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# A STUDY ON THE INFLUENCE OF GROUND UPON EARTHQUAKE-INDUCED DAMAGE TO STRUCTURES THROUGH SEISMIC RESPONSE ANALYSIS

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## ABSTRACT

From the investigation of structures of grounds under earthquake-damaged objects, earthquake damage has been clarified to be liable to occur at discontinuous sites of ground condition and upside-down type grounds. It is estimated that earthquake damage is mainly caused by a differential ground displacement through seismic response analyses of representative earthquake-damaged embankments and bridges.

## KEYWORDS

Earthquake damage; case study; effect of ground condition; damaging mechanism; seismic response analysis; discontinuous site; upside-down type ground; differential ground displacement.

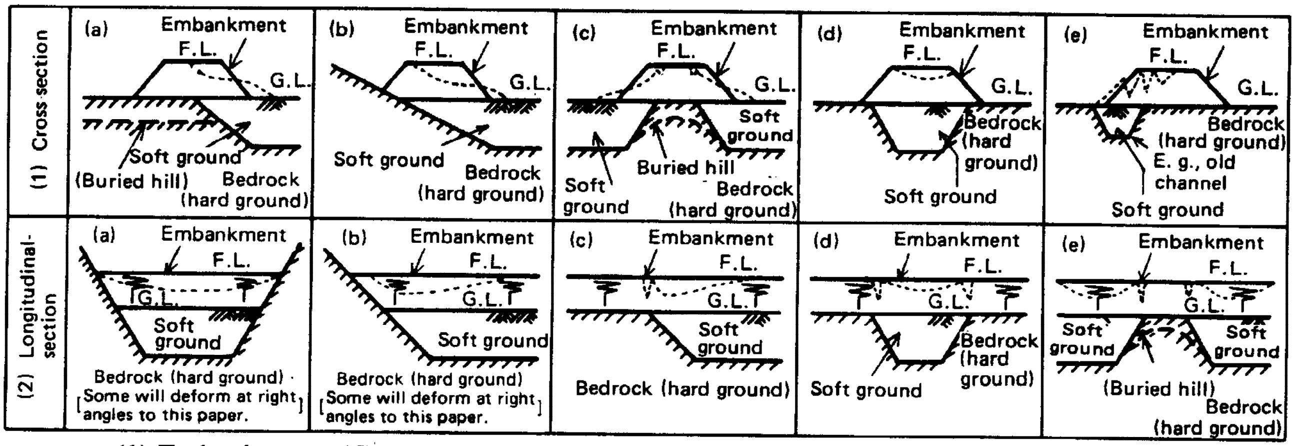
## INTRODUCTION

From much damage observed with embankments, buildings and bridges, the shapes of grounds and their soil layer composition vs. for the structures of grounds on which these objects are liable to be damaged by earthquake have been summarised. Also, the damaging mechanism has been investigated by seismic response analyses of representative embankments and bridges.

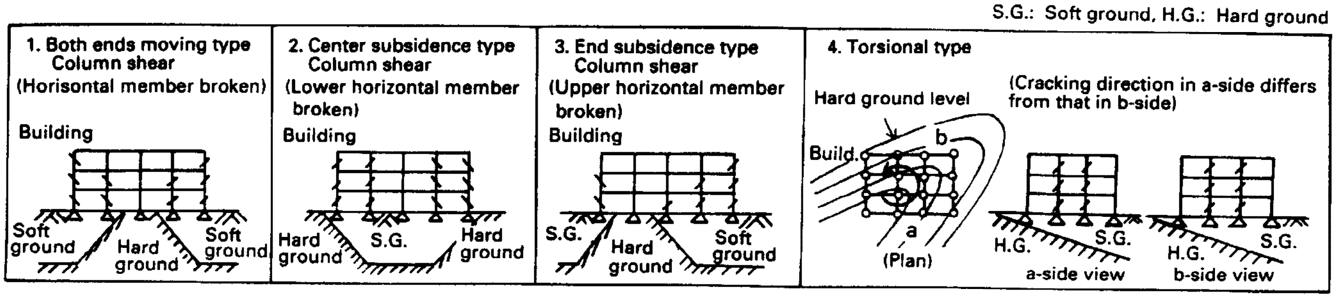
## STRUCTURES OF GROUNDS ON WHICH OBJECTS ARE LIABLE TO BE DAMAGED BY EARTHQUAKE

