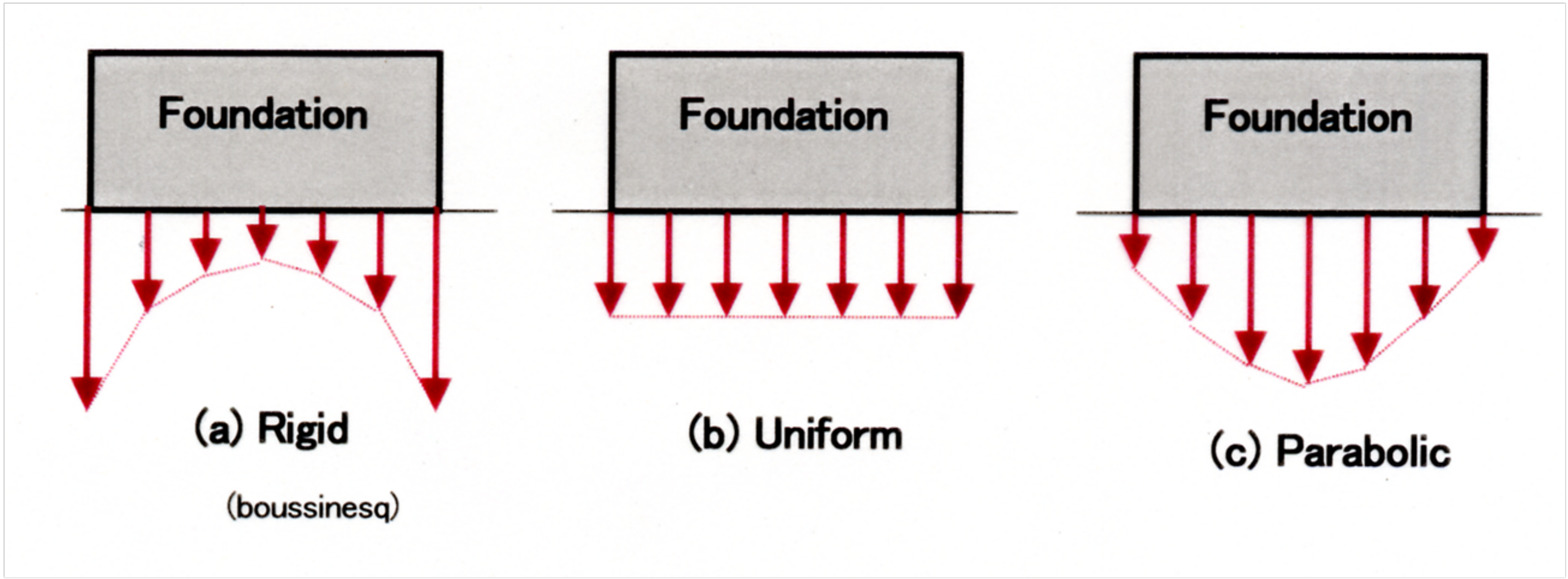
Three types of distribution (Rigid, Uniform, and Parabolic distribution as shown) are observed.

The types of the distribution are altered depending on :

