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INTEGRATION AMONG MECANISM OF LIQUEFACTIONS DURING EARTHQUAKE

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Abstract

The liquefaction phenomena of saturated sandy soil during a large earthquake were often observed at many alluvium grounds in the past. The main cause of the phenomena is the existence of soft and flexible clayey layer beneath the liquefied sandy layers and the process of the phenomena can be explained with the multi-reflection theory and dynamic response calculation using FEM, through the thick sedimentary layers from the bed rock. The energy of seismic waves is stored into such soft layers as clayey soils near the surface. The seismic energy absorbed in the soft and flexible clayey layer excites the predominant shaking waves with long periods in this soft layer, which transfer large shear strain waves to the saturated sandy layer above and provokes the excess pore water pressure to lead liquefaction.

In 2018, a large earthquake with M=7.5 occurred at Sulawesi in Indonesia and people of about 1300 were buried alive in the mud flow by liquefaction. In the same month, another earthquake with M=6.7 occurred at Hokkaido in Japan and liquefied volcanic ash flowed out along the slope, damaging residential area. The causes of both liquefactions are common that the weathered soft clayey layer makes to liquefy the less cohesive layer above. This mechanism of liquefied soils by the excess pore water pressure is similar to the liquefaction on the alluvium deposits

Finally, the paper indicates the method to judge the possibility of liquefaction depending on the structure of geology from the bedrock and the scale of the earthquake. Furthermore, it shows the basic countermeasures for the liquefaction.

Keywords: liquefaction, multi-reflection theory, dynamic response analysis, shear strain wave, impact wave

1. Mechanism of liquefaction on alluvial ground 〔1〕

The phenomenon of liquefaction is observed in saturated sandy grounds on the alluvial deposit during the large earthquakes. Generally, liquefaction is originating from excess pore water pressure and diminishing effective stress among the sand grain structures by the repeated large

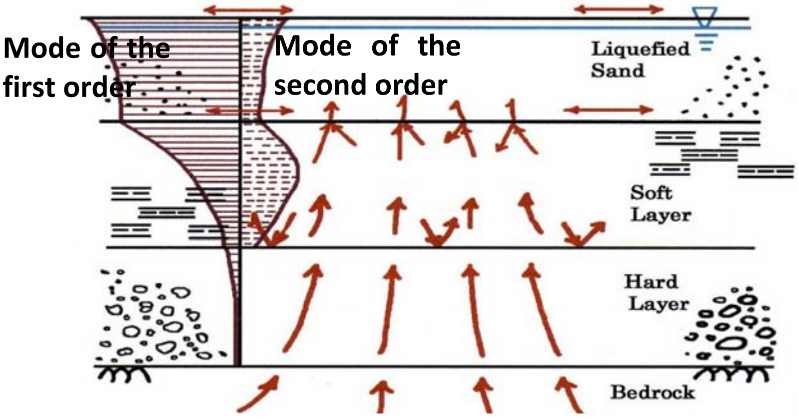


Fig.1 Concept of mechanism of liquefaction

shear waves. A model of the liquefaction mechanism based on this concept is illustrated in Fig. 1.

The seismic waves transferred from the bedrock tend to accumulate in the relatively soft near-face formation. During a large earthquake, the soft formation absorbs a great deal of wave energy and begins to vibrate finally at its own predominant periods. If a strong hard layer overlays on the soft formation, the vibration mode is the second order, if not, it is the first order. A thicker soft formation allows the accumulation of a large amount of wave energy, which brings about large shear deformation in the upper saturated sand layer. The shear deformation of the saturated sand layer increases the pore water pressure in a confined situation and diminishes the effective stress among the sand grain structures. Then, the sand layer decreases own rigidity gradually and liquefies finally. The liquefaction in the sand layer progresses upward from the border of the soft formation, depending on excess pore water pressure, and sand boils or springs with subsidence generate on the ground surface. In case of the vibration mode of the second order, the movement of the soft layer is restrained and transfers the strain of shear waves to the upper sand layer, which convey the original acceleration waves from the lower strata to the surface.

