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EFFECT OF SANDY GROUND STRUCTURES UPON EARTHQUAKE-INDUCED DAMAGE TO VARIOUS OBJECTS

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ABSTRACT :

To make clear the structures of sandy grounds on which various objects are liable to be damaged by liquefaction what is called and the damage mechanism, much damage to embankments, buildings, bridges, slopes, quays, power substations and so on have been investigated. In this paper, a liquefaction-induced damage mechanism is studied comparing the deformation of objects and grounds with structures of grounds. It is presumed that most of the damage was caused by large differential displacements due to uneven thickness of soft clayey layers within grounds and by sliding displacements occurring in thin and equally soft clayey ones.

KEYWORDS: EARTHQUAKE DAMAGE, SANDY GROUND, SOFT CLAYEY LAYER, SEISMIC DIFFERENTIAL GROUND DISPLACEMENT, SLIDING DISPLACEMENT

1. INTRODUCTION

Structures of grounds on which various objects are liable to be damaged by earthquakes and their damaging mechanism have been investigated from many case histories. It is already reported that much damage to embankments, buildings and bridges has occurred at sites where the ground condition changes suddenly[1)]. In this paper, many examples of various objects damaged by liquefaction what is called are cited and damage mechanism is estimated.

2. GROUND STRUCTURES UNDER REPRESENTATIVE LIQUEFACTION-DAMAGED OBJECTS AND THEIR DEFORMATION

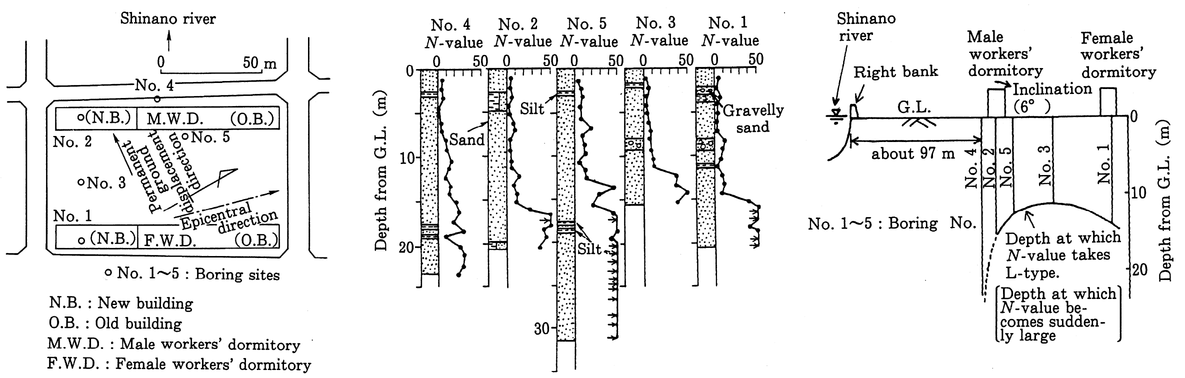
In representative examples of buildings, bridges and embankments damaged by earthquakes, some relations between their damaged states and grounds will be described below in detail[2)-5)].

2.1 Buildings

(1)Male workers' dormitory of the Niigata Transport Ltd. Co. with pile foundation (1964 Niigata earthquake)

As shown in Figure 1, the male workers' dormitory building on sandy grounds subsided and was inclined largely, and an inclination of about 6° in the span direction occurred in the southeastern direction in which the surface of a buried dune composed of comparatively dense sand over 10 in N-values of Standard penetration test(SPT) became shallow[3)]. This building shook largely in the span direction, and next largely in the ridge direction. Its inclination direction of about 6° and the permanent displacement direction of ground surface due to the earthquake are reverse to each other. It is shown in Figure 1(a) that at the depth of about 18 to 20m under the ground level, thin clayey layers are inclined in the direction of Bor. No.5 to No.4 that is nearly parallel to a permanent ground displacement direction, or in the direction of Bor. No.5 to No.2. Foundation piles were inclined almost in the same direction as the inclination of the building. It is estimated that the span direction of the building was inclined in the direction of the buried dune surface becoming shallow, because a landslide-like movement occurred and a rotation occurred in ground under its displacement by the earthquake.