### The Shapes of Grounds and the Soil Layer Composition

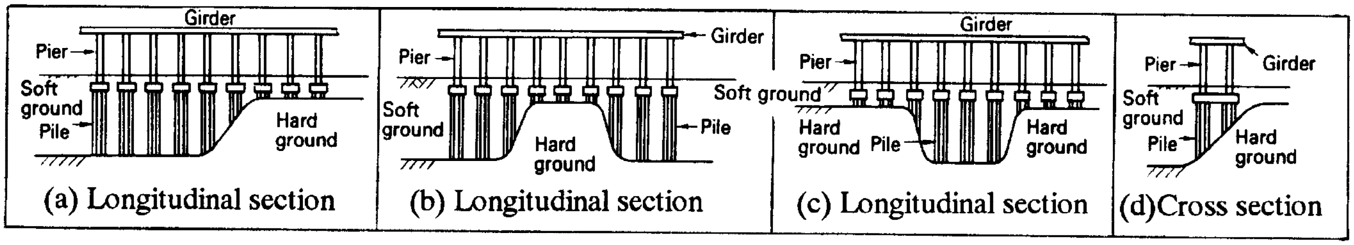
The author (Nasu, 1992) has already made clear from case studies of embankments, buildings, bridges and so on which are liable to be damaged by earthquakes at the discontinuous sitesof ground condition and in buried



(1) Embankments (Ground will possibly include buried hill and valley. In case of (2)(c),(d) and(e), some will deform at right angles to this paper.)



(2) Buildings (Buildings with pile foundation will also be damaged like this figure, with grounds possibly including buried hill and valley.)



(a) Longitudinal section

(b) Longitudinal section

(c) Longitudinal section

(d)Cross section

(3) Bridges (Bridges with spread foundation will also be damaged like this figure, and in case of (c), some will deform at right angles to this paper.)

Fig. 1 Structures of grounds liable to induce earthquake damage to objects

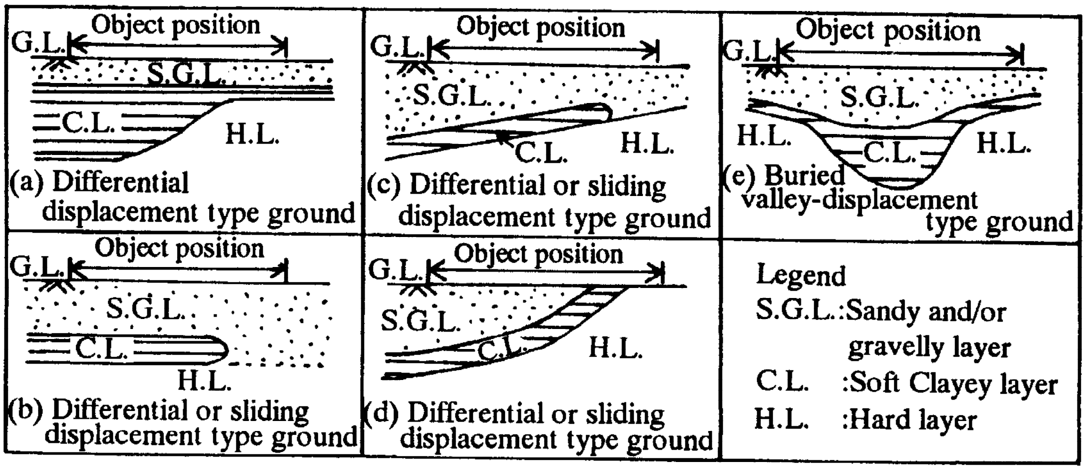


Fig. 2 The structures of grounds liable to induce damage to objects due to earthquake (Objects show embankments, buildings, bridges and so on.)

valleys. Namely, these objects are liable to be deformed by earthquakes when they stand on grounds where the bottom of soft soil layer is inclined, or when they straddle both soft ground and hard ground, as shown in Fig. 1. In the latter case, they are liable to be deformed remarkably by earthquakes.