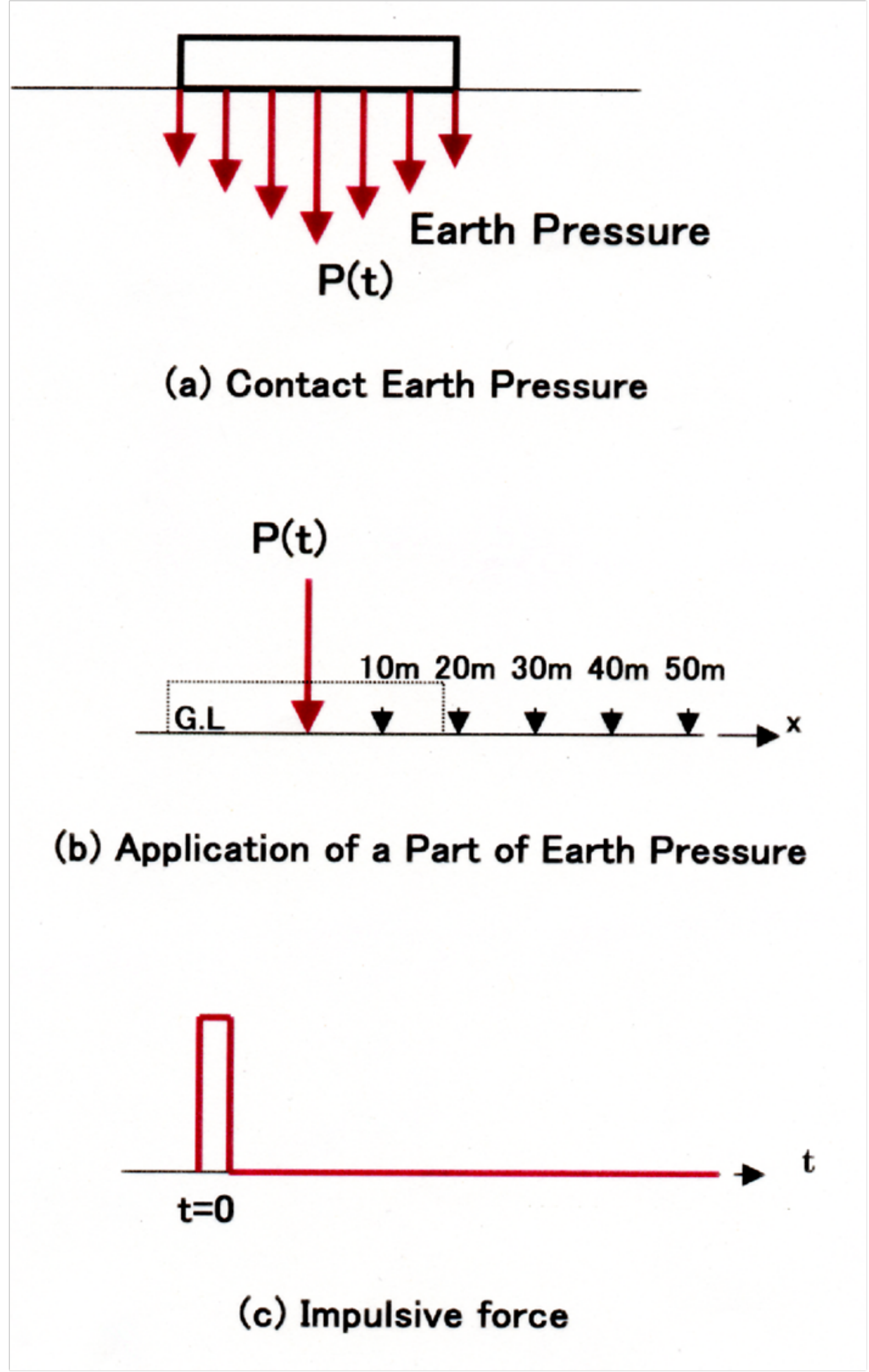
(a) foundation rigidity

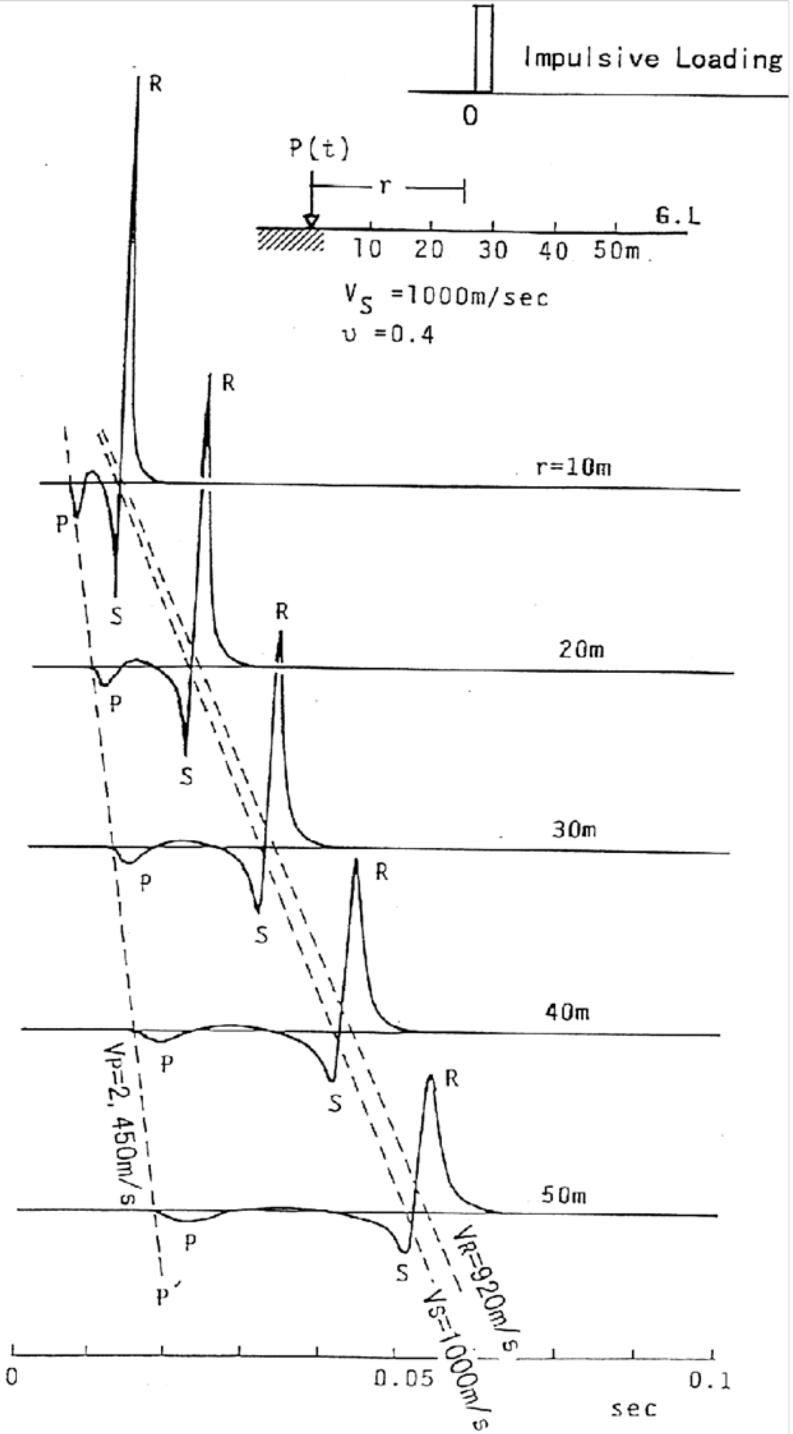
(b) soil classification

(c) soil nonlinearity.



When a part of the vertical contact earth pressure is picked out and applied on the ground surface, the vertical displacements of the ground surface can be calculated.



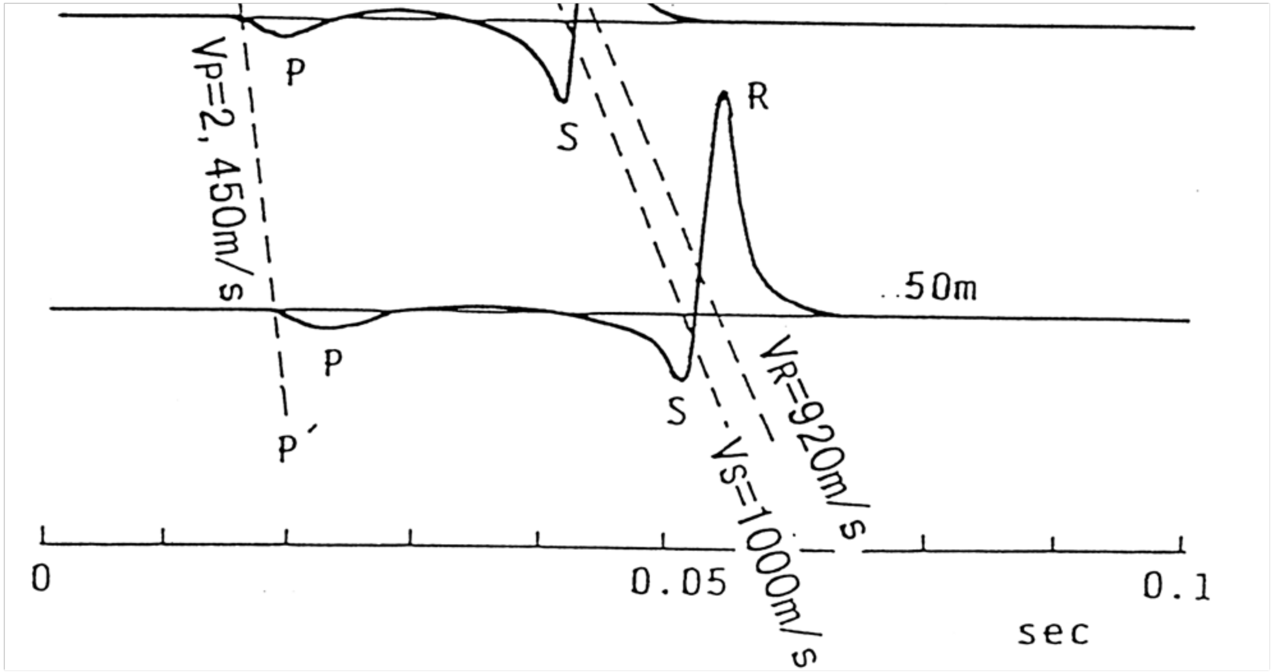


At a distance of 10 m from the point where the impulsive force is applied, the first peak denoted by P is appeared, and two peaks denoted by S and R are appeared following the P.

With increasing distance from the force application point, these peaks appear at an increasingly later time, and it can be seen that these peaks are propagated at a certain velocity.

Connecting the occurrence times of these peaks by straight lines and estimating the propagation velocity from the inclination of these lines.

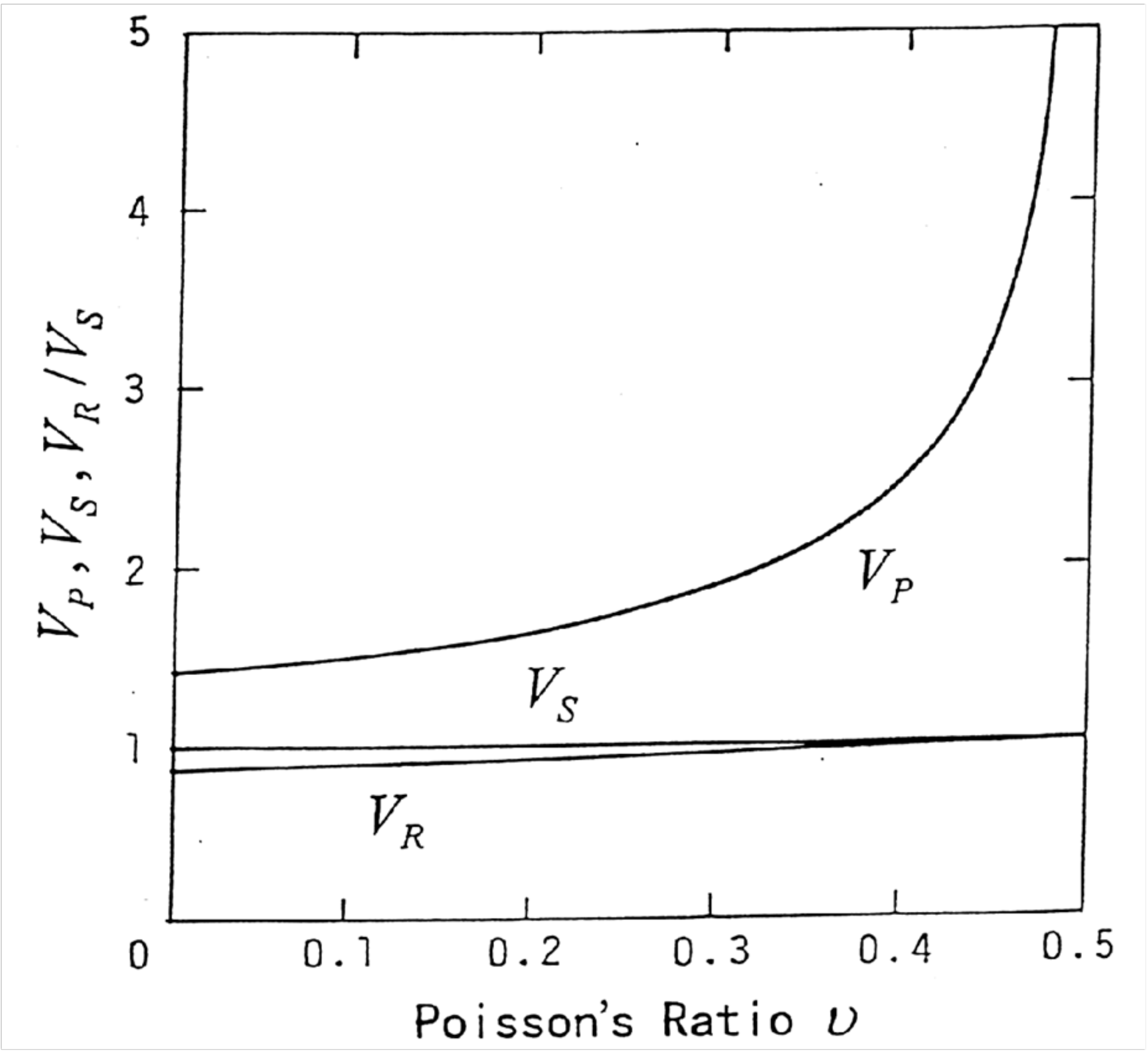
It can be found that the propagation velocity for the peak P is 2450m/sec, that for the S is 1000m/sec, and that for R is 920m/sec.



The seismic waves consist of ;(a) P-waves , (b) S-waves and (c) Rayleigh's waves called " Surface Waves".

These peaks correspond to the P-waves, the S-waves, and the Rayleigh's waves.

In the case of a homogeneous half space, the relation of propagation velocity between these waves is decided only by the Poisson's ratio of the ground as shown in the Figure.



The Poisson's ratio of the ground is normally in the range of 0.4 to 0.5.

The propagation velocity of the Rayleigh's waves is about 10 % lower than that of the S-waves.