(2)Prefectural Kawagishi-cho apartment with spread foundation (1964 Niigata earthquake)



(a) Plan (b) Soil profiles (c) Ground

Figure 1 The workers' dormitory of the Niigata Transport Ltd. Co. (1964 Niigata earthquake)[3)]

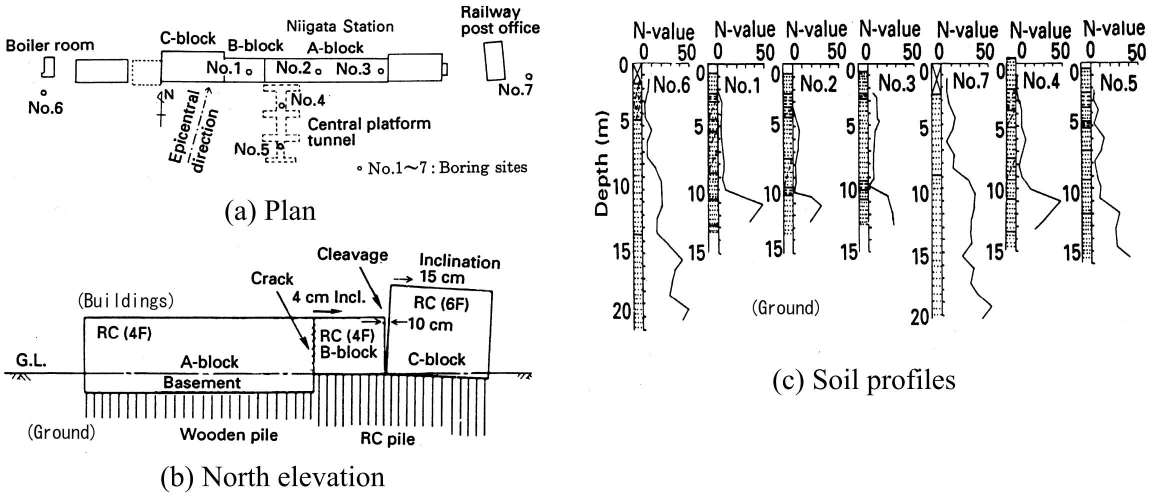


Figure 2 The Niigata station (1964 Niigata earthquake)[3)]

The sandy ground under the prefectural Kawagishi-cho apartment buildings was built up by reclamation of an old river location of the Shinano river in the ridge of the dune in its northern part[3)]. From the neighbouring ground condition, it is estimated that the ground under this building is uneven and soft clayey layers which exist about G.L.-20m deep over the old river bed surface became sliding planes under earthquake. Various inclinations and subsidence of the buildings seem to correspond with the ground condition.

(3)Niigata station building with pile foundation (1964 Niigata earthquake)

The surface strata under the Niigata station building are composed of loose sands as shown in Figure 2. Both B-block and C-block buildings on an inclined dense sandy layer surface tilted in their inclined direction to the west[3)]. This inclination direction is approximately at right angles to the epicentral direction. The loose sandy ground bottom under its almost non-damaged A-block was approximately horizontal. But in detail, very soft clayey layers on dense sandy layer surface at about 10m depth are loosely inclined to the west. Consequently it is estimated that this layer has become a sliding plane under the earthquake and the almost non-damaged A-block has moved to the west under the earthquake. In any other way, the C-block building is estimated to have tilted to the west because sandy layers in the outside of its building moved to the east, bended the piles to the east and the piles became short.

2.2 Bridges

(1)Showa O-hashi bridge (1964 Niigata earthquake)

The Showa O-hashi bridge with pile foundation, as shown in Figure 3, straddles both thin part on the right bank side and thick part on the left bank side of loose sandy layers Um and Um ~Us in the bridge axis direction[4)]. Consequently, seismic differential displacement of ground is estimated to have happened largely in the bridge axis direction and the bridge girders are considered to have collapsed under the earthquake. Furthermore, the fallen zone of girders from the piers-2P to 7P agrees with an extent of very soft clayey layers with extremely small N-values of SPT, and these layers are made of clayey soil at the A-point and peaty soil at the B- and C-points and have tilting sedimentary structures. And bending of the pier-P4 is estimated to have happened because the loose sandy layer near it flowed largely in a slightly tilting direction of the sandy layer Um and Um~Us bottom on the right side, with sliding planes of very soft clayey soils.