Also, earthquake damage is liable to occur on the upside-down type grounds in which soft clayey or peaty layers underlie coarse soil ones of sandy and/or gravelly ones as shown in Fig. 2 (Nasu, 1995a). Fig. 2 shows the case that objects such as embankments, buildings, bridges and so on straddle thick and thin parts of a soft clayey layer, that a soft clayey layer is partial and horizontal or oblique and an object stands on both the soft clayey layer and the part void of such layer, and that an object crosses a buried valley made of the upside-down type grounds. As aforementioned, its earthquake damage occurrence is influenced largely by existing states of soft clayey or peaty layers.

### Presumption of the Earthquake Damage Cause

Large horizontal and/or vertical differential ground displacements will occur in the grounds including soft clayey or peaty soil layers with uneven thickness, and slide-like displacements in ones with horizontal or oblique thin soft ones under earthquakes (Nasu, 1992 and 1995a). In a buried valley of an upside-down type ground, the ground motion, especially a soft one's motion is presumed to be extraordinarily amplified in the valley axis direction under earthquakes.

## SEISMIC RESPONSE ANALYSIS OF REPRESENTATIVE EARTHQUAKE-DAMAGED EMBANKMENT AND BRIDGE

In order to investgate into the damage cause of an embankment and a bridge that were actually damaged by earthquakes at the discontinuous sites of ground condition, seismic response analyses have been done by the FEM computer program. The soft soil layer in the ground under the embankment becomes thick in the cross-sectional direction. The bridge stands on thick and thin parts of soft clayey layer in the bridge axis direction. The analyzing models of the ground-object systems have been made by finite elements. In soil properties the relation between shear moduli and damping factors and shear strain are non-linear. Horizontal seismic motions have been inputted from two analyzing ground model bottoms.

### Seismic Response Analysis of an Embankment

In the Nipponkai-Chubu earthquake of 1983, the embankment between Koikawa and Kado on the Ou main line of Japanese Railways failed on the ground in which the bottom of the soft soil stratum including a thick peaty layer greatly tilted in both the longitudinal and transversal directions of the embankment, as shown in Fig. 3 (Nasu, 1992). Still, it is noted that the right end of this embankment failure zone agrees with the right end of the zone of a very soft peaty soil. A neighboring embankment underlaid with a verysoft and almost horizontal clayey stratum did not subside nor was deformed. Furthermore, the embankment strength around this site is

