Mechanism, Quantitative Calculation and Countermeasures of Liquefaction during Earthquake

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SUMMARY
The authors show that the main cause of the liquefaction is the soft and flexible clayey layer beneath the liquefied sandy soil, and that the process of liquefaction can be explained with the multi-reflection theory and dynamic response calculation from the bedrock through the thick sedimentary layers above. The seismic waves and their energy gather from the hard bedrock to the soft surface layers. The seismic energy absorbed in the soft and flexible clayey layer generates self vibration of the layer with long periods, which transfers shear strain to the saturated sandy layer above and induces liquefaction.
This calculation method is useful for speculating the limit and the level of liquefaction for various geological ground types and for investigating countermeasures against liquefaction. Then, we can know the possibility of liquefaction based on the scale of strain by the energy of an earthquake at any places.

Keywords: Liquefaction, Shear strain, Multi-reflection theory, Rigidity of soil, FEM analysis

1. INTRODUCTION

The large-scaled liquefaction of saturated sandy soil was observed in many places during the 2011 East Japan Earthquake. With regard to the liquefaction phenomena described as originating from excess pore water pressure and diminishing effective stresses among grain structures caused by repeated of strong acceleration waves, the following curious points are noted, ①the maximum accelerations observed at the sites are not large (<200 gal). ②the seismic waves with little acceleration during liquefaction have relatively long periods. ③the liquefaction appears after the main shock. ④the liquefaction continues for a long time after the earthquake. ⑤the liquefaction is seen in gravel or silt layers at times and ⑥ large landslide is sometimes observed without sand boils being apparent.
Such phenomena seem to depend on the soft and flexible cohesive layer beneath the liquefied sandy soil. This means that it is necessary to clarify the influence of this soft layer using response calculations.
To resolve the curious points above-mentioned, a series of dynamic response analyses were conducted, which led to the formulation of a new hypothesis. This hypothesis was applied to previous liquefaction phenomena in order to generate a clearer explanation of the liquefaction mechanism than one provided by existing theories. It gives a reasonable explanation of these phenomena and the influence of the soft layer during large earthquakes, making it possible to simulate and thereby predict actual liquefaction.
The hypothesis is applied to the liquefaction in Urayasu City (which neighbors Tokyo) that resulted in many houses being severely damaged. It offers a sound explanation for why liquefaction occurred in this instance, and why it did not occur in past earthquakes. It is also applicable to other areas that have experienced liquefaction.

2. HYPOTHESIS FOR THE LIQUEFACTION MECHANISM

The liquefaction of saturated sandy soil is the result of large shear strains which destroys the particle structure of the sand bearing the effective stress, resulting in a high excess pore water pressure in a suspension of sand. Where do such large shear strains come from?

At the liquefied places there exists without exception a thick, soft and flexible cohesive layer. This cohesive layer absorbs and stores the energy of seismic waves propagating upwards from the bedrock layer. The seismic waves easily propagate from hard layers to soft layers but propagation from soft layers to hard layers is minimal. As a result, the seismic waves move upwards and concentrate in the surface layers, repeatedly, reflecting and refracting through the intermediate layers below. Most of the seismic energy is stored in the cohesive layer near the surface.

This cohesive layer vibrates at its own first mode of natural frequency, with a relatively long periods and small accelerations in the case of a weak upper layer. It then transmits the large amplitudes and large shear strains of the seismic waves, and its vibration continues for long time. In the case of a firm upper layer, it vibrates in its own second mode or high modes of natural frequency with short periods and large accelerations because the upper layer binds the soft lower cohesive layer together strongly (**Figure 2.1**).

The large shear strain generated by waves with long periods travelling upwards from the soft lower soil destroys the particle structures of the saturated sand layer. Then, the effective stress in the sand layer is transferred to the pore water pressure. If the pore water is confined under the surface, the pore water pressure increases and the liquefaction results with suspended sand.

The liquefaction of sandy soils results in various phenomena, such as spout of ground water, sand boils, settlement of structures or the ground surface, cracks and fissures in the ground, horizontal displacement of slope, inclining of piers or tower, sliding or collapse of embankment, etc.

The abovementioned kinds of damage occur on the upper side of the cohesive layers. Effective measures to prevent liquefaction are defined as release of excess pore water pressure, rigid walls to constrain the shear strain, rigid foundation for structures, connecting beams between the tops of piers or towers, consolidation of sandy soil, dewatering of the ground water table, etc.