(2)Bandai bridge (1964 Niigata earthquake)

The existing Bandai bridge with pile foundation under abutments and with caisson foundation under piers, to which damage was comparatively slight, is shorter than the old bridge[4)]. Soft grounds under the bridge become stronger approximately in proportion to the depth and the whole strata of the ground are approximately horizontal. In this ground, seismic differential ground displacements will be difficult to occur under the earthquake.

(3)Sasakuchi viaduct (1964 Niigata earthquake)

In the Sasakuchi viaduct (the East viaduct) with pile foundation, as shown in Figure 4, the span between the front and rear piers with bearing pile foundation of girders which straddled the railways was enlarged, and girders on the movable end fell down[4]. This bridge was constructed at the boundary between a dune and a loose sandy reclaimed land at an old river location. The loose sandy layers become thick in this direction. It is considered that the girders fell down because seismic differential displacements occurred between the loose sandy layers and the dune under the earthquake.

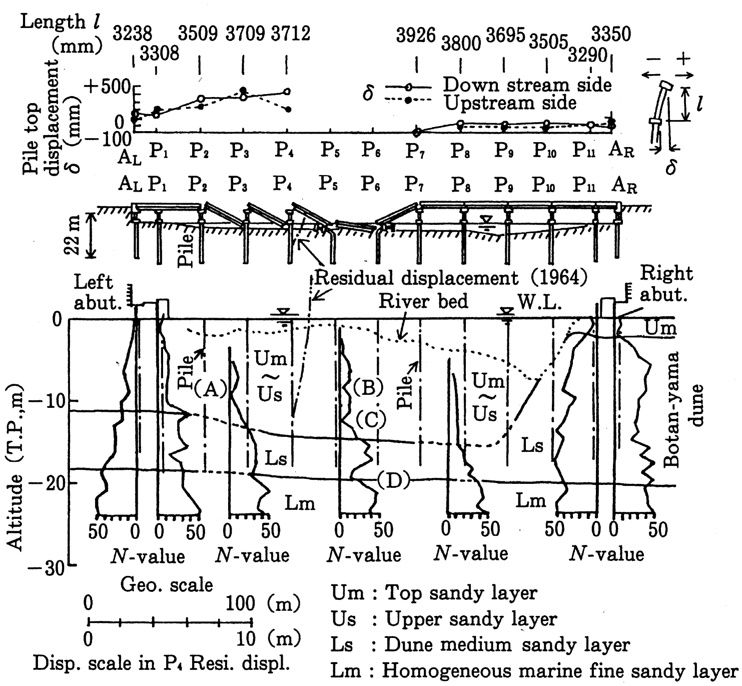


Figure 3 The Showa O-hashi bridge (1964 Nigata earthquake, original figure revised)[4]

2.3 Embankments

(1) Embankment between Deto - Nishime (1964 Niigata earthquake)

An embankment which has broken between Deto station and Nishime station on the Uetsu Line of the Japanese National Railways, traverses a branch valley within dunes as shown in Figure 5[5]. About 7m high embankment consisting of dune sand flowed out toward the downstream of the branch valley to a maximum extent of as long as 115 m. According to Fig.6(a), the embankment straddles both a soft peaty layer with a maximum thickness of about 3 m and a hard strata. The latter is composed of a