2. Liquefaction at Hachinohe harbor by the 1994 Far-Off Sanriku Earthquake〔1〕

The 1994 Far-Off Sanriku Earthquake with a magnitude of 7.5 caused grave damage in Hachinohe region, 200 km west of the epicenter, on December 28,1994. Liquefaction during this earthquake with the maximum acceleration of 675 gal, was concentrated chiefly in the harbor area and significantly damaged harbor facilities. Large and small boiling, subsidence of reclaimed ground, displacement of quays and other damage were observed at the 2nd Port. The ground consists of fill soil from the top layer to 15 m below, alternating layers in the Pleistocene Period from 15 m to 45m, and of the Tertiary Period below 45 m (Fig.2).

To investigate these phenomena, a series of response analyses based on the multiple reflection theory were performed using a two-dimensional FEM analysis (FLUSH). In these analyses the seismic waves with

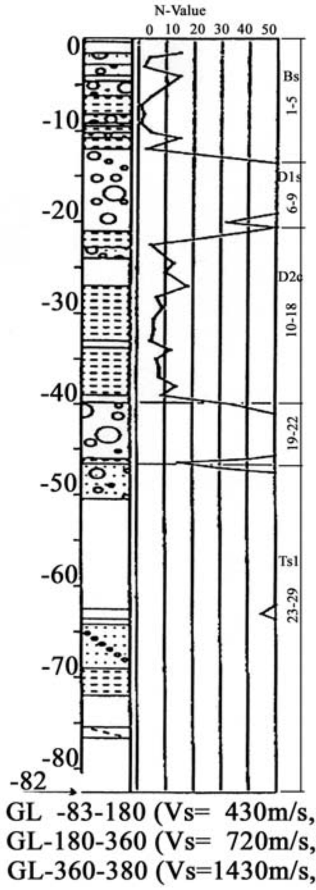


Fig. 2 Soil profile at 2nd Port

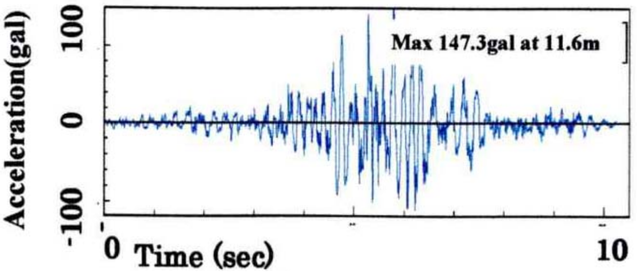


Fig.3 Input wave observed at H.I.T.

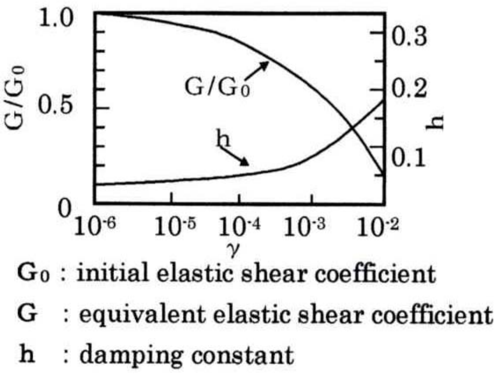


Fig.4 Equivalent linearingation of elastic shear coefficient G and dumping constant h

a maximum acceleration of 147 (Fig. 3), recorded in the Paleozoic hard mudstone 20 m bellow Hachinohe Institute of Technology (HIT), were injected in the bedrocks at the Port, and the elastic shear coefficients G of each layer were derived from the velocity of shear wave Vs. Elastic shear coefficient G and dumping coefficient h of various geologies change in a narrow curve width, according to shear strain (Fig. 4).

The curves of the maximum value of acceleration, velocity and shear strain from the response calculation for the grounds of the 2nd Port are indicated in Fig. 5. At the 2nd Port, though the value of acceleration does not amplify so much, the velocity grows the large, the shallow depth and the shear strain increases rapidly at the cohesive layer near the surface, to reach a sufficiently great value to liquefy the upper sand layer. The value of shear strain of 2.4 x 10^{-2} at a depth of 10 m, is enough for the primary liquefaction.