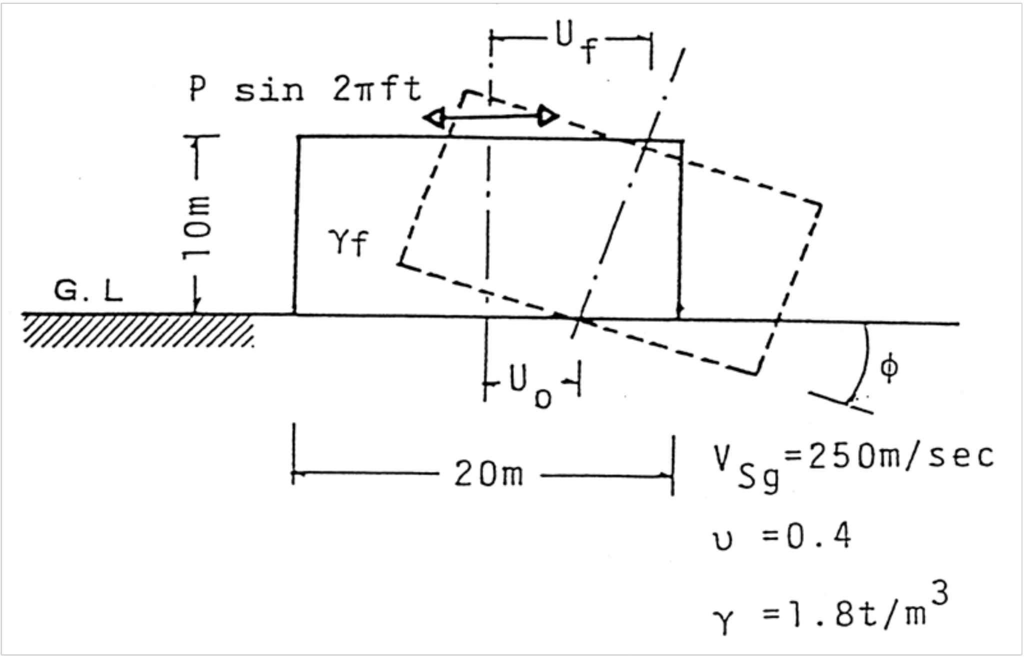
The vibration of energy to the ground is transmitted by P-waves, S-waves, and Rayleigh's waves, and in the case of a homogeneous half space, the contribution ratio of the energy transmission for the these waves are 7%, 26%, and 67% respectively for P, S, and Rayleigh's waves.

So, the calculation shows that more than one half of the energy is transmitted by the Rayleigh's waves.

The above explanations with regard to the radiation waves are restricted to a homogeneous half space. When the ground is consists of layered strata, the waves transmitted from the building are reflected at the layer interfaces and are returned to the building. Therefore, the radiation damping becomes normally smaller and the entire phenomenon becomes more complicated.

1.3 Vibration of the Foundation on Ground

The vibration of the foundation is considered for the case when the dynamic force is applied to the top of the foundation on the ground surface.

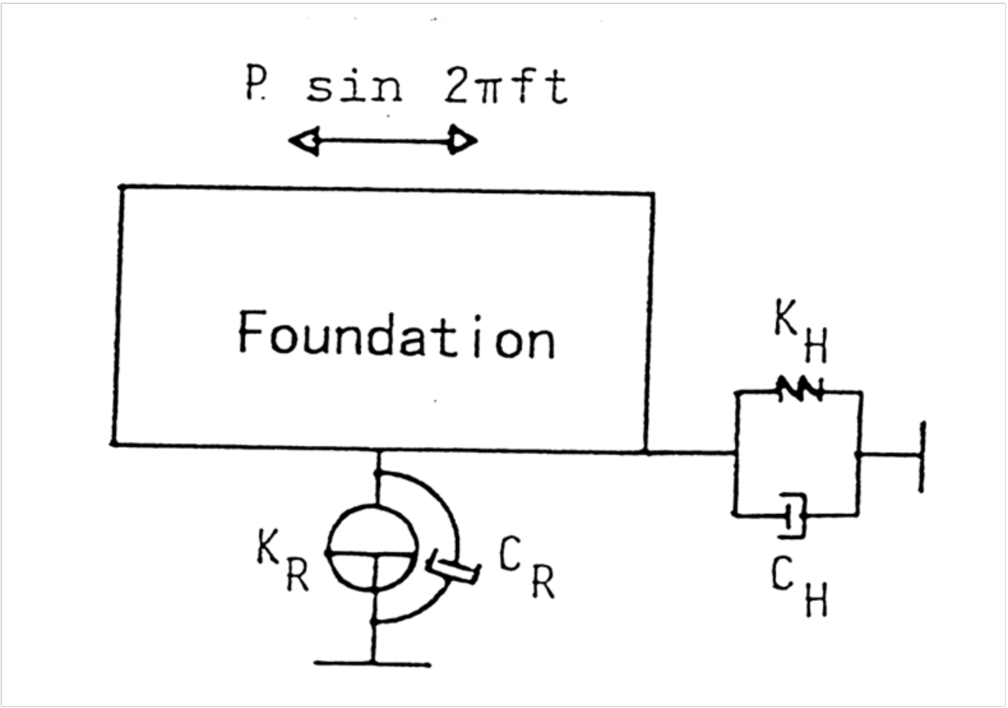


For simplification, it is assumed that the foundation is not deformed locally and that there are no shape changes during the vibration.

When the sine excitation is applied in horizontal direction, the horizontal displacement U_o and the rotation φ occur at the foundation bottom.

Contact earth pressure resisting this displacement U_o and the rotation φ is generated at the interface between the bottom surface of the foundation and the ground surface, and the radiation waves are transmitted to the ground.

When the ground is represented by a spring and a dashpot to resist the displacement U_o and the rotation φ, the numerical modeling for the foundation can be expressed by:

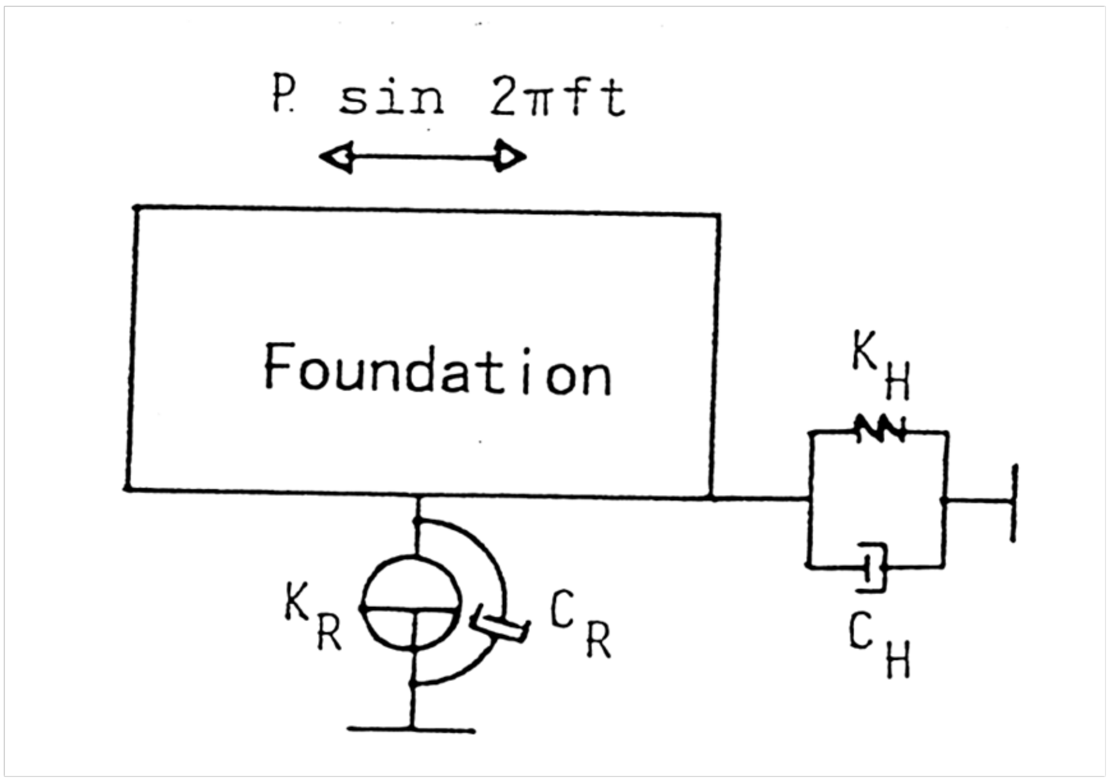


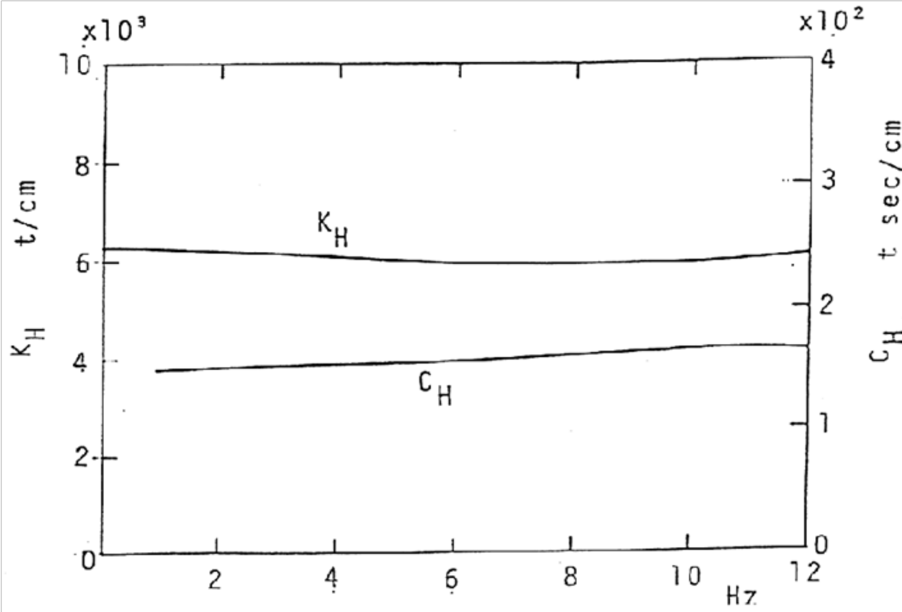
As this foundation has two degrees of freedom in the horizontal displacement and the rotation, this model is called " Sway Rocking Model" , abbreviated to S-R model.