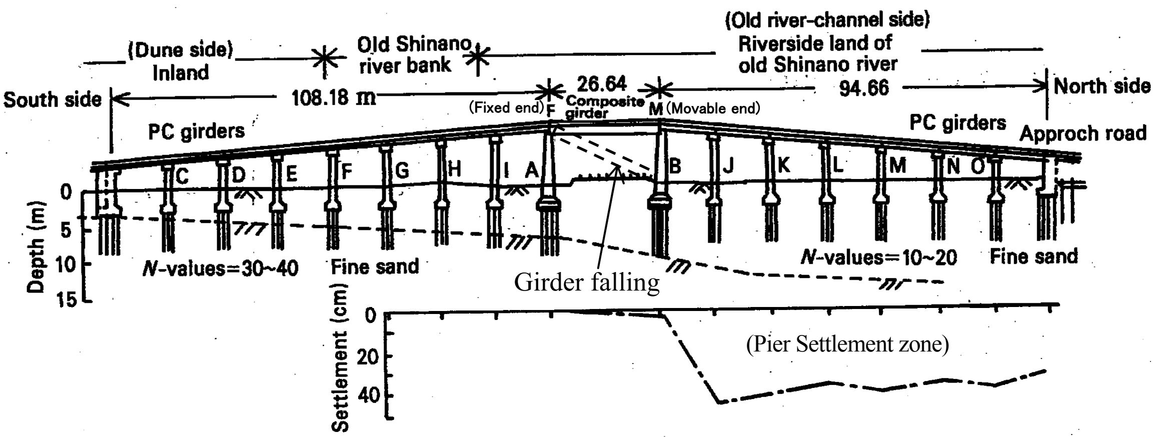


Figure 4 The Sasakuchi viaduct (the East viaduct, 1964 Niigata Earthquake)[4]

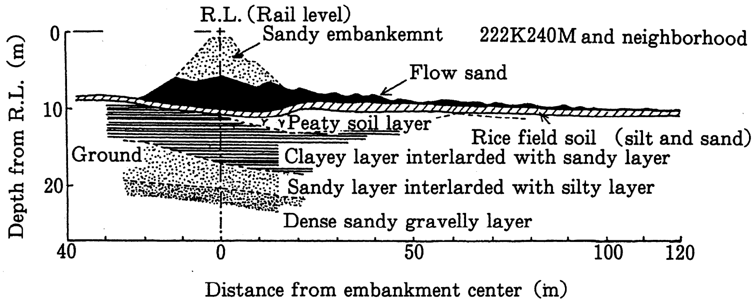
clayey layer interlarded with a very compact sandy layers, a compact sandy layer done with clayey layers and a dense sandy gravelly layer. The embankment soil flowed out in the thickening direction of the peaty layer. The phenomenon occurred only in the zone of the existing peaty layer. The embankment failure must have occurred by a large seismic differential ground displacement in the direction where the soft peaty layer becomes thicker.

(2)Hakusan substation (1964 Niigata earthquake)

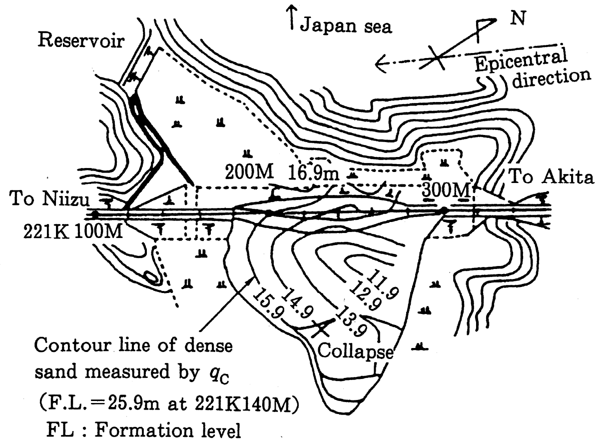
The loose sandy ground under the Hakusan substation on a ground with tilting soil layers around a dune tip slided largely to an extent of max. about 7m toward the Shinano river[5]. The strength of this ground is uneven and its minimum points are very small locally. Namely, very loose soil layers of about 0 in N-values exist at about 15 to 17m depth in Bor. No.1, and N-values are the minimum at about 13 to 15m depth in Bor. No.3 and at about 20m depth in Bor. No.2 in its substation site.

(3)Embankment at Hakusan station - Niigata station (1964 Niigata earthquake)

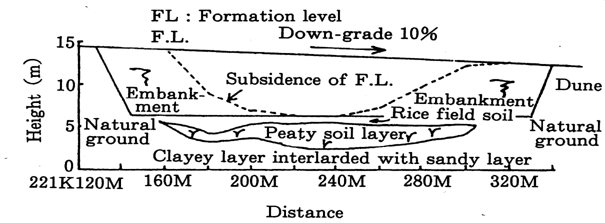
Embankments which have broken at Hakusan station - Niigata station on the JNR Echigo Line and had sliding, subsidence etc., exist on a sandy reclaimed ground in an old Shinano river location and in the dune ridge, and were deformed in the tilting direction of the buried dune surface[5]. They occurred heavily on buried branch valleys within dunes. In the ground, soft clayey and peaty layers are found comparatively thin and tilting.