Fig.6 is the result of the calculated accelerations from the deep layers at the 2nd Port and it demonstrates the acceleration waves decreased extremely comparing with the lower strata. Fig. 7 shows the shear waves at several depths and it explains the tendency of their amplification with a long period toward the surface. The shear waves with long periods have large energy and transfer large shear strain to the saturated sandy layer above. In this calculation the adopted input waves are only one-direction waves and the calculated figures are the values at the center of section. Fig. 8 shows the transition of seismic wave energy expressed in term of 1/2・V^2.

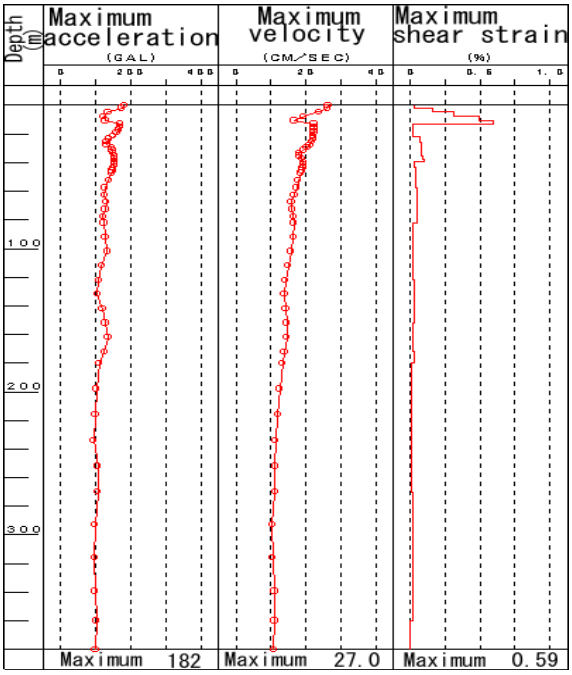


Fig.5 Amplification of wave at the 2nd Port

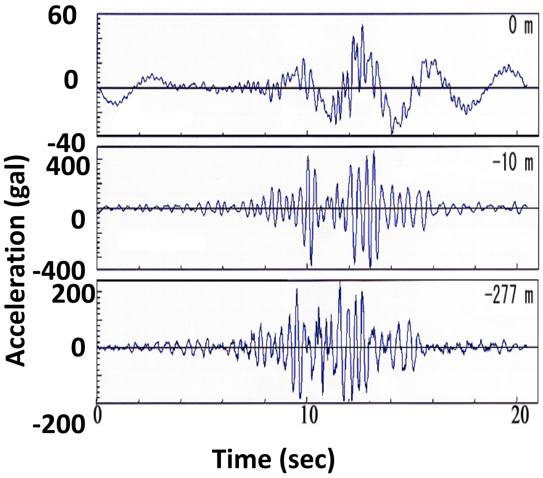


Fig.6 Calculatied waves by FLUSH

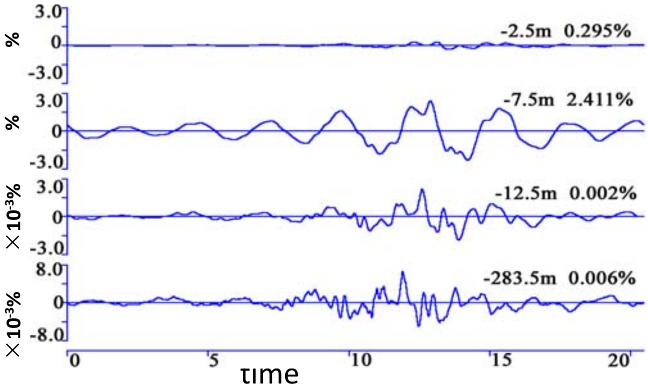


Fig.7 Shear waves in depth at the 2nd Port

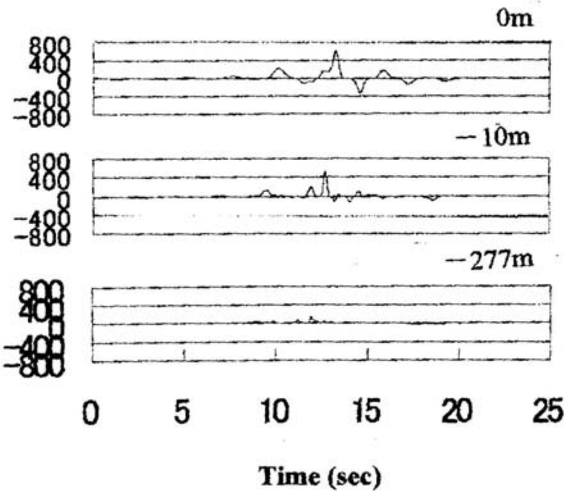


Fig.8 Transition of seismic energy

From these results, several points related with liquefaction are clarified.