K_H denotes the spring value of the ground resistance regarding the horizontal displacement U_O.

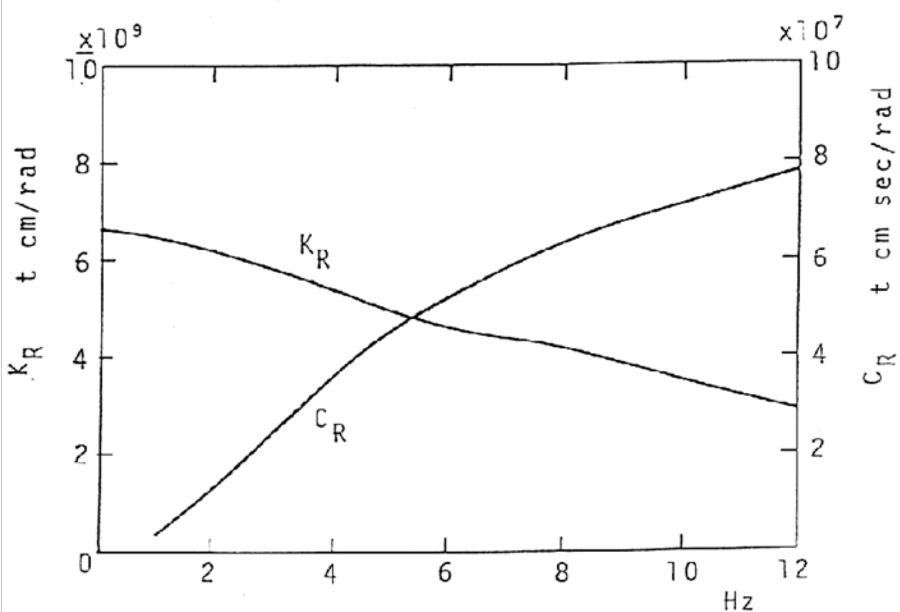
C_H denotes the coefficient viscous damping absorbing energy proportional to the velocity dU_O/dt as the energy is dissipated into the ground by the radiation waves.

K_R and C_R are the same quantities as mentioned above regarding the rotation.





(a) Horizontal

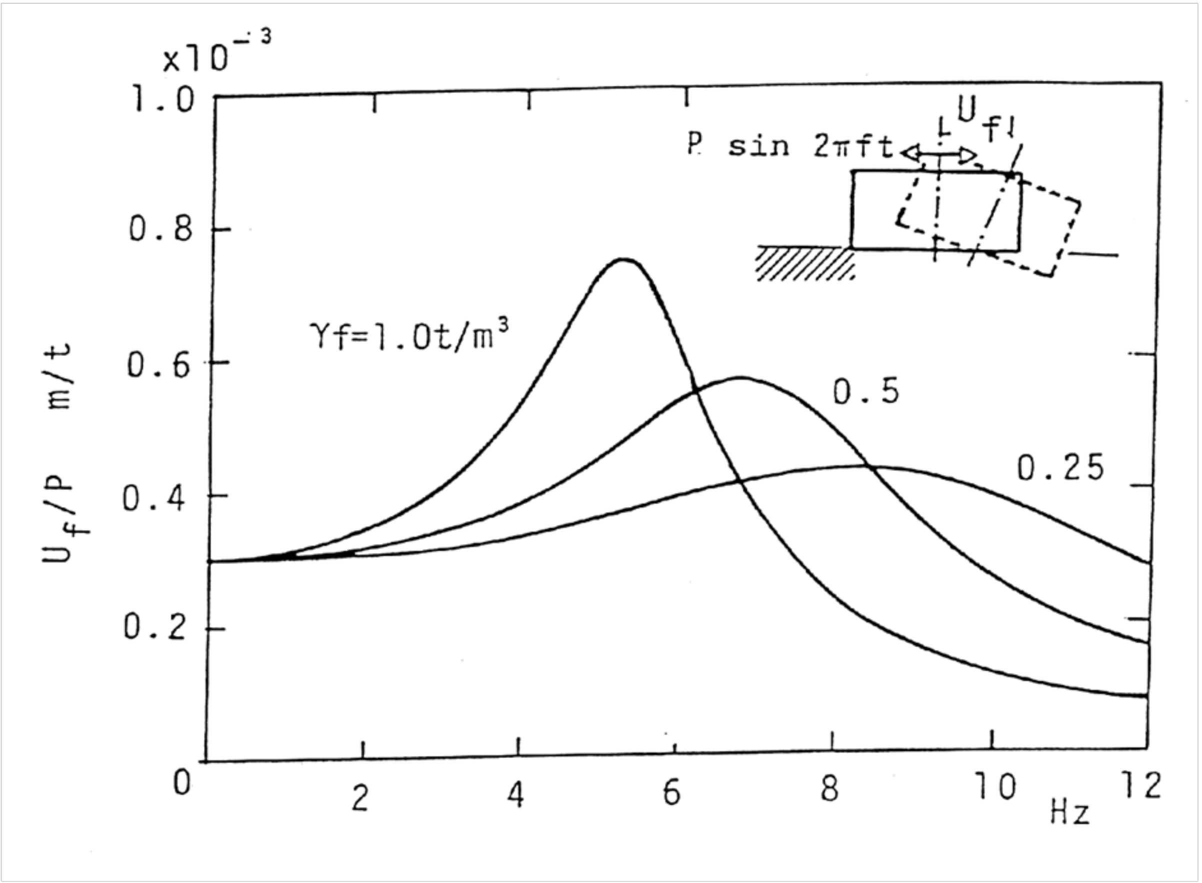


(b) Rotation

The figures show the calculation results for K_H, C_H, K_R and C_R under that the ground and the bottom of the foundation are in perfect contact with each other.

The horizontal spring value K_H and the dashpot coefficient C_H are nearly constant with increase of the vibration frequency.
But, K_R and C_R exhibit remarkable frequency dependency.

The K_R decreases gradually with increasing frequency, and the C_R shows opposite characteristic.



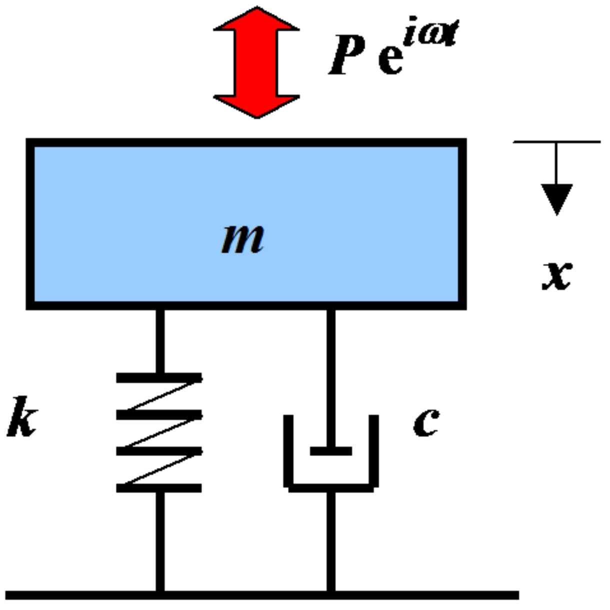
The figure shows the horizontal displacement U_f at the top of the rigid foundation.

The displacements are normalized by the exciting force .

γ_f in the figure indicates the unit volumetric weight of the foundation.

When the γ_f becomes smaller, that is, when the foundation becomes lighter, it can be seen that the peak frequencies (" Resonance frequencies") of the resonance curve become higher, and that the vibration amplitude becomes smaller.