3. LIQUEFACTION AT URAYASU CAUSED BY THE 2011 EAST JAPAN EARTHQUAKE

The 2011 East Japan Earthquake (Magnitude 9) occurred at 14:46 on the 11th of March 2011, 130 km far from the main land (**Figure3.1**). Its source region extends 500 km in length and 200 km in width and consists of three hypocenters, two of which are located off Miyagi prefecture and one off Ibaraki prefecture. Though the majority of damage to life and property was caused by the

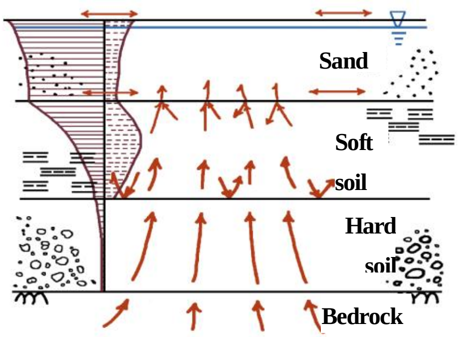

Figure 2.1 Concept of mechanism of liquefaction

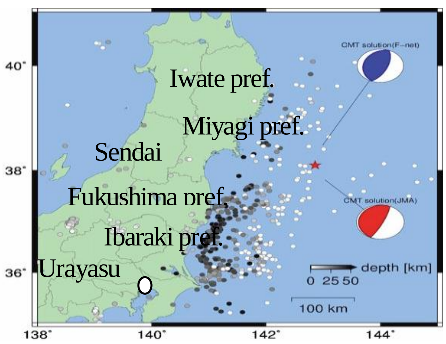

Figure 3.1 The 2011 East Japan Eq.