(a) Cross section



(b) Plan



(c) Relation between embankment subsidence and peaty soil layer

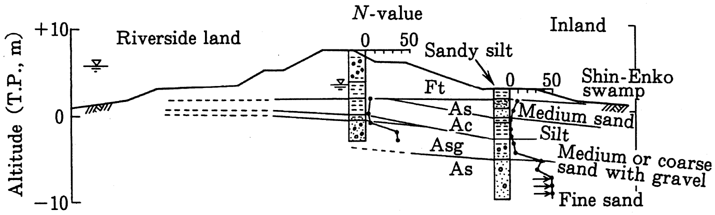
Figure 5 The embankment at Deto-Nishime (1964 Nigata earthquke)[5]

(4)Niigata airport (1964 Nigata earthquake)

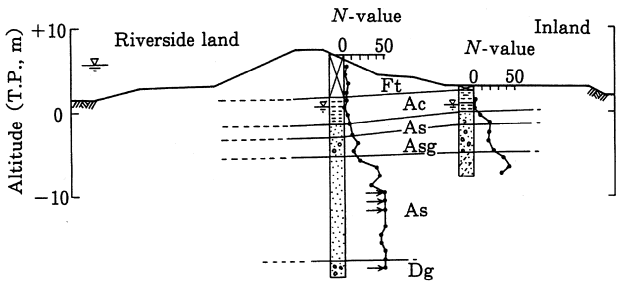
The B-runway of the Niigata airport curved horizontal largely to an extent of 4.5m at a sandy reclaimed land in a boundary between a seashore dune and a flood plain and toward an old swamp[5].

(5)Upper Yuriage dike (1978 Miyagiken-oki earthquake)

Near A-A' cross-section of the Upper Yuriage Dike of Figure 6(a), embankment cracks and deformation of a swamp including a sliding failure etc. occurred. This dike straddled both thin and thick parts of soft soil layers[5)]. The landside ground under this dike has a very soft silty layer under medium grain sandy layer. On the other hand, in neighboring non-damaged B-B' cross-section of Figure 6(b), a slope portion on the landside is located in a sedimentary layer which is inclined opposite to its slope surface, while top and slope portions on the riverside stand on almost horizontal soil layers. It is estimated that the soil layer Ac in Figure 6(a) has become a sliding plane under the earthquake and slope has been damaged.



(a) Ground condition under damaged dike (A-A'cross section)



(b) Ground condition under non-damaged dike (B-B'cross section)

Figure 6 The upper Yuriage dike (1978 Miyagiken-oki earthquke)[5)]

2.4 Other damage induced by liquefaction what is called

In many other liquefaction-induced damages due to the 1964 Niigata earthquake, the 1968 Tokachi-oki earthquake, the 1983 Nipponkai-chubu earthquake and so on, clayey layers including peaty ones with low strength are found under sandy layers. The permanent displacement in many grounds occurred in the tilting direction of loose sandy layers. Also, in many cases, when soft clayey layers underlying sandy layers are comparatively thick they are of uneven thickness; and when they are thin or oblique, they exist partially. In grounds under various objects which received damage due to the 1989 Loma Prieta earthquake in San Francisco, soft bay muds with uneven thickness including soft peats are found under dunes and reclaimed lands[2)].

3. SUMMARY AND CONSIDERATION

Structures of sandy grounds in which liquefaction-induced damage is liable to occur, are classified in Figure 7 additionally referring to other examples and considering deformed behavior of grounds and objects under earthquakes[6)]. Arrows in Figure 7 indicate positions of objects which include buildings, bridges, embankments and so on. Damaging mechanism is estimated as follows:
(1)Liquefaction-induced damage of objects is hardly recognized in grounds composed of a single sandy layer and in a widely horizontally stratified ground.
(2)Much liquefaction-induced damage occurred in upside-down type grounds whose soft clayey layers exist thick or thin or partially in intermediate, bottom and lower parts of sandy and/or gravelly layers within alluvial or reclaimed grounds. But even in upside-down type grounds of which strata are horizontal, liquefaction-induced damage is hardly found.
(3)Afore-mentioned soft clayey layers are made of peat and/or clay.
(4)In many cases, when soft clayey layers underlying sandy and/or gravelly ones are thick, their thickness is uneven or inequally thick as shown in Figure 7(a), and when soft clayey ones are thin they are inclined and thickness of sandy ones overlying them is uneven as shown in Figure 7(b). Also, in some cases thin soft clayey layers exist partially horizontal under sandy layers, for example, as shown