Equation of One Degree of Freedom System



Eq. of Motion: $$m\ddot{x} + c\dot{x} + kx = Pe^{i\omega t} \quad (1)$$

Static (ω=0) Displacement: $$Xs = P/k \quad (2)$$

Natural Circular Frequency: $$\omega_o = \sqrt{k/m} \quad (3)$$

Natural Frequency: $$f_o = \omega_o/(2\pi) \quad (4)$$

Damping Factor : $$h = c/(2m\omega_o) = c/(2\sqrt{mk}) \quad (5)$$

Putting $x = Xe^{i\omega t}$ **and using Eq.(2) to Eq.(4), Eq.(1) leads.**

$$\{1-(\omega/\omega_o)^2 + i2h(\omega/\omega_o)\}X = Xs \qquad (6)$$

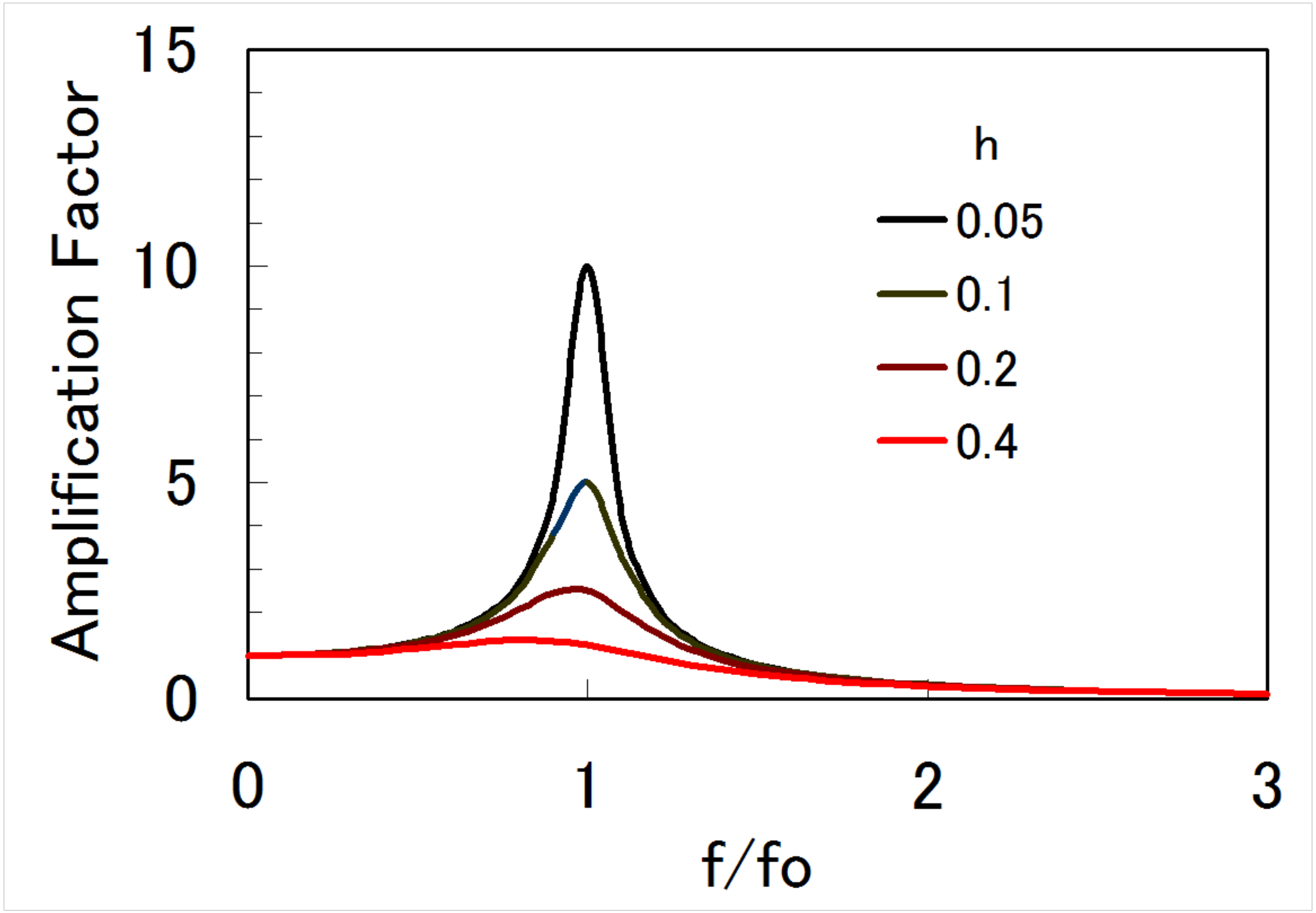
then,

$$|X/Xs| = 1/\sqrt{\{1-(\omega/\omega_o)^2\}^2 + 4h^2(\omega/\omega_o)^2} \qquad (7)$$