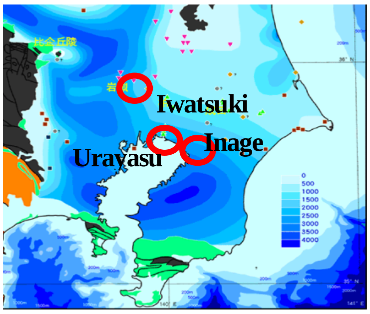

Figure3.2 Depth of bed rock under Kanto Plain

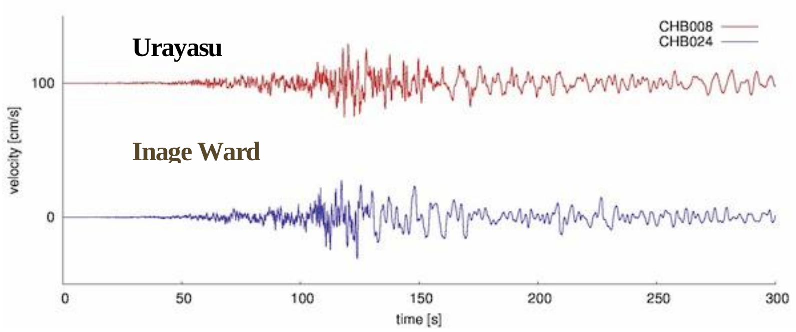

Figure3.3 Velocity waves at Urayasu and Inage Ward

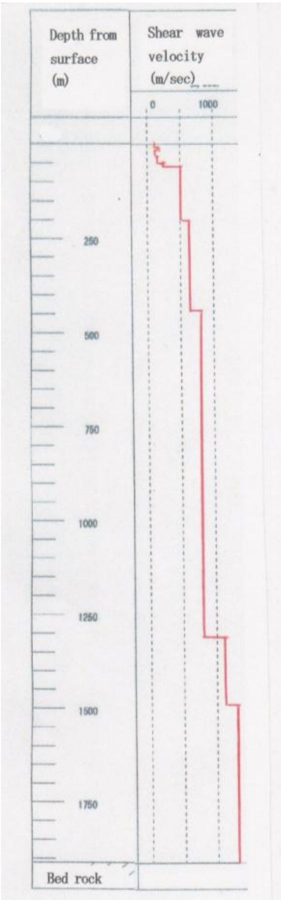

Figure 3.4. Shear wave velocities of each layers

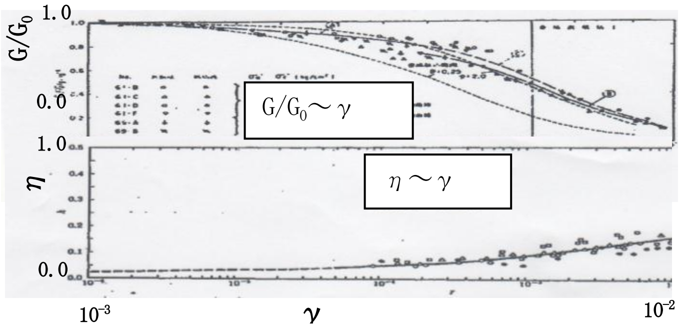

Figure 3.5. Rigidity G/G_0 and damping ratio η for γ

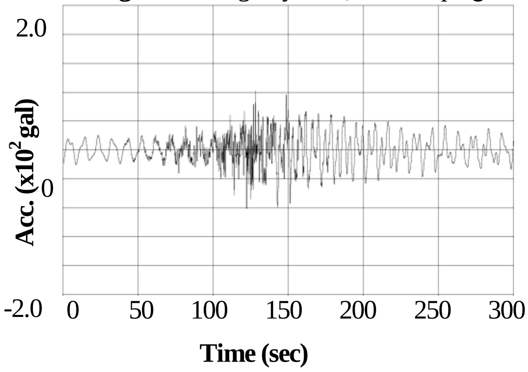

Figure 3.7. Acceleration waves at surface

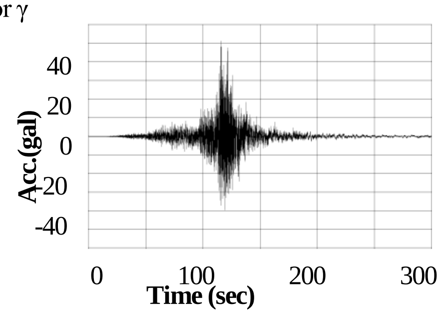

Figure 3.6. Input waves to bedrock

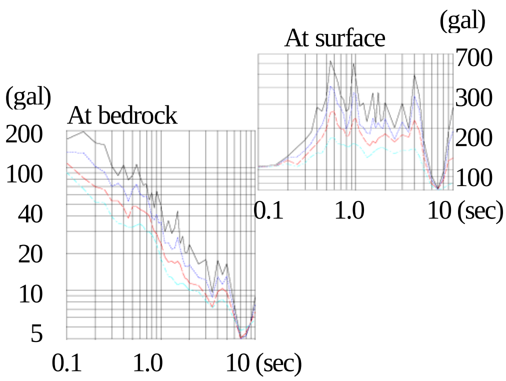

Figure 3.8. Comparison of acc. waves spectra

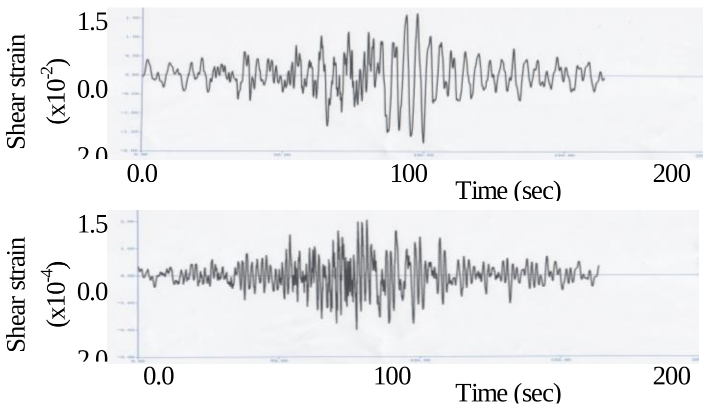

Figure 3.9. Shear strain waves at surface and 150m below

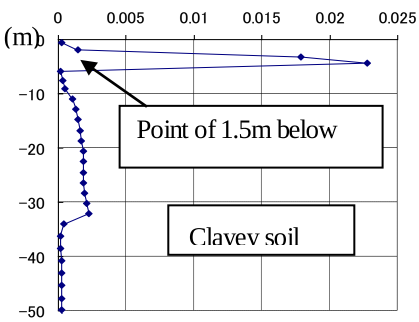

Figure 3.10. Shear strains at surface

tsunami, damage caused by liquefaction was dispersed across a wide stretch of East Japan and resulted in uneven settlement and breakage of houses on alluvium ground.

Urayasu City is separated from Tokyo by the Edo River and encompasses newly extended reclaimed land in the Tokyo Bay. Residential areas in the City without soil improvement experienced severe liquefaction as a result of this earthquake. These areas had not experienced liquefaction caused by earthquake before this event. It is necessary to investigate the reason why this occurred and to provide the countermeasures against liquefaction for the future.

Urayasu is situated on the Kanto Plain, which has very deep sedimentary layers around 2,500 m in total thickness from the bed rock (**Figure 3.2**). Therefore, the seismic waves (at Urayasu City and in Inage Ward of Chiba City) moving up from the bedrock can continue for a long time (**Figure 3.3**), as they reflect and refract through many layers in the case of a very large earthquake. The waves have longer periods than those at the bedrock, although their accelerations are not large. This means that the shear strains caused by the seismic waves become large and continuous, and the energy of the seismic waves moves upwards and concentrates in the surface layers. To investigate the process of liquefaction at Urayasu City a series of seismic response analyses were performed from the bedrock to the surface.

The depth of the bed rock (Vs=2,000~2,500m/sec) at Urayasu is estimated to be about 2,000 m from the surface. The intermediate layers are made up of diluvium deposits and the surface layer is of alluvium deposits of about 50 m in depth. The velocities of shear waves (Vs) in these geologies are shown in **Figure 3.4**. The shear modulus at the strain of 10^{-6} is given from the shear wave velocity. Its value decreases and the damping ratio increases until a strain (γ) of 10^{-2} (**Figure 3.5**).

The input waves to the bedrock use the records of the 2011 East Japan Earthquake (**Figure 3.6)** at a depth of 3,500 m from the Iwatsuki Observatory. A series of the response analyses conducted using SHAKE and FLUSH on the geology at Urayasu were performed to ascertain the transformations of the acceleration, velocity, shear strain, etc. The calculated waves and their acceleration spectra at the surface are shown in **Figure 3.7** and **Figure 3.8** using SHAKE, and prove the amplification of the long-period waves and the extended duration of the observed waves. The waves continue for a long time corresponding to the duration of liquefaction.