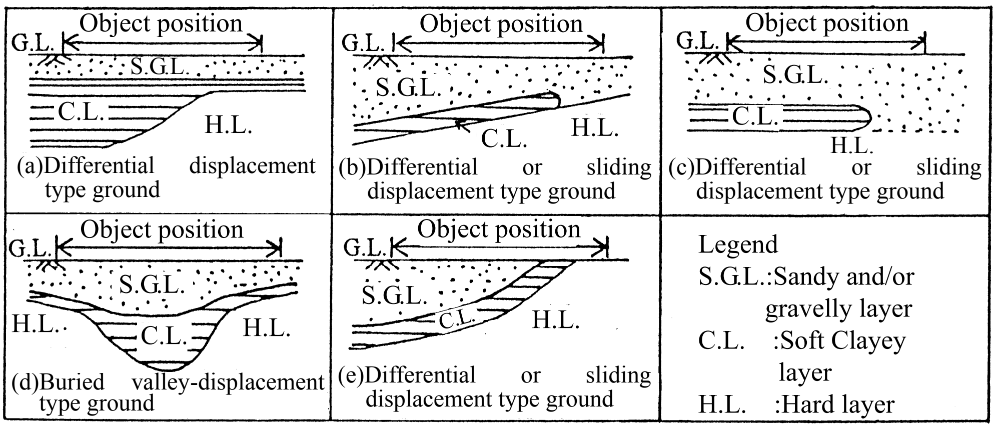


Figure 7 The structures of sandy grounds liable to induce damage to objects due to earthquake[6)]

in Figure 7(c).

Besides, objects which cross valleys of an upside-down type ground as shown in Figure 7(d) are liable to be damaged by earthquakes. Objects on grounds shown in Figure 7(e) will also be damaged by earthquakes. In this ground, a clayey layer is inclined under a sandy one underlying objects.

(5)Generally, seismic motion is amplified larger in clayey layers than in sandy ones, and the thicker clayey layers are, the larger their motion is. Consequently, in Figure 7(a), large horizontal and/or vertical differential displacements will occur at a boundary between thin and thick clayey layers, and a strong tensile force or compressive force will act on objects. Sliding displacement is liable to occur in thin clayey layers. Consequently, in Figure 7(b) and (c), landslide-like displacement will occur in the ground, and some objects on such grounds will suffer various deformations like subsidence, inclination and so on, and piles will be broken or cracked in thin clayey layer. Also, in grounds in which thin soft clayey layer exists partially as shown in Figure 7(b) and (c), large horizontal and/or vertical differential displacements will occur in objects at the boundary of existing and non-existing parts of soft clayey layer under earthquakes, and they will be damaged.

In buried valleys of an upside-down type ground shown in Figure 7(d), their ground motion, especially clayey layer motion is presumed to be extraordinarily amplified in valley axis direction under earthquakes. Furthermore, it is estimated that on right and left sides of a buried valley in which the thickness of soft clayey layers is variable suddenly, large horizontal and vertical differential diaplacements occur in objects under earthquakes and the objects will be damaged. In a ground shown in Figure 7(e), a slide-like displacement occurs in an inclined clayey layer and parallel to its layer. Consequently, large horizontal and/or vertical differential diaplacements will occur in objects on this ground.

(6)Damaged states including subsidence, tilting, cracking etc. of objects due to liquefaction correspond to ground structures like those of other earthquake-damaged objects .