(1) The waves of acceleration, velocity and shear strain moving upwards from the bedrock amplify and accumulate in soft layers near the surface.
(2) The seismic waves calculated at the surface on a soft layer become the waves of relatively small acceleration with elongated periods and continue long time after the main shock.
(3) The stored shear waves with long periods have the energy of high level enough to liquefy the upper saturated sandy layer and to continue liquefaction long time.
(4) The seismic wave energy gradually becomes large through the intermediate layers from the bedrock.

3. Application of response analysis to other large liquefactions〔1〕

Since the results gained from the response analysis method at Hachinohe Harbor are qualitatively very reasonable, the same analyses have been applied on the grounds where heavy liquefactions have been observed in the past large earthquakes. They are the 1948 Fukui Earthquake, the 1964 Niigata Earthquake and the 1983 Mid Japan Sea Earthquake. Though on each geology the waves at HIT in Hachinohe were injected to each bedrock in the response analyses, the values of shear waves calculated in the surface sandy layer are enough to generate liquefaction phenomena and every shapes of shear waves are quite different depending on each stratum structure. Their analyzed phases of liquefaction are similar to the calculated results at the 2nd Port of Hachinohe harbor above-mentioned.

Furthermore, the influence of rigidity of surface layer is investigated in the analysis of liquefaction about the 1948 Fukui Earthquake. In the 1948 Fukui Earthquake a large-scaled liquefaction covered whole Fukui basin of loose alluvial deposit shown with parenthesis in Table 1. Specially, along the Kuzuryuu River, many bridges were fallen down as shown in Fig.9. On the relatively hard ground (Table 1) at the edge of the basin, an old building was broken but another new building behind remained unhurt (Fig.10). Perhaps, the former building might take no seismic design compared with the latter equipped it.