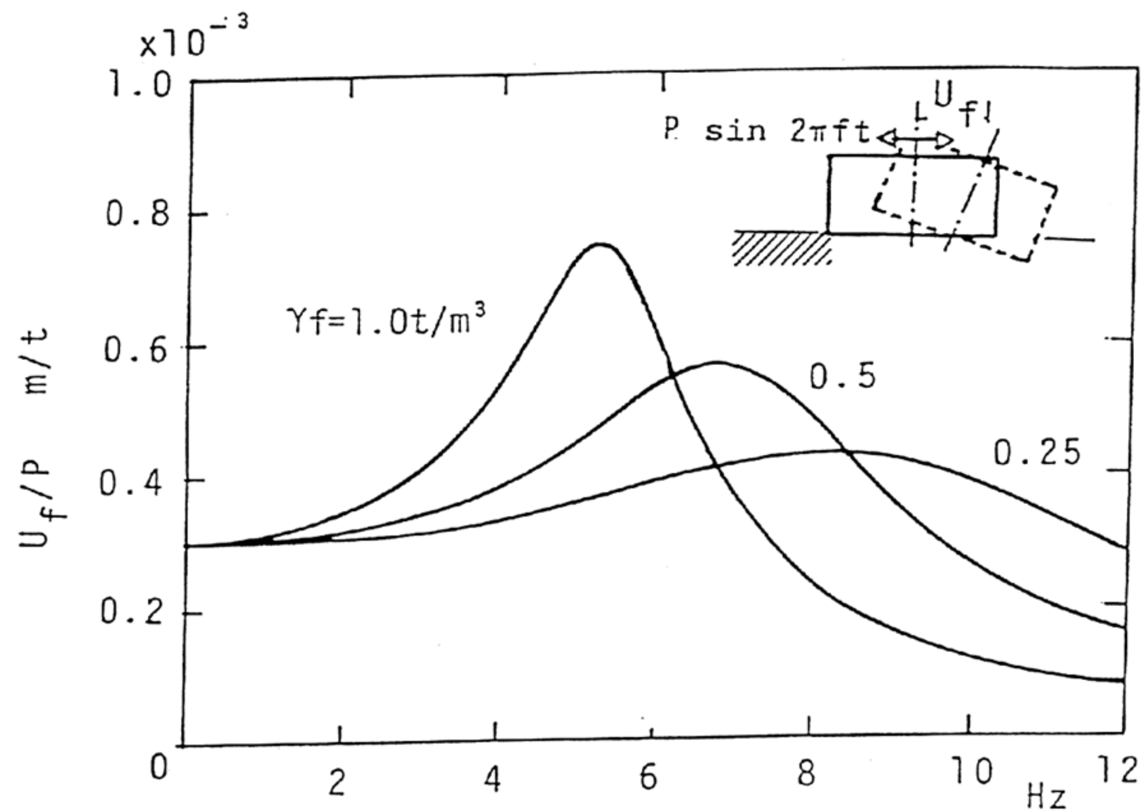
or,

$$|X/Xs| = 1/\sqrt{\{1-(f/f_o)^2\}^2 + 4h^2(f/f_o)^2} \qquad (8)$$

$|X/Xs|$ **is called " Amplification Factor".**

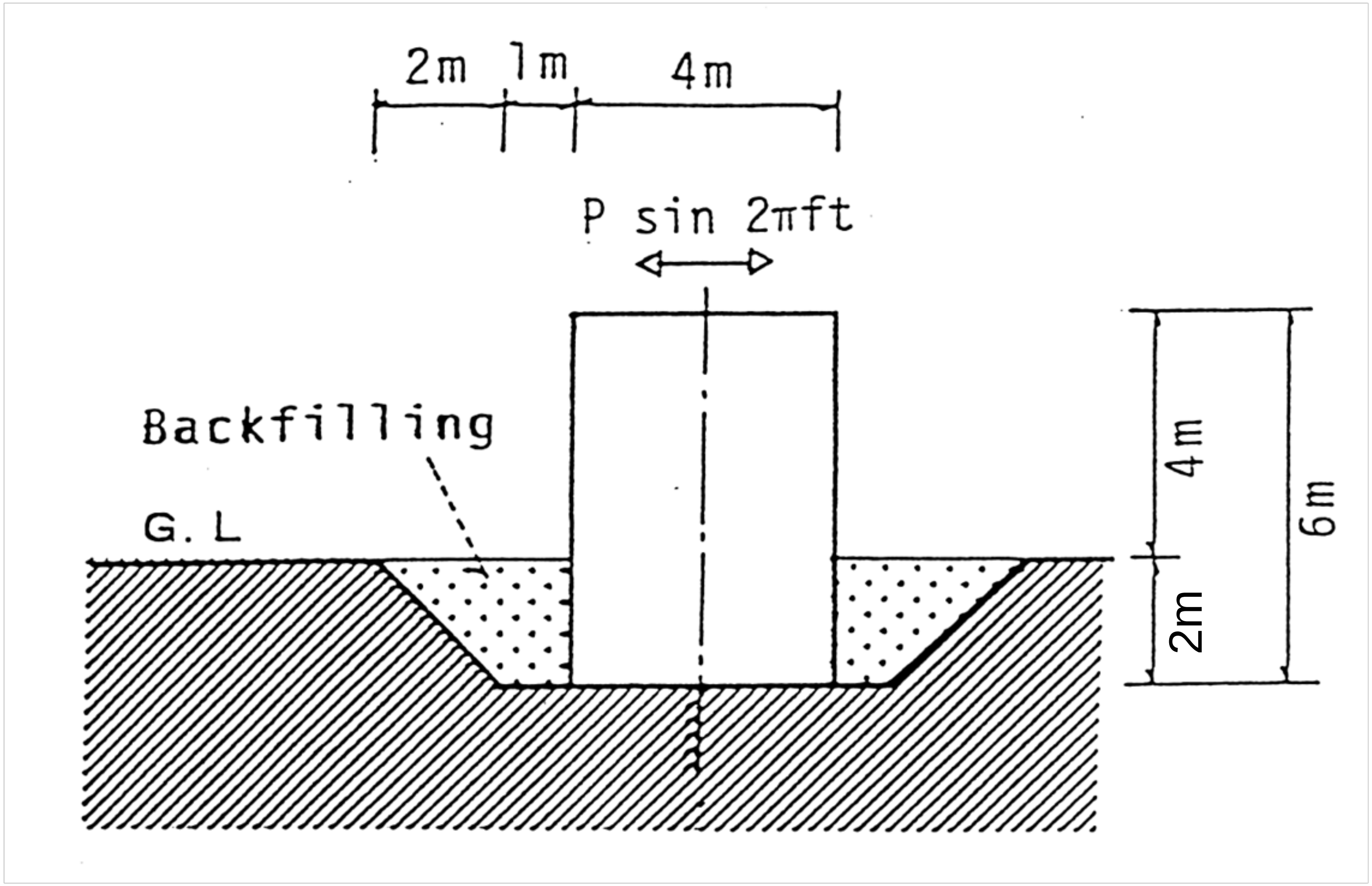


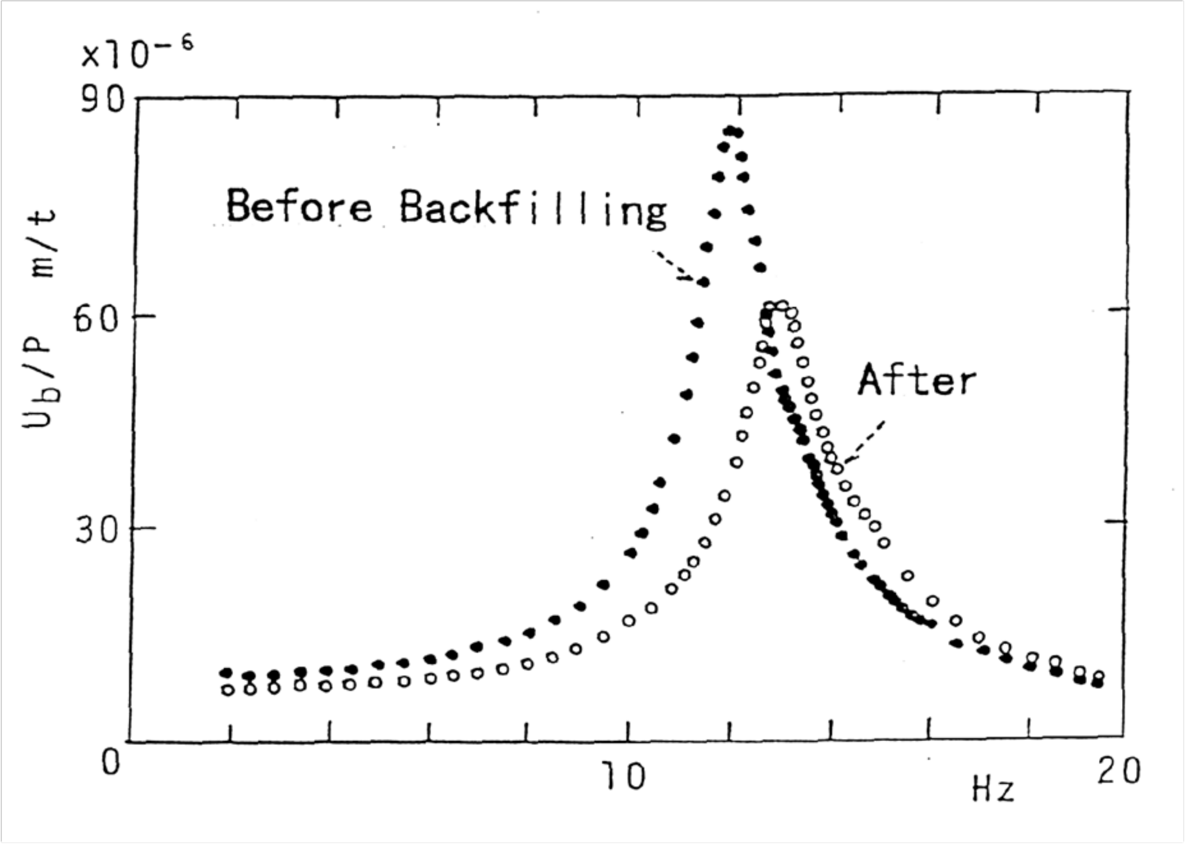
The figure shows the amplification Factor changing the damping factor *h*. The smaller the damping factor, the larger the amplification factor at the natural frequency f_o. (Resonance Phenomena)


x10⁻³
1.0
0.8
0.6
0.4
0.2
0
2
4
6
8
10
12
Hz
U_f/P m/t
P sin 2πft
U_f
γf=1.0t/m³
0.5
0.25

1.4 Effect of Embedding

Let us now consider the SSI when the foundation is embedded. In order to investigate the effect of embedding, forced vibration tests were carried out using a test specimen as shown below.





The figure shows the resonance curve for the displacement at the gravity center of the test specimen before and after backfilling the excavation with sand.

The embedding increases the resonance frequency and that the resonance curve near the peak is not sharp, but rather rounded.

The damping factor is used in vibration mechanics to express the degree of sharpness of this resonance curve.

The damping factor of the test specimen is increased from 5.7% to 6.3% by the embedding effect.

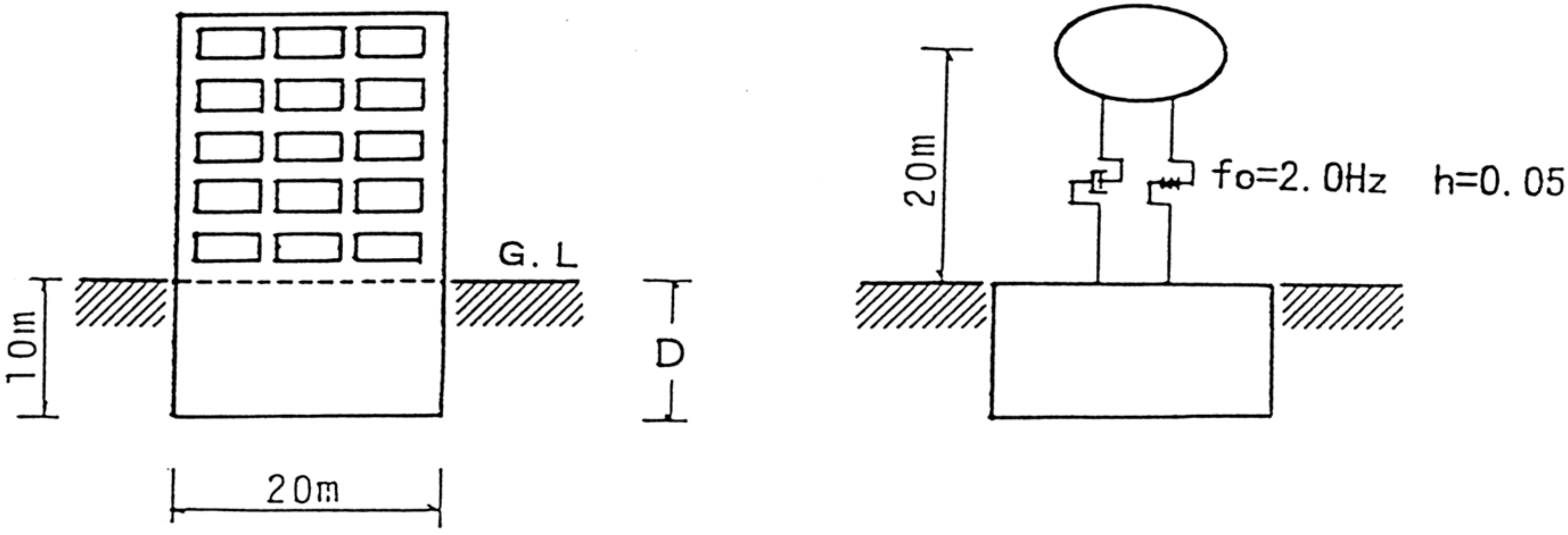
1.5 Coupling System of Building and Ground

When the forces are applied to the building by an earthquake or by means of an exciter etc., the building and the ground vibrate with influencing each other.

This system is called " Coupling System of Building and Ground".