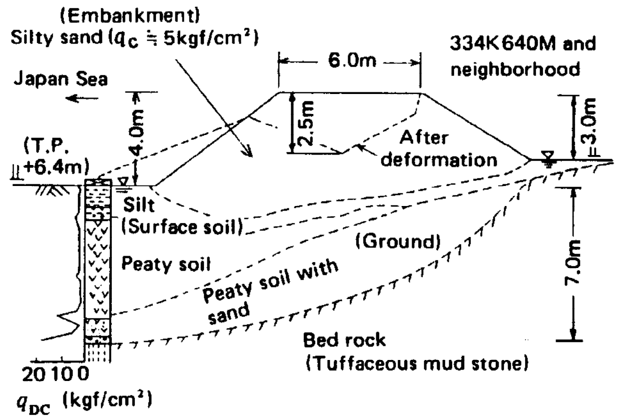


Fig. 3 Railway embankment in Koikawa

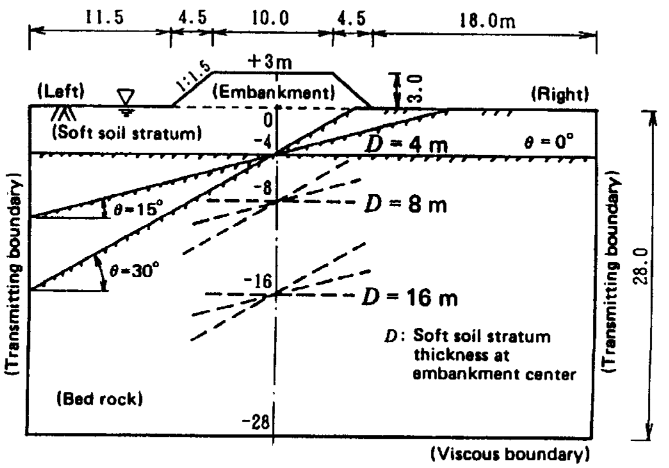


Fig. 4 Shape and size of analytical models

fairly low, that is $q_c$=5kgf/cm$^2$ (≅0.5MPa), regardless of failed or not.

Analytical Condition of Embankment. The soil constants, the geometrical shapes etc. of the two-dimensional analytical models have been decided by referring to the relevant data on an embankment shown in Fig.3 (Nasu, 1995b). Fig. 4 shows the analytical model. Three kinds of soft soil stratum thicknesses $D$ and inclination angles $\theta$ of the bedrock surface are used. In some material properties, mudstone of the bedrock was considered linear-elastic, and the shear modulus and damping factor of the clay and the sand were considered to depend on the shear strain and the effective confining pressure as shown in Fig. 5. The soil properties are summarized in Table 1. As the boundary condition of the model, an energy-transmitting boundary is set on both the right and

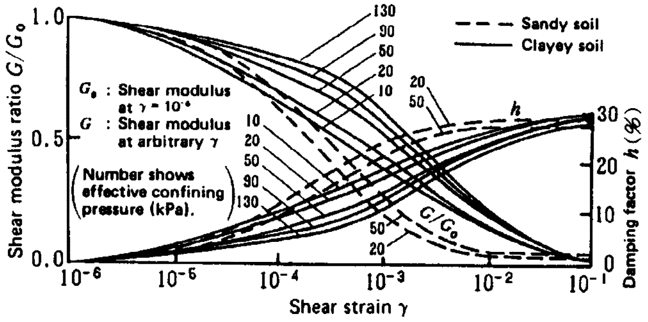
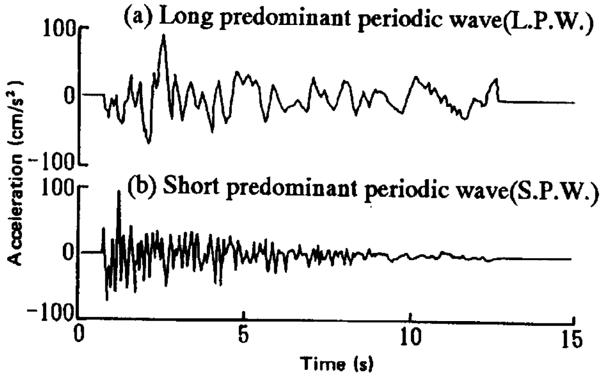


Fig. 5 Relation of shear modulus ratio and damping factor with shear strain


(a) Long predominant periodic wave(L.P.W.)

(b) Short predominant periodic wave(S.P.W.)