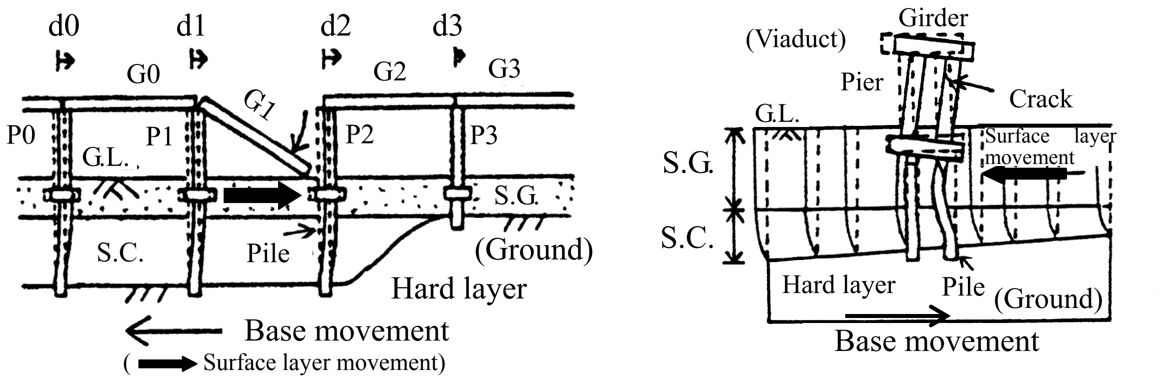
(7)The grounds including soft soil layers with uneven thickness, thin soft soil layers, valley type ground, tilting sedimentary structures etc. are similar to ones in which landslides, subsidence, lateral flows etc. occur in various objects at normal time. At the sites where large dynamic and residual ground displacements occur under earthquakes, their ground movements are likely to occur.

(8)Sandy or gravel layers with comparatively large strength overlying soft clayey soil layers may behave peculiarly under earthquakes. They include natural deposits of alluvial layers and sand banks, artificial embankments or reclaimed lands and so on. It is estimated that objects are liable to be damaged under earthquakes, because these sandy or gravelly layers can push stronger objects including their substructures than soft clayey ones, namely because a coefficient of lateral or vertical subgrade reaction is larger in sandy or gravel layers than in soft clayey ones.

(9)For example, a mechanism of earthquake damage to bridge is shown in Figure 8[7)]. Displacement of soft soil layer occur larger than that of hard soil layer during earthquake. Also, as the coefficient of

G0∽G3:Girders P0∽P3:Piers S.G.:Sandy and/or gravelly layer S.C.:Soft clayey layer

Pier top displacement(d0=d1=d2,d2>d3) - - - before earthquake, —— after earthquake



(a) In the bridge axis direction (b) At right angles to the bridge axis direction

Figure 8 An estimation of mechanism of earthquake damage to bridge[7)]

subgrade reaction of the sandy and/or gravelly layer (S.G.) is far larger than that of soft clayey layer (S.C.), S.G. will be able to push pile and footing foundation stronger than S.C. Consequently, the following are the conceivable mechanism.

A bridge with bearing piles shown in Figure 8(a) straddles both soft clayey layer (S.C.) and hard layer in the bridge axis direction. If the surface soil layer (S.G.) move to the right under earthquake, the piers P0, P1 and P2 of the bridge on the soft clayey layer will move comparatively larger to the right than the pier P3 on the hard layer, and the span between pier P2 and P3 will contract. Successively, because the seat area of the movable end of the girder G1 at the top of the pier P2 become small, it will fall down.

In case of a viaduct with bearing piles as shown in Figure 8(b), if surface soil layer (S.G.) move to the left under earthquake, right piles of viaduct will bend larger to the left than the left piles by receiving an large eccentric earth pressure, the right pile become shorter than the left pile, and the viaduct will incline to the right.

4. CONCLUSIONS

Structures of sandy grounds on which that various objects are liable to be damaged by liquefaction and their damaging mechanisms have been investigated. The structure of grounds and the soil layer composition have something to do with a liquefaction-induced damage occurrence. Liquefaction-induced damage occurs in an upside-down type ground in which soft clayey or peaty layers underly sandy and/or gravelly layers, and its occurrence influences largely upon existing states of soft clayey or peaty layers. It is estimated that liquefaction-induced damage occurs by large differential displacements or sliding displacement or extraordinarily amplified motion of valley axis direction in soft clayey or peaty layer and so on. The author is convinced that their deformed states reflect faithfully the condition of grounds[6)].

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