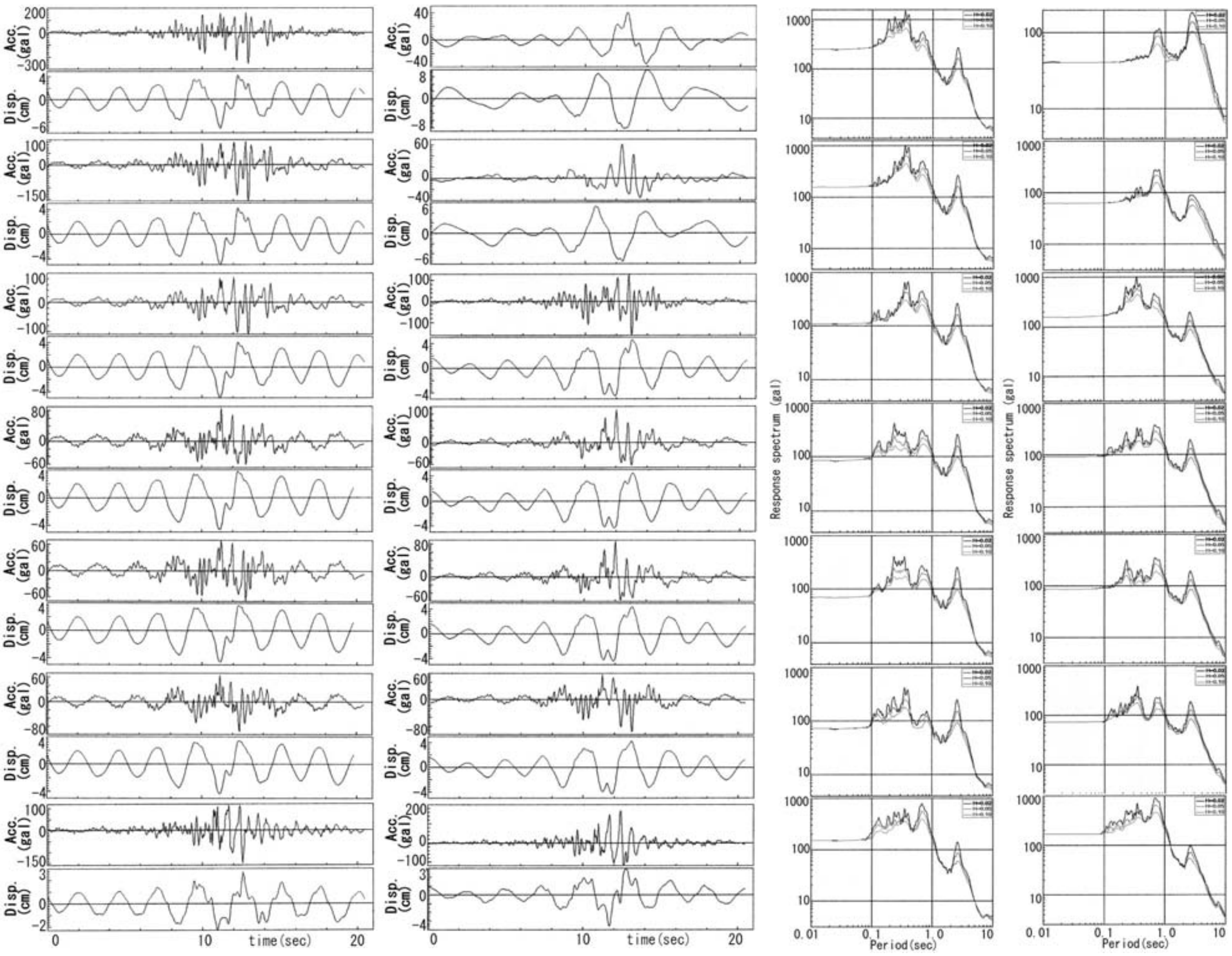
The results of the response calculation through stratum structure on two grounds are given Fig.11. In case of the ground with loose surface layer, the small waves accelerated to a maximum of 36 gal, with two long peak periods of 0.8 and 3 seconds, and the maximum shear strain became the level of 2.5 x 10^{-2} enough

Fig.9 Rail way bridge fell down by liquefaction

Fig.10 Fallen and sound buldings

Table 1 Geology at Fukui basin

number	geology	velocity of shear wave (m/s)	thick -ness (m)
1	sand	70	1.5
2	sand (Holocene)	720 (70)	8.5
3	sandy silt (Holocene)	420	24
4	gravel (Pleistocene)	800	10
5	gravel (Pleistocene)	1000	32
6	sand (Pleistocene)	720	50
7	sand·silt	420	122
8	bed rock	1700	–



Comparison of acceleration and displacement waves calculated at Fukui basin (hard layer)

Comparison of acceleration and displacement waves calculated at Fukui basin (loose layer)

Response spectra (hard layer)

Response spectra (loose layer)

Fig.11 Acceleration & displacemant waves and reponse spectra of acceleration waves in each strata of the grounds with loose & hard surface layers

to invite liquefaction. In case of the ground with hard surface layer, the acceleration became about 300 gal with short periods, and the maximum response acceleration increased to more than 1,000 gal at the period of 0.2~0.3 seconds in the spectra (Fig.11). Though this level of acceleration can be covered with the conventional seismic coefficient method, the structure without a seismic design can not endure. These results show that the liquefaction or damage of structures depends on the rigidity of the surface (see Fig.1).

Thus, the response analysis method from the bedrock is useful to understand liquefaction and gains rational knowledge on liquefaction.

4. Knowledge on liquefaction at Tokyo Bay by the 2011 East Japan Earthquake 〔2〕

The 2011 East Japan Earthquake (Magnitude:9) occurred at 14:46 on the 11th of March 2011, 130 km far from the main land. Though the majority of damage to life and property was caused by the 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 and Makuhari are located along the northern coast line of Tokyo Bay where the wide residential areas without soil improvement on the newly reclaimed lands experienced severe liquefaction as a result of this great earthquake. These areas had not experienced liquefaction caused by earthquake before.