Fig. 6 Main parts of input waves

Table 1 Soil properties of embankment and ground

| Soil | Density<br>$\rho$(t/m$^3$) | S-wave velocity $V_s$(m/s$^2$) | Initial shear modulus $G_0$(MPa) | Poisson's ratio $\nu$ |
|---|---|---|---|---|
| Embankment (Silty sand) | 1.50 | 80.0 | 10.0 | 0.49 |
| Softt soil stratum (Silt) | 1.50 | 80.0 | 10.0 | 0.49 |
| Bedrock (Mudstone) | 2.10 | 500.0 | 530.0 | 0.20 |

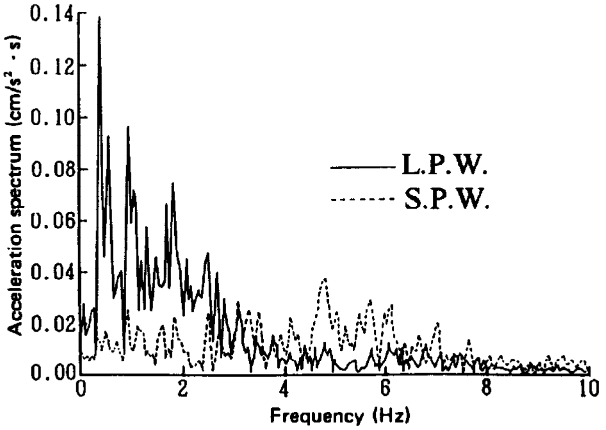


Fig. 7 Fourier spectra of input waves

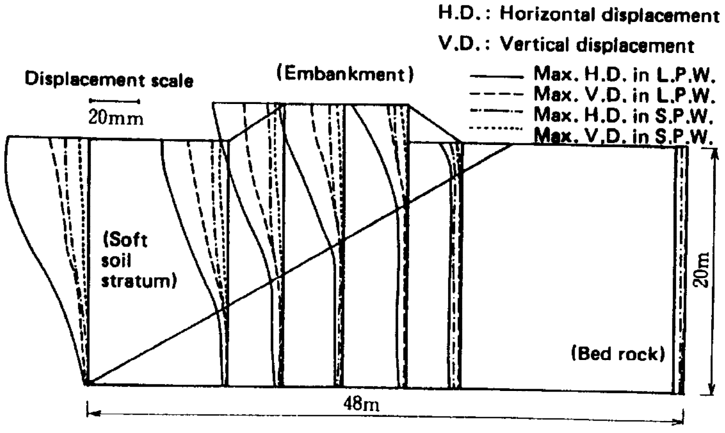


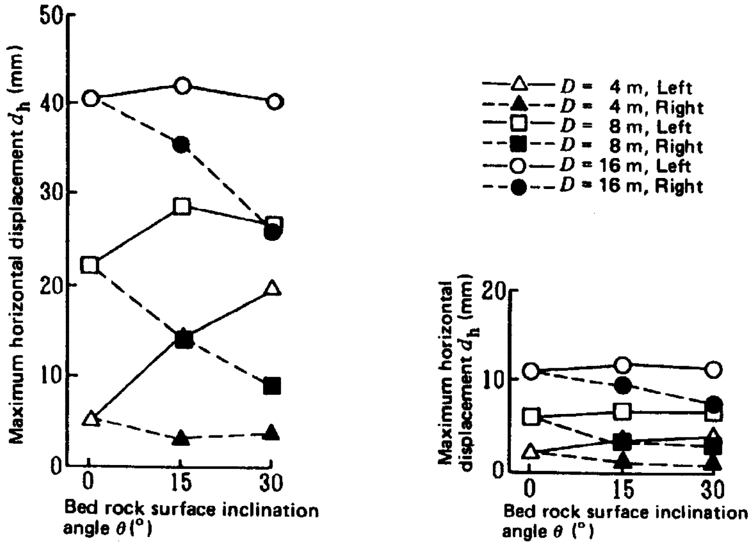
Fig. 8 Vertical distribution of maximium displacements ($D$=8m, $\theta$=30°)

left side of each model and a viscous boundary is set on the bottom. Input acceleration waves are two kinds of Hachinohe wave (L.P.W.) and Shin-Kikugawa wave (S.P.W.) which are long and short predominant periodic respectively, as shown in Figs. 6 and 7. Both horizontal vibrational waves with maximum value of 100cm/s$^2$ have been inputted from the model bottom. Above-mentioned calculations have been carried out by a seismic analytical finite element method program MFLUSH.