The level of strain, which is more than 10^{-3}, is enough to provoke liquefaction at the surface. **Figure 3.9** shows the shear strain waves at the surface calculated using FLUSH, which are amplified compared with those at the intermediate layer 150 m below. **Figure 3.10** shows the amplification of shear strain in clayey soil and loose sand layers near the surface.

4. LIQUEFACTIONS AT OTHER PLACES BY THE PAST EARTHQUAKES

4.1. The 1994 Far-Off Sanriku Earthquake

Hachinohe City is located in the northern-eastern part of Japan (**Figure 4.1**). The 1994 Far-Off Sanriku Earthquake with a magnitude of 7.5 on the JMA (Japan Meteorology Agency) scale, caused very serious damage in the Hachinohe region, 200 km west of the epicenter, on December 28, 1994.

Figure 4.1. Liquefied places in the past in Japan

Photo 4.1. Damage by liquefaction at the Hachinohe Port

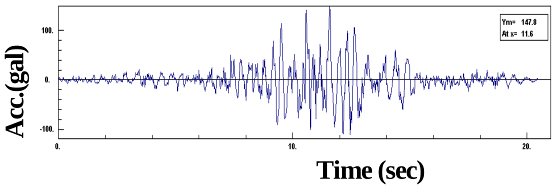

Figure4.3. Input waves observed at H.I.T.

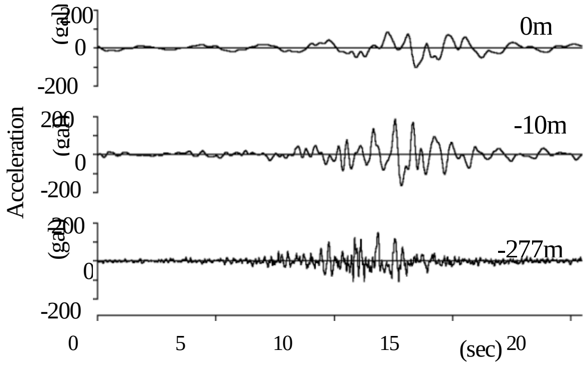

Figure 4.4. Calculated acc. waves by SHAKE

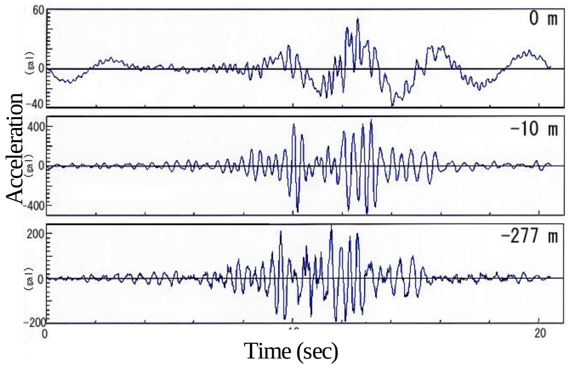

Figure 4.5. Calculated acc. wave by FLUSH

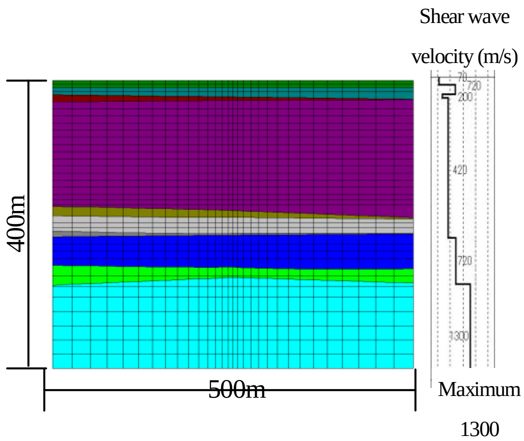

Figure 4.2. Model of geology at the 2nd port

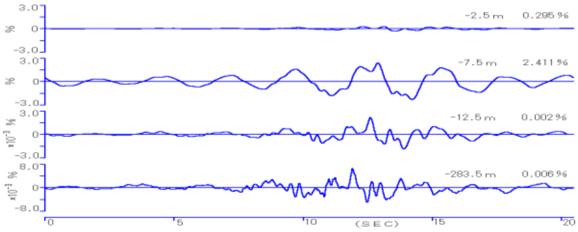

Figure 4.6. Shear strain waves at the 2nd port

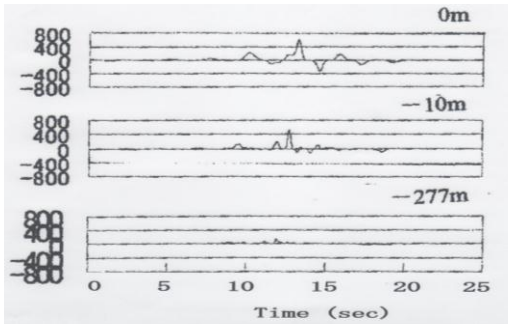

Figure 4.7. Transition of seismic wave energy

Liquefaction during this earthquake, which had a maximum acceleration of 675 gal, was concentrated chiefly in the harbor area and significantly damaged harbor facilities (**Photo 4.1**).