These areas are situated on very deep sedimentary layers around 2500 m in total thickness from the bed rock (Fig.12). The seismic waves moving up from the bedrock can continue for a long time, because they repeat reflection and refraction through multiple sedimentary layers in the case of a great earthquake. This means that the shear strains caused by the seismic waves with long period and low acceleration, become large and continuous and the seismic wave energy moving upwards concentrates in soft layers near the surface.

A series of seismic response analyses were conducted from the bedrock to the surface using FLUSH and SHAKE (linear calculation method). The input waves to the bedrock using the records of the 2011 East Japan Earthquake in the firm rock of a depth of 3500 m from the Iwatsuki Observatory. The shear moduli of the intermediate layers of diluvium and alluvium deposits at the strain of 10^{-6} is given from the shear wave velocity (V_S). Its value (G/G_0) decreases and the damping ratio (η) increases, from a strain (γ) of 10^{-4} until that of 10^{-2} (Fig.14). The calculated waves and their acceleration spectra by SHAKE are shown in Figure 15 and Figure 16. Figure 17 is the amplified shear waves (level of 10^{-2}) at the surface, enough to provoke liquefaction, compared with those at the intermediate layer 150 m below.

National Institute for Land Infrastructure Management of Ministry of Land Infrastructure and Transport published the record of measured acceleration waves at Makuhari (Fig.18). Fig.19 is a running spectrum of these acceleration waves 〔3〕. The calculated waves from the bedrock 2000 m deep in Fig15 nearly reproduced the waves in Fig.18. The shapes of this spectrum are approximately similar at the range of predominant period with the spectrum of the dumping constant of 10% (red line) in Figure 16.