Distribution of Maximum Displacement. From Fig. 8, in both input waves, horizontal and vertical displacements $d_h$, $d_v$, in the soft soil stratum, the thicker it is, the larger they become. When the surface of bedrock is inclined, $d_v$ becomes large. The horizontal and vertical displacements are larger in case of L.P.W. input than in case of S.P.W. input, and the tendency becomes significant as $D$ and $\theta$ increase.

Relationship of Horizontal Displacement with Bedrock Inclination Angle and Soft Soil Stratum Thickness. In case of L.P.W. input, Fig. 9(a) shows that the larger $D$ is, the larger $d_h$ becomes, and for each thickness $D$ $d_h$ at the slope toe over a thicker soft soil stratum is larger than d h at the right slope toe over a thinner soft soil stratum. When $\theta$ is 0° , the displacements $d_h$ at both sides slope toes are equal because the thickness of the right soft soil stratum is equal to that of the left one, but the tendency issuch that, $d_h$ decreases in case of $D$ =8m and 16m as $\theta$ decreases, and on the contrary $d_h$ increases in case of $D$=4m. Also, as $\theta$ increases, the difference between the displacements at both sides slope toes becomes large. In case of $D$ =4m of the thin soft soil stratum of $D$ =16m, $d_h$ at the left slope toe is hardly influenced by $\theta$, but $d_h$ at the right slope toe is largely affected by $\theta$, and at both sides slope toes it changes by nearly equal values. In case of L.P.W. input, the soft soil stratum thickness and the inclination angle of the bedrock influence largely the displacement and their influenceappears more clearly at the slope toe than at the slope crest.

In case of S.P.W. input, Fig. 9(b) shows that the displacement $d_h$ in case of S.P.W. input is considerably smaller than d h in case of L.P.W. input. In this case, also at bothsides slope toes, the larger $D$ is, the larger $d_h$ becomes. When $\theta$ varies, $d_h$ varies, and when the bedrock surface is inclined, a difference appears between $d_h$ at the both slope toes. The variation of $d_h$ due to $D$ and $\theta$, and the difference of $d_h$ between the right and left slope toes due to $\theta$ are remarkably small.



(a) L.P.W. input (b) S.P.W. input

Fig. 9 Relation between maximum horizontal displacement and bedrock inclination angle in slope toe

## Seismic Response Analysis of a Bridge

In the Toshibetsugawa bridge wich has caisson foundation, bearings on the pier-8P tumbled down and the girder fell on the top of the pier in the 1993 Off-Kushiro earthquake (Nasu, 1995a) in Fig.10. As shown in Fig.11, in the surface layer of the ground, a gravelly sandy layer GS is distributed all over the bridge, and under it clayey layers of clay C, gravelly clay GC and sandy clay SC and so on are deposited thin on the right bank side and thick on the left bank side. In order to investgate into the damage cause, a seismic response analysis of the bridge-ground system has been carried out by the M-FLUSH of the FEM computer program and by input of a horizontal seismic motion from the analyzing model bottom. Maximum value of incident wave of the input motion is 100 cm/s$^2$. The soil and bridge member properties of the analytical model of the bridge-ground system are summarized in Tables 2 and 3. In Fig. 12, broken lines show a simultaneous vertical distribution of the horizontal displacement of the bridge and ground in the left and right directions. The figure shows that the largest separation between neighbouring pier tops occurs between the piers 8P and 9P, and that it occurs at a changing site of the clayey layer thickness. Consequently, it was presumed that the girder fell down on account of large differential displacements which happened in the clayey layers in the bridge axis direction under the