Large and small sand boils, subsidence of reclaimed land, displacement of quays and other kinds of damage were observed at the 2nd Port, where the bedrock is estimated to lie about 400 m underground. The ground consists of fill soil from the surface to 15 m down, alternating layers from the Pleistocene Period from 15 m to 45 m, and layers from the Tertiary Period below 45 m.

To confirm the mechanism of liquefaction at the saturated sand layer on the soft cohesive layers, SHAKE and FLUSH analyses were performed using a soil profile at the 2nd Port, as shown in **Figure 4.2**.In the response calculations, seismic waves with a maximum acceleration of 147 gal (**Figure 4.3**), recorded in the hard Paleozoic mudstone were injected into the bedrock, and the elastic shear coefficients of each layer were derived from the shear wave velocity.

The calculated results for **Figure 4.2** using SHAKE and FLUSH are shown in **Figure 4.4** and **Figure 4.5**. **Figure 4.6** shows the waves of shear strain at several depths at the 2nd Port and explain the tendency of shear strain waves with a long period to amplify as they progress toward the surface. **Figure 4.7** shows the transition of seismic energy expressed in $1/2V^2$.

These results mean that ①The maximum acceleration is not so large. ②The periods of the waves are rather long. ③The generation of liquefaction comes some time after the main shock. ④It continues for a long time.

4.2. Other incidences of liquefaction caused by past earthquakes

The concept of the mentioned hypothesis was applied to analyze past incidences of liquefaction. The 1948 Fukui Earthquake, on the Fukui Plain in Japan (**Figure 4.1**) provoked the most severe liquefaction. It caused a large amount of damage to Fukui City, which is sited on a relatively firm ground (**Photo 4.2**) and liquefied the surface layers around the entire plain including the gravel surface along the Kuzuryu River (**Photo 4.3**).

Two response analyses of firm and loose surface layers of 10 m on the silt layer were performed using the section in **Figure 4.8** to evaluate the influence of rigidity at the surface. Regardless of the input waves (**Figure 4.3**) sent to the bedrock 248 m below, measured at Hachinohe, the calculated results reasonably explain the influence of the rigidities of surface in **Figure 4.9** and **Figure 4.10**. In the case of the firm layer, the acceleration became about 300 gal with short periods, and the maximum response increased to more than 1,000 gal at 0.2~0.3 seconds. In the case of the loose layer, the small waves accelerated to a maximum of 36 gal,

Photo 4.2. Collapse of building and houses

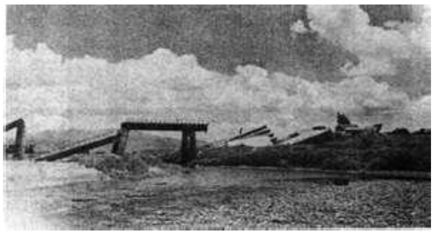

Photo 4.3. Fallen bridges caused by liquefaction on the Kuzuryu R.

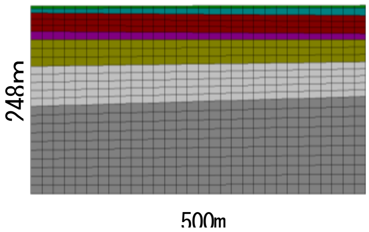

Figure 4.8. Section for FLUSH

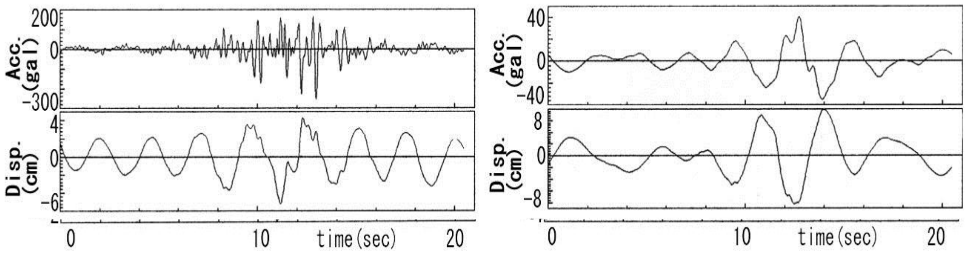

Figure 4.9. Acceleration and displacement waves on the firm (left) and loose (right) surfaces

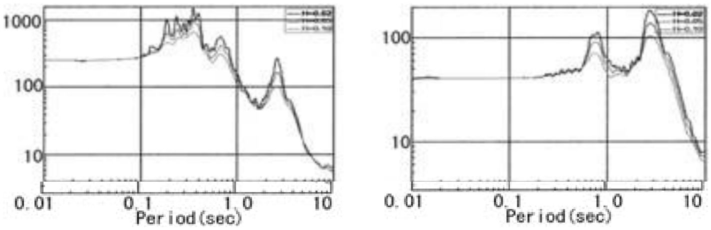

Figure 4.10. Response spectra of acceleration on the firm (left) and loose (right) surfaces