The SSI as treated foregoing connects the building to the ground in this coupling system.

Let us now investigate the influence of the SSI onto the coupling system.

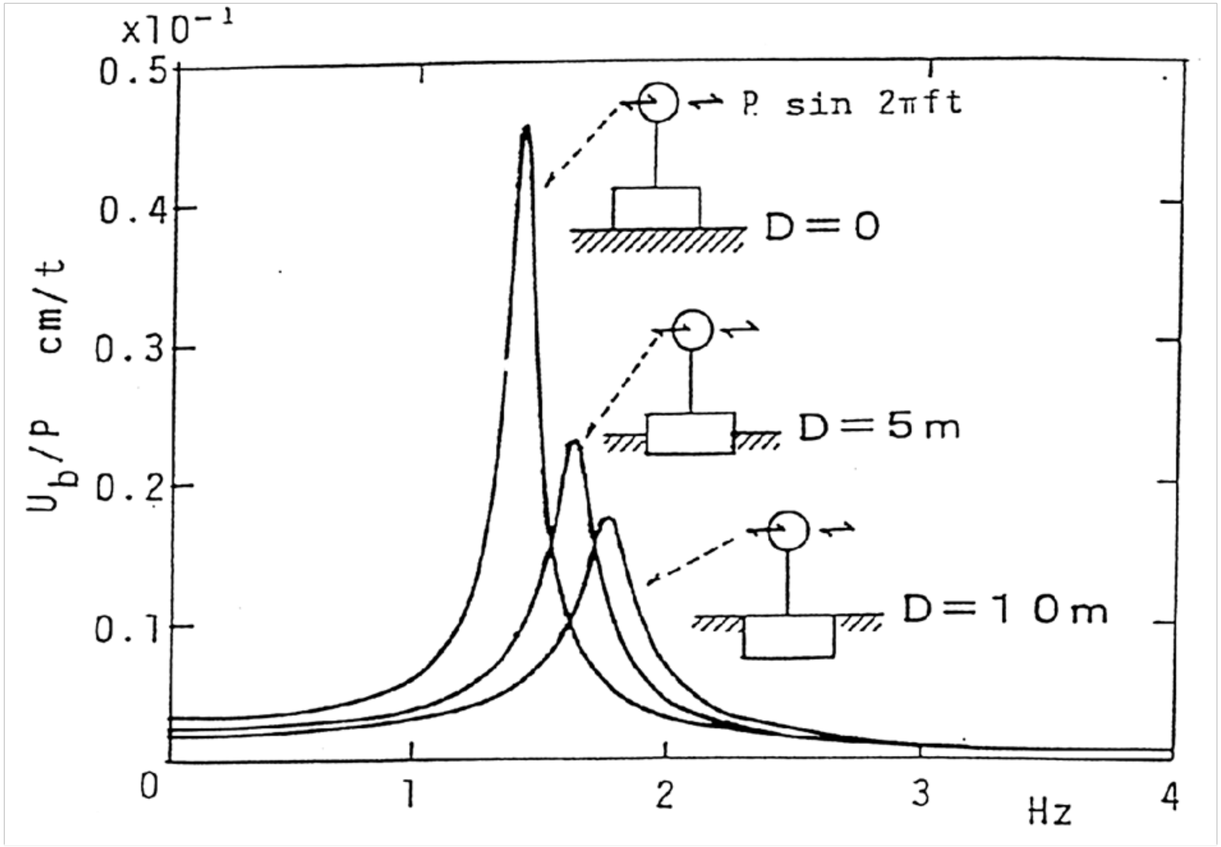


(a) Structure (b) Modeling

This building is represented in simplified form by the spring *K*, connecting the mass point and the basement, and the dashpot *C*.

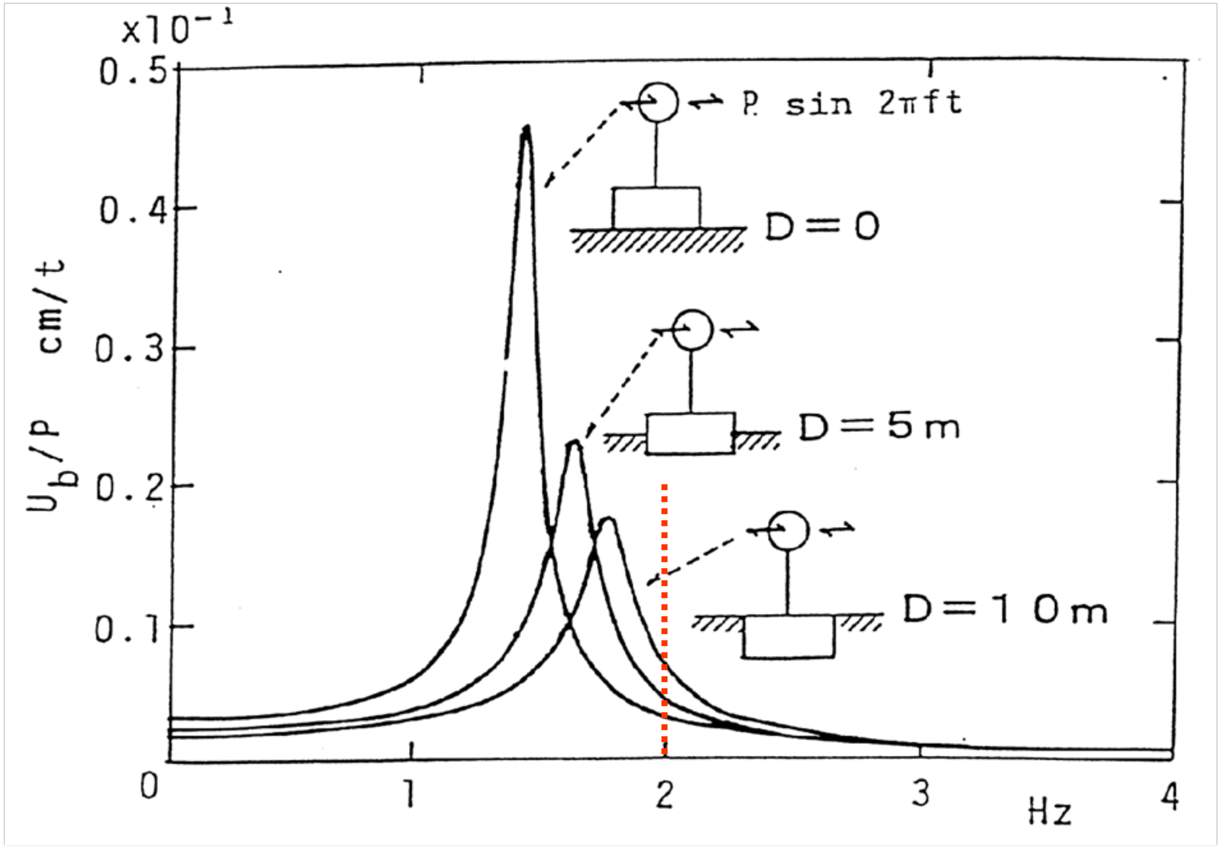
When the basement is fixed, the natural frequency of the building is set on 2 Hz and the damping factor *h* on 5 % .

The basement is assumed as a rigid body with a unit volumetric mass of 0.5 t/m^3, and the ground is homogeneous half space.



The figure shows the calculation results for the resonance curves of the horizontal displacement of the building top when a horizontal excitation is applied at the top of the building. In the calculation, embedding depth of the basement is a parameter.

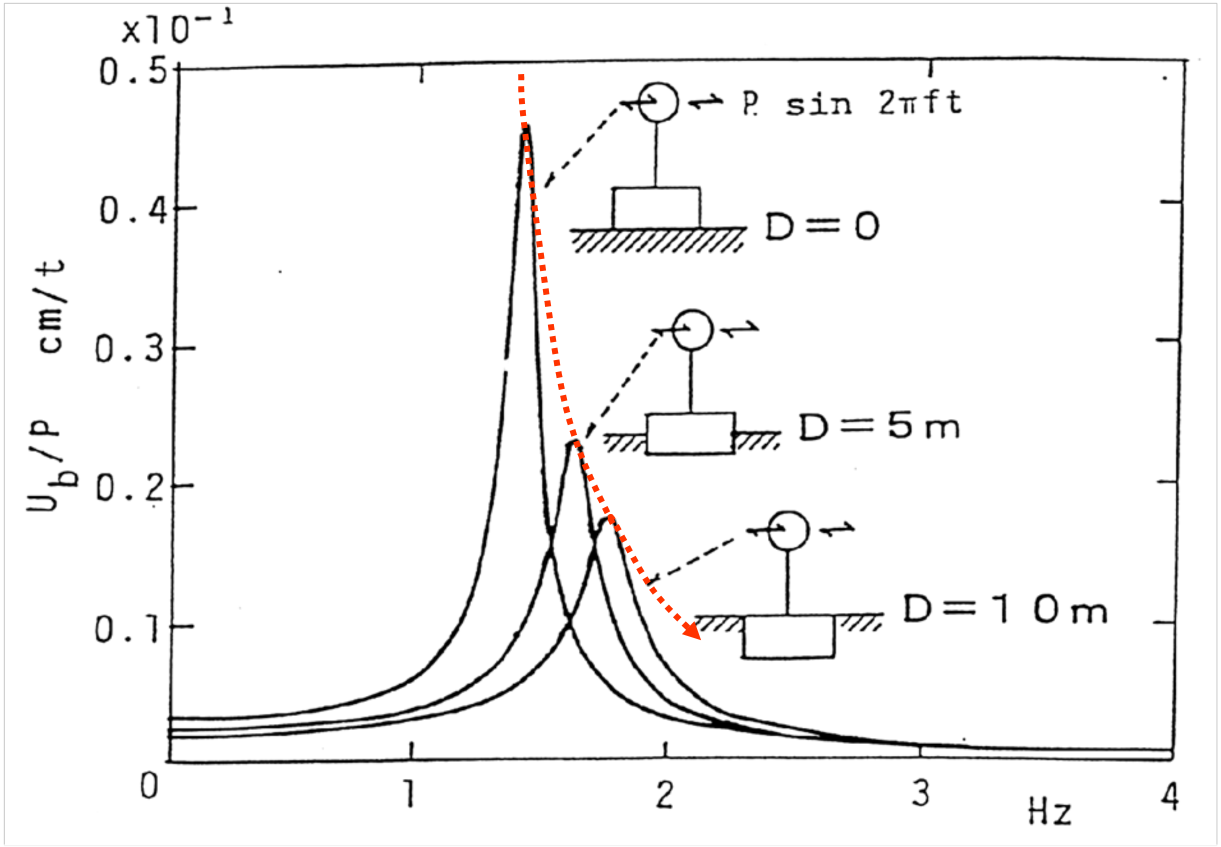
As already described above, the natural frequency of the building itself under the fixed basement condition is 2 Hz.