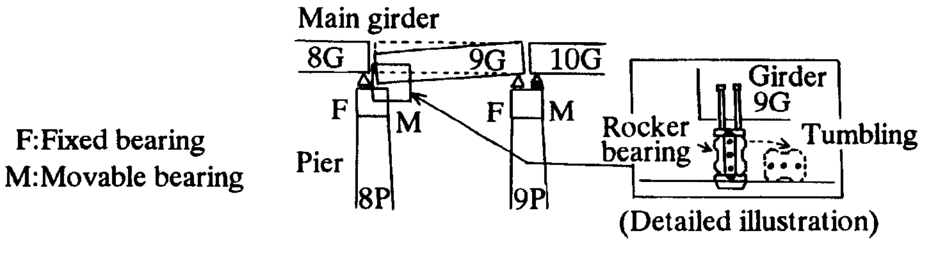


Fig. 10 Deforming state of girders and bearings of the Toshibetsugawa bridge due to the 1993 Off-Kushiro earthquake

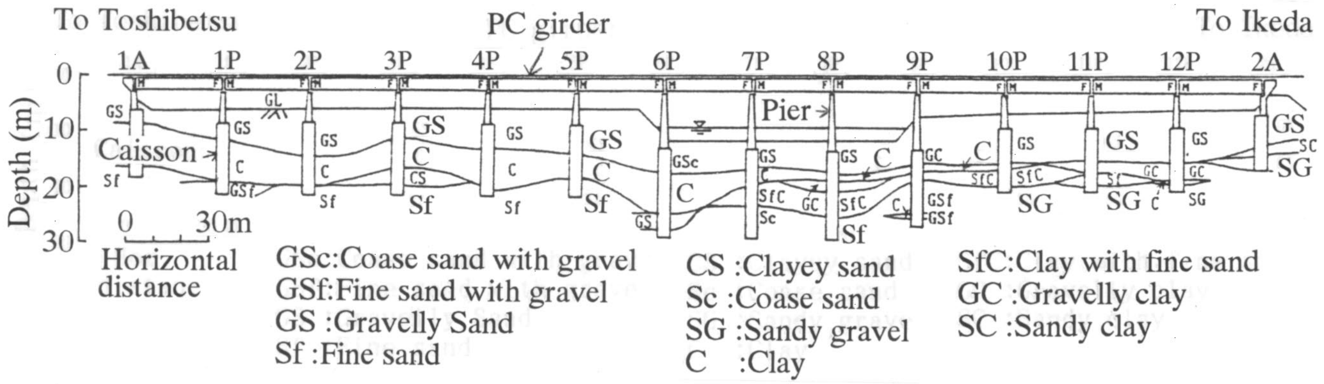


Fig. 11 Bridge and ground condition of the Toshibetsugawa bridge

Table 2 Soil properties of ground

| Soil | Density $\rho$ (t/m$^3$) | Initial shear modulus $G_0$ (MPa) | Poisson's ratio $\nu$ |
|---|---|---|---|
| GS (Gravelly sand) | 2.00 | 78.5 | 0.45 |
| C (Clay) | 1.50 | 33.4 | 0.49 |
| SfC (Clay with fine sand) | 1.60 | 41.2 | 0.49 |
| Sf and SG (Fine sand and sandy gravel) | 1.95 | 170.0 | 0.40 |

Table 3 Member properties of bridge

| Member | Density $\rho$ (t/m$^3$) | Shear modulus $G$ (MPa) | Sectional area $A$ (m$^2$) | M.I.A. $I$ (m$^4$) | Poisson's ratio $\nu$ |
|---|---|---|---|---|---|
| Caisson (RC) | 2.50 | $9.56\times10^3$ | 7.514 | 4.063 | 0.20 |
| Lower pier (RC) | 2.50 | $9.56\times10^3$ | 2.751 | 0.181 | 0.20 |
| Upper pier (RC) | 2.50 | $9.56\times10^3$ | 1.794 | 0.628 | 0.20 |
| Girder (PC) | 2.50 | $9.56\times10^3$ | 0.503 | 0.269 | 0.20 |