Photo 4.4. Leaned apartments

Photo 4.5. Fallen bridges

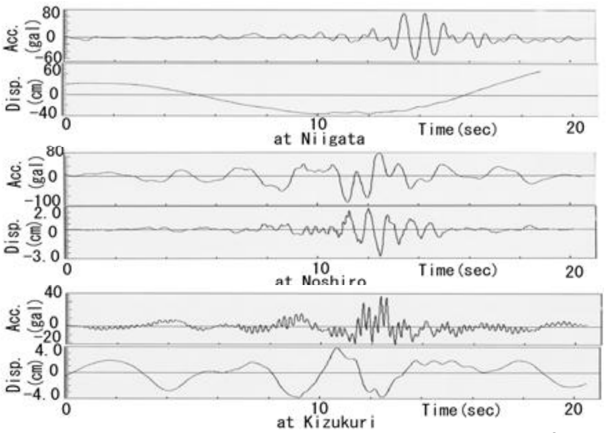

Figure 4.11. Accelerations and displacements on surface

Photo 5.6. Collapsed bank

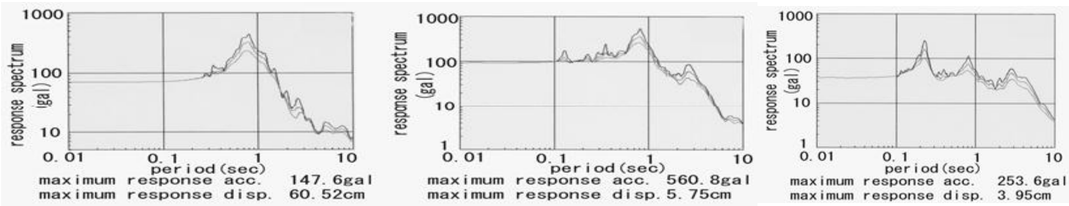

Figure 4.12. Response spectra of accelerations on surfaces in 3 cities

with two long peak periods of 0.8 and 3seconds, and the maximum shear strain became 2.5 x 10-2. These results show that the possibility of liquefaction occurring depends on the rigidity of the surface.

The 1964 Niigata Earthquake with a magnitude of 7.5 (Figure4.1) was the first earthquake in Japan to provoke notice of the serious damage caused by liquefaction (Photo4.4, Photo4.5). The 1983 Mid Japan Sea Earthquake, with

a magnitude of 7.7, spread a large amount of damage over a wide area due to the effects of liquefaction and tsunami. The low-lying areas of Niigata city suffered serious liquefaction. Land along the coastline near Noshiro was damaged (Photo5.6) and Kizukuri was slightly affected by the amount of sand boils caused by the 1983 Mid Japan Sea Earthquake.

In Figure4.11 and Figure4.12 calculated with the same input waves from Hachinohe sent to the bedrock in the modeled section at three places, the accelerations and the displacements, and their maximum response spectra on the surface grounds are illustrated. Figure4.11 and Figure4.12 show the properties of the liquefied ground. The seismic waves at the surface possessed small accelerations with long predominant periods. The shear strains caused by each wave became 0.6 x 10-2 in Niigata, 4 x 10-2 in Noshiro and 0.1 x 10-2 in Kizukuri, which are all enough to generate liquefaction. From these calculations each place can be seen to show their own unique reactions, even though the same input waves were sent to the bedrocks.

In the 1964 Alaska Earthquake with a magnitude of 9.2 and the 2011 Canterbury Earthquake with a magnitude of 6.1, there occurred land slides without apparent sand boils (Photo4.7, Photo4.8 and Photo4.9). Even though it is speculated that these phenomena are related to liquefaction, the casual mechanism is not yet proved.

In a geological survey for the 2012 East Japan Earthquake, Mr. Inasaki, a senior researcher at the Public Works Research Institute, performed a very precise boring experiment at a liquefied area in Makuhari between Urayasu and Inage. **Photo 4.10** shows the partially liquefied sand layer on a clayey layer. It indicates a possibility that this liquefied layer may carry out to slide the upper layer. This phenomenon may be proved by the response analysis using SHAKE or FLUSH.

Photo 4.7. Damage by land slide in Alaska Eq.

Photo 4.8. Land slide at Christchurch

Photo 4.9. Crack on the land slide at Christchurch

Sand layer

Liquefied sand layer

Clayey layer

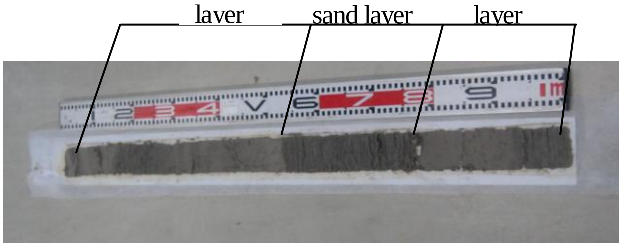

Photo 4.10. Partially liquefied sand layer on clay

5. COUNTERMEASURES AGAINST LIQUEFACTION

To prevent the liquefaction of saturated sand in an earthquake, it is necessary to estimate the possibility of liquefaction. In Japan an estimation method using the FL value (FL=R/L ---Factor of Liquefaction, R: Resistance of Ground, L: Seismic Force) is popular. However, the main cause of liquefaction is not the intensity of seismic force but the shear strain originating from seismic waves with relatively long periods of the cohesive layer below. The Resistance of Ground also needs to adopt the value of the static shear strength, not the dynamic tri-axial test, as mentioned above.