But, the resonance frequency shown in this figure is considerably lower than 2 Hz.

In earthquake engineering, this resonance frequency is called " the resonance frequency of the coupling system ", and this frequency is always lower in comparison with the natural frequency under the fixed-based condition.

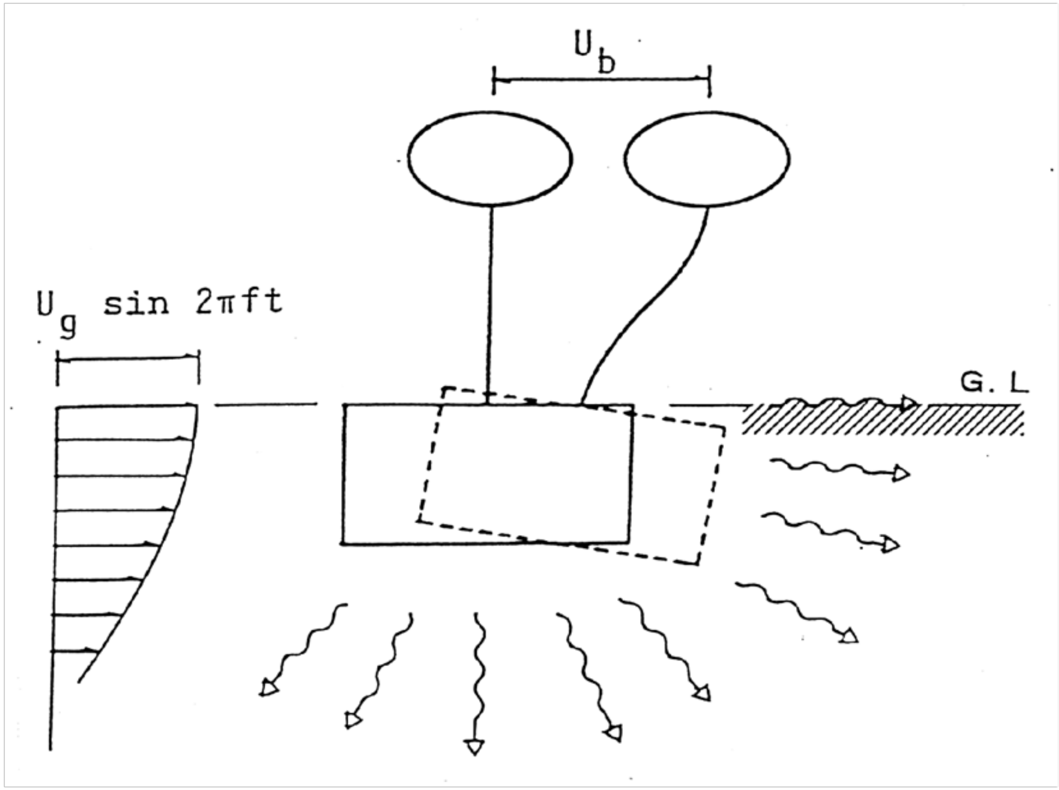
With the increasing embedding depth of the basement, the resonance frequency of the coupling system increase and the amplitude shows a decreasing tendency.



This is caused by both the increased restraint effect and the radiation damping due to the embedding, as previously described.

The vibration of the coupling system during an earthquake is considered.

The figure shows the behavior of a building with a basement during an earthquake.



For simplification, the seismic waves are assumed as sine waves with the frequency f Hz and with displacement only in horizontal direction.

They are propagating upward at a right angle to the ground surface. (This type of seismic waves is called SH-waves)
As shown, the amplitude of the seismic waves amplifies when the seismic waves approach the ground surface.

The seismic input motion into the building through the basement takes place not only through the bottom surface, but also through the side walls.

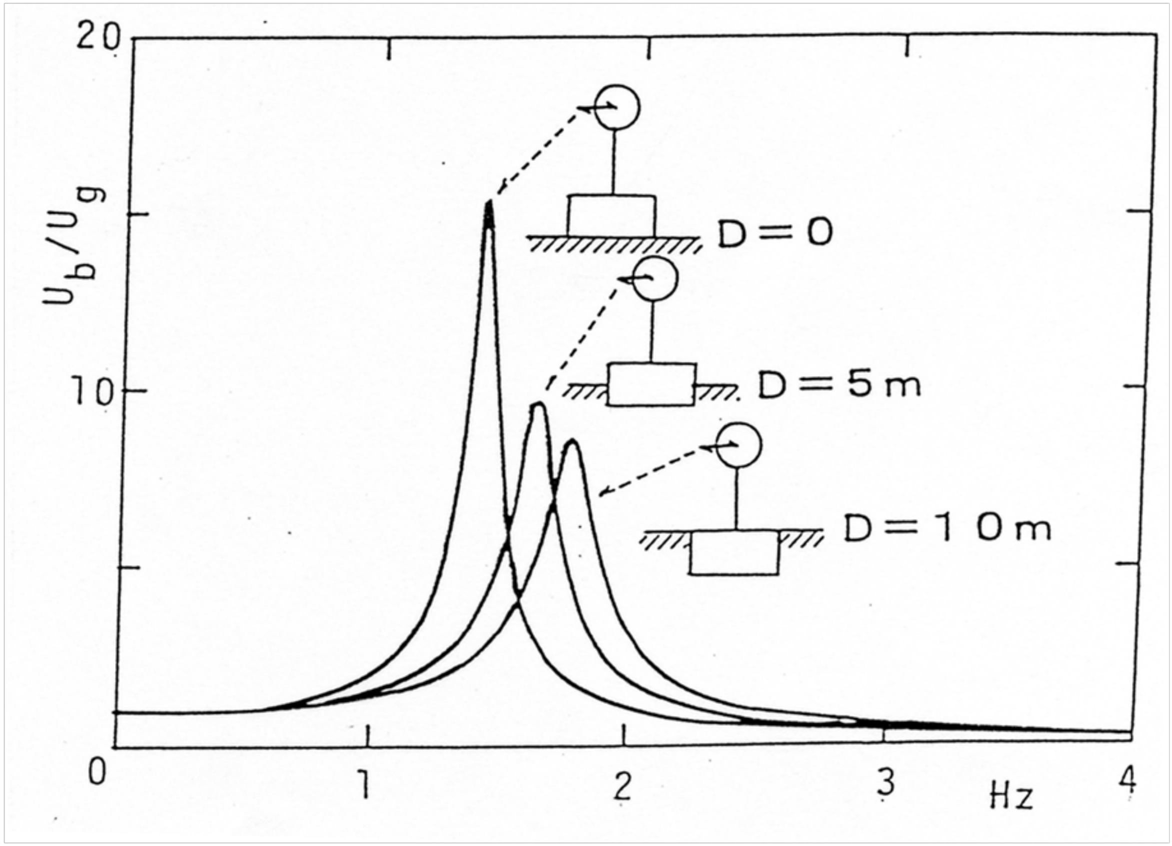
The seismic input motion from the bottom surface becomes smaller, since the amplitude of the ground vibration decreases with increasing depth of the basement.

However, the input from the walls increases, since the contact area of the walls to the ground becomes wider.

When the basement has a high rigidity in comparison to the ground, this input from the walls becomes the input averaging the deformation of the ground.

Next, the input motion that has entered into the building vibrates the building, and the vibration energy escapes from the bottom surface of the basemen and the side walls as radiation waves.

The figure shows the resonance curves at the top of the building.



The response amplitude U_b at the top of the building is normalized by U_g at the surface of the free field.

The free field indicates the ground, which is located so far that the response of the ground is not affected by the existence of the building.

The resonance curves shown exhibit the embedding effect described above.

E N D

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