M.I.A.:Moment of inertia of area

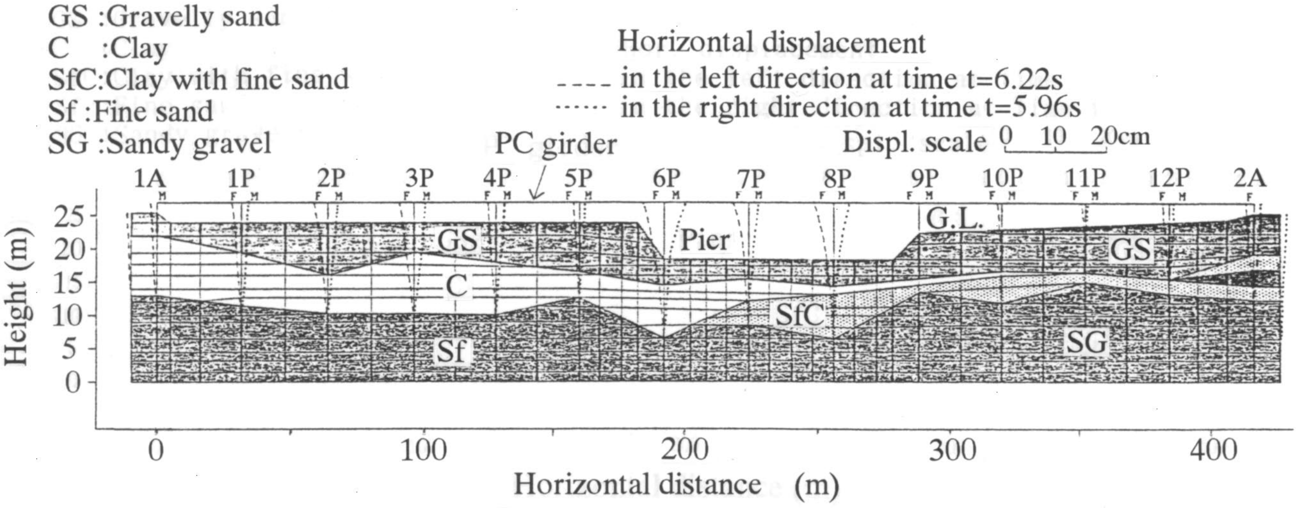


Fig. 12 Simultaneous vertical distribution of horizontal displacement of bridge-ground system in seismic response analysis of the Toshibetsugawa bridge

earthquake. Similarly, it is estimated that the San Francisco-Oakland Bay bridge wasbroken in the 1989 Loma Prieta earthquake, as the bridge straddled both thick and thin parts of the Bay mud and large differential displacements occurred at a changing site of the mud thickness under the earthquake (Nasu, 1992).

## RESULTS

It has been summarised that the earthquake damaging occurrence is affected by the shapes of grounds and the soil layer composition, and earthquake damage occurs in an upside-down type ground in which soft clayey or peaty layers underly sandy and/or gravelly layers, and its occurrence is influenced largely by existing states of soft clayey or peaty layers. It has been found out by the seismic responce analysis of the embankment-ground s ystem that the horizontal and vertical ground displacements occur larger on the thick side of the soft soil layer than on the thin side of it, and that a large differential displacement occurs in the embankment bottom. Also, it has been found out by the seismic response analysis of the bridge-ground system that the horizontal ground displacements occur larger on the soft soil layer than on the thin side of it, and that a large separation occurs between the tops of two piers which are before and behind a changing site of the soft soil layer thickness. Consequently, it is estimated that the embankment was failed by the extension of its bottom, and that the girder of the bridge fell down by a large separation of neighbouring pier tops.

## CONCLUSIONS

Structures of grounds on which various objects are vulnerable to earthquakes and their damaging mechanism has been investigated. Earthquake damage is liable to occur in discontinuous grounds and upside-down type grounds. Earthquake damage is estimated to be caused by the ground displacement. Namely it has become clear by the seismic response analyses that large horizontal and/or vertical differential displacements occur at the discontinuous sites of ground condition under the earthquake. Therefore, it will be necessarry to consider the ground displacement in the earthquake resistant design in the future.

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