For estimation of the possibility of liquefaction, it is necessary to conduct a response analysis reaching the sedimentary layers from the bedrock. Liquefaction is usually generated in cases of more than 10^{-3} level of shear strain at the saturated sandy soil layer. It seldom occurs at the saturated gravel or bolder layers, depending on the scale of earthquake and the thickness and the rigidity of the intermediate cohesive layers. The grade of liquefaction of saturated sandy soil at each place can be estimated by response analysis using the soil profile, all way to bedrock and the rigidities of all layers, which are given by geophysical exploration methods, and the scale and the duration of the earthquake (seismic energy).

The countermeasures to prevent or to decrease the influences of liquefaction can be deduced from the above mentioned mechanism as follows.

①(Mitigation of excess pore water pressure) As the measures to mitigate the excess pore water pressure caused by the collapse of the effective stress in the sand layer, sand drain piles (**Figure 5.1**), sand compaction piles, gravel drain piles (**Photo 5.1**), paper drain methods (**Photo 5.2**) and other methods are applicable. However, in these cases a small settlement of the ground is inevitable caused by spout of ground water. **Photo 5.3** shows the settlement of a quay by paper drainage at Hachinohe Port. The screwed hollow steel pipe with strainers (**Figure 5.2**) is considerably effective as a measure to release the excess pore water pressure.

②(Ground improvement & consolidation of surface layer) To endure the shear strain caused by the seismic waves, ground improvement (**Figure 5.3)** and the consolidation of surface layer (**Figure 5.4**, **Figure 5.5**) are effective countermeasures as mentioned in the case of the 1948 Fukui Earthquake. (**Figure 4.2**). In case of spread foundation, the consolidation of surface layer is required to a certain depth and width.

③(Deep rigid foundation & reinforcement of foundation) At the places where it is feared liquefaction may occur, foundations of a proper rigidity (**Figure 5.6**, **Figure 5.7**) should be built into the bearing stratum. If necessary, ground improvement may be executed for the reinforcement of foundation (**Figure 5.8**, **Figure 5.9**).

④(Restriction frame for soil shear strain) Sometimes, rigid frame walls (**Figure 5.10)** are adopted to restrict the shear strain in the saturated sand and they have been proved to prevent liquefaction effectively. For oil tank the method shown in **Figure 5.11** is proposed. The method shown in **Figure 5.12** is a seismic reinforcement for an existing pile foundation.

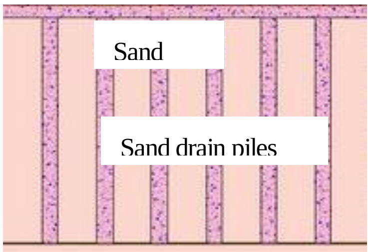

Figure 5.1. Sand drain piles

Photo 5.1. Gravel drain piles

Photo 5.2. Paper drain method

Photo 5.3. Settled quay by paper drain method

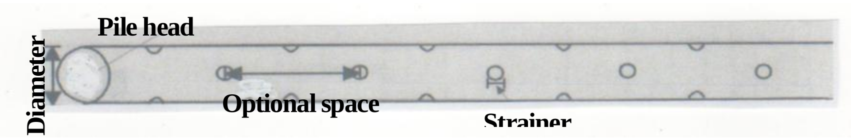

Figure 5.2. Steel pipe pile with strainers

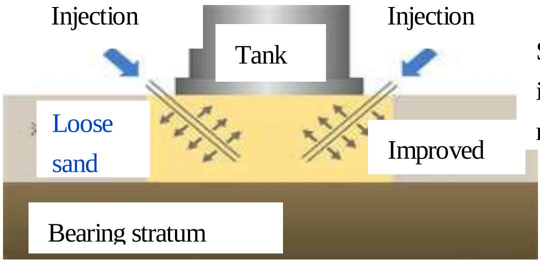

Figure 5.3. Ground improvement under a tank foundation

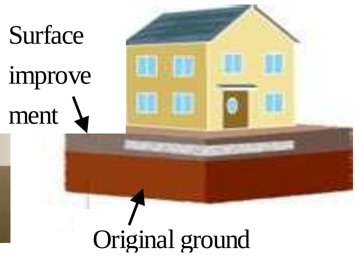

Figure 5.4. Surface improvement

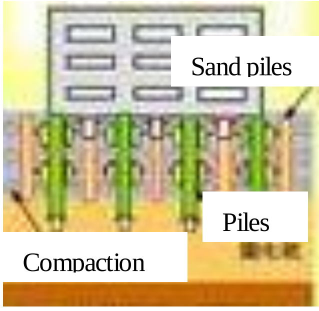

Figure 5.5. Shallow soil improvement

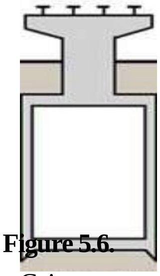

Figure 5.6. Caisson foundation

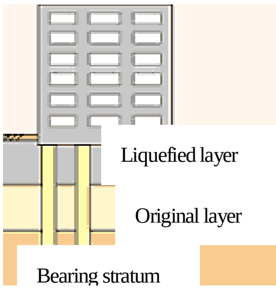

Figure 5.7. Pile foundation

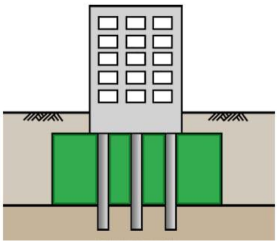

Figure 5.8. Reinforced pile foundation

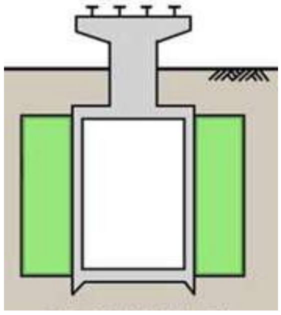

Figure 5.9. Reinforced caisson foundation

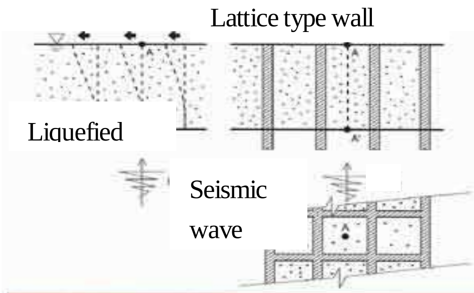

Figure 5.10. Rigid frame wall

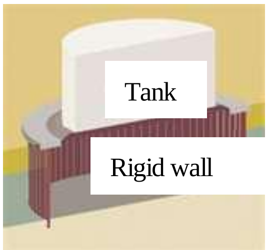

Figure 5.11. Rigid steel pipe wall

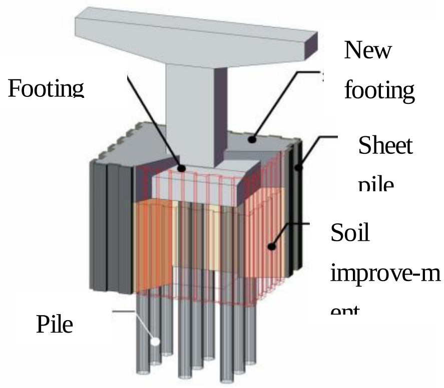

Figure 5.12. In-Cap Method

Photo 5.4. Conveyer on ground liquefied severely

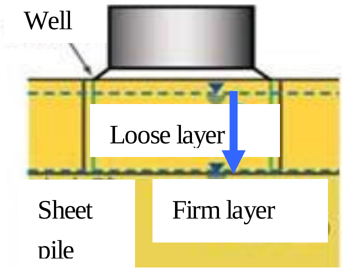

Figure 5.13. Dewatering method

⑤(Ties between structures) During liquefaction, the acceleration is not large, but the displacement is large. Therefore, it may be enough to stop the deformation of structures with ties. **Photo5.4** is an example of a high-raised belt conveyer which maintained functionality without damage on the severely liquefied ground.

⑥(Dewatering etc.) If the sand on the surface is not saturated, liquefaction will not occur. One proposal is to lower the ground water table through wells (**Figure5.13**). However, the maintenance costs required by this proposal are significant and there is a fear to settle the surrounding area.

6. CONCLUSIONS

A series of dynamic analyses applied to multiple layers above the bedrock, has verified the concept of the mechanism of liquefaction of saturated sand layer during a large earthquake. The physical coefficients of each layer used in the analysis can be estimated by elastic wave exploration. The results obtained using SHAKE and FLUSH and based on the multi-reflection theory correspond with actual phenomena observed in the past large earthquake as follows.

(1) Waves moving upwards from the bedrock amplify and pile up in soft layers such as clay or silt.
(2) Waves that reach the surface through soft layers tend to have elongated periods.
(3) Waves with a relatively long period continue for a long time after the main shock.
(4) The shear strain of such waves near the surface has the potential to reach a level high enough (more than 10^{-3}) to liquefy the upper saturated sand layer.
(5) The seismic energy to generate liquefaction becomes large gradually through the intermediate layers from the bedrock to the surface.
(6) Calculations using FLUSH are more realistic than those using SHAKE.

Furthermore, the concept of general applicability has been proved through several response calculations using FLUSH for six sites that suffered severe liquefaction caused by large earthquakes in the past. From a series of these calculations, it has been found that calculations based on this concept, can reproduce and predict actual liquefaction in a quantitative fashion. Optimal countermeasures to prevent or to decrease the impact of liquefaction can be selected by taking into consideration of the above mentioned mechanism. This conception will contribute to the improvement of seismic design method for liquefaction.

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