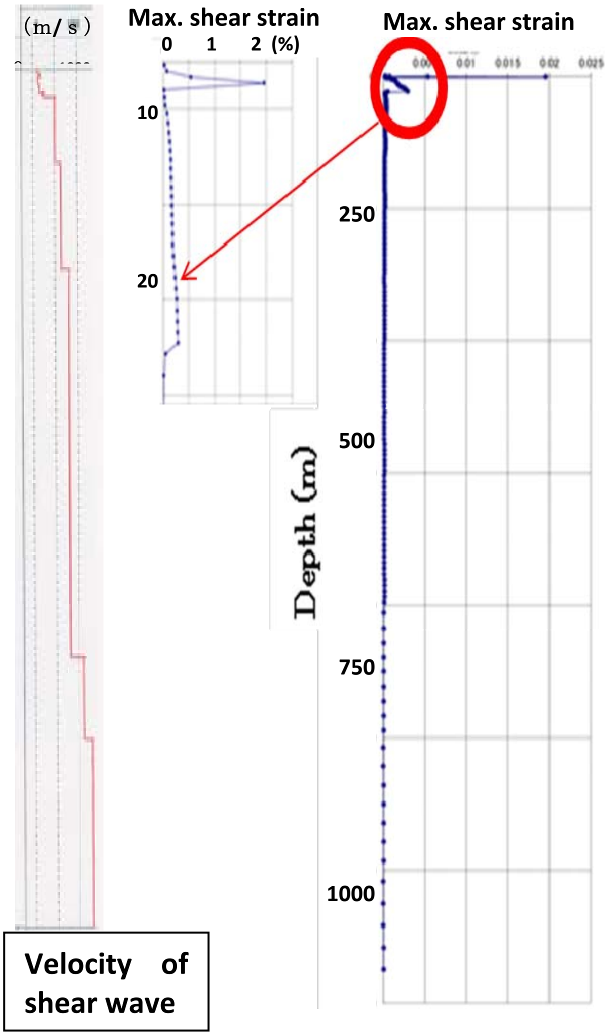


Fig.12 Velocity of shear wave & Max. value of shear strain

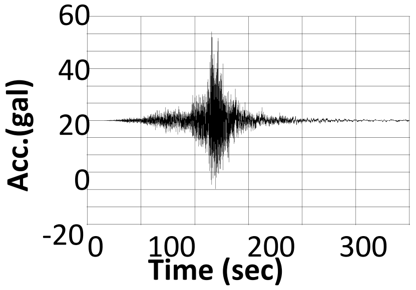


Fig.13 Input waves to bedrock

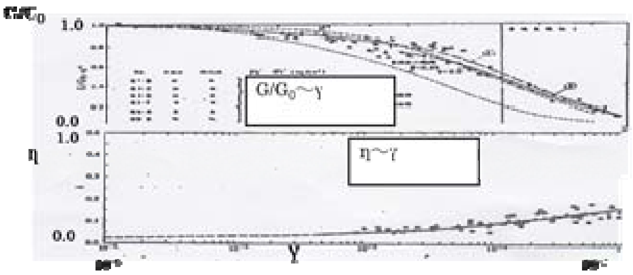


Figure 14 Rigidity G/G0 and damping ratio η for strain γ

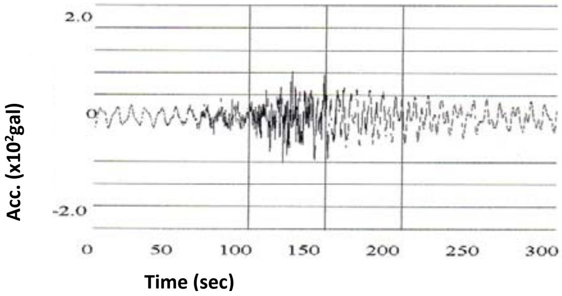


Figure 15 Calculated acceleration waves

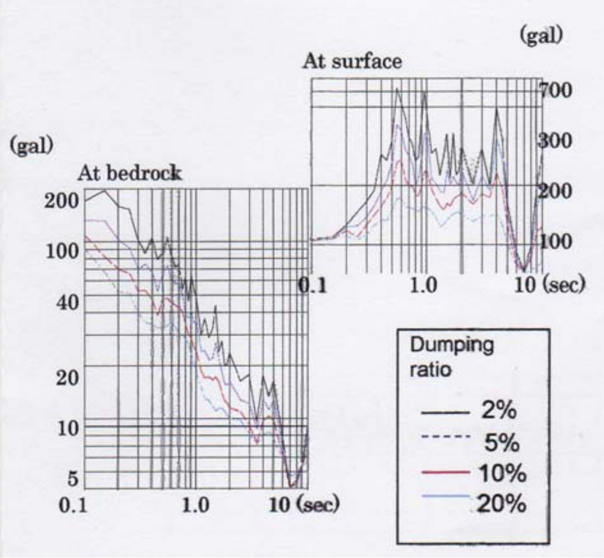


Figure 16 Comparison of spectra

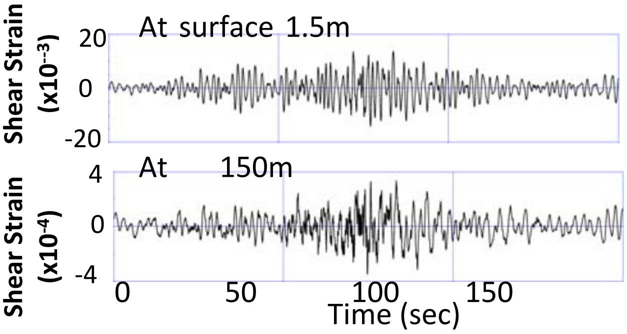


Fig. 17 Shear strain waves at surface and 150m below

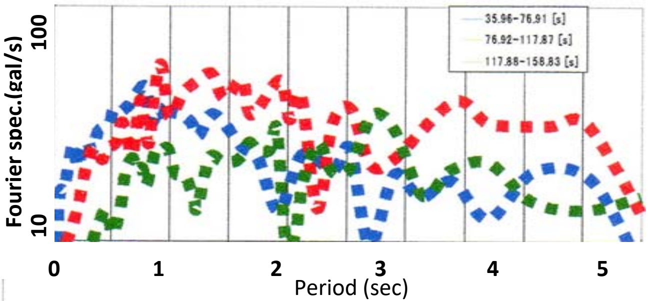


Fig.19 Running spectra of acceleration

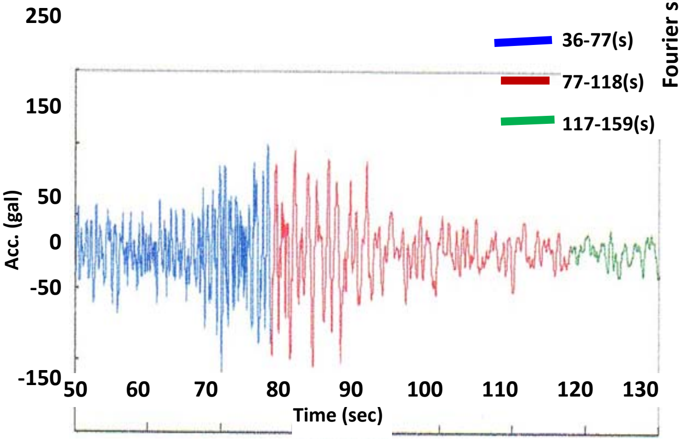


Figure 18 Record of acceleration waves on liquefied ground

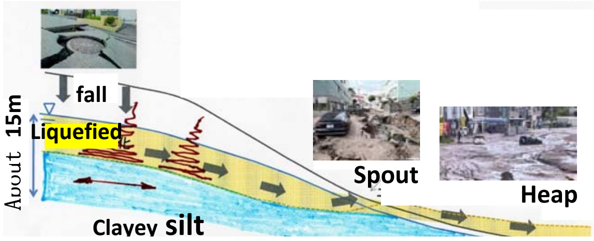


Fig. 21 Assumed mechanism of liquefied volcanic ash flow

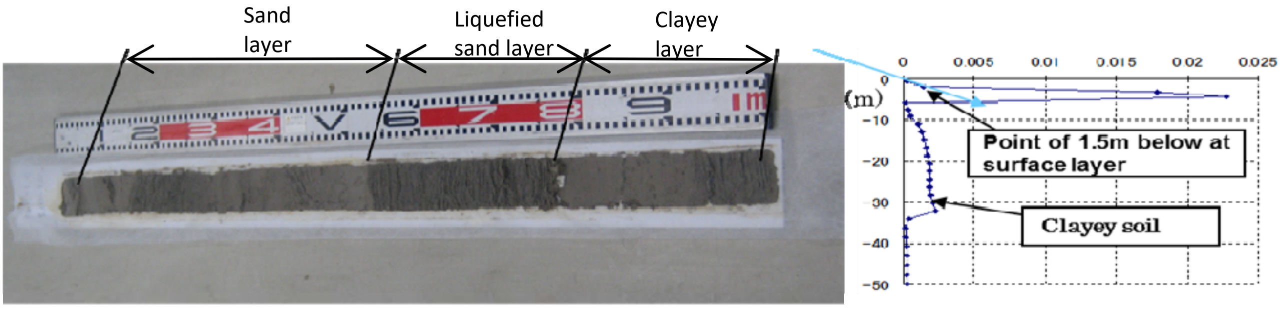


Fig.20 Partially liquefied sand layer on clay and amplified shear strains at surface

In this chapter, a series of analyses at Tokyo Bay coast proved the quantitative reasonableness of this response analysis method following its qualitatively proper performance mentioned in the former chapter. Furthermore, more valuable fact was found through the analysis and measurement. Fig.20 shows a sharp shear strain at the border between soft soil and sandy layer above, and liquefaction stopping midway from the border. This demonstrates the process of liquefaction to progress in the saturated sandy layer. The similar phenomena in Hokkaido were observed on the ground of volcanic ash (Fig.21), where liquefaction occurred

Fig.22 Mud flow

Fig.23 Houses swallowed in landslide

on a weathered layer under the ground water level〔4〕. The liquefied volcanic ash flowed out of a weak point, coupled with leakage from the broken water supply pipe, on the midway of slope before reaching the ground surface and heaped up at the foot of slope, damaging residential area with settlement.

In 2018, a large earthquake with M=7.5 occurred at Sulawesi in Indonesia and people more than 1300 were buried alive in the landslide by liquefaction (Fig.22). Though the detailed geology is not yet published, the liquefied soils look as clayey and sandy soil including clay, gravel and boulders from the photos (Fig.23). It is reported that a few sand boils were observed outside the sliding areas. It suggests that extinguishing or releasing excess pore water pressure is effective to prevent occurrence of liquefaction.

5. Mountainside collapse with debris flow〔2〕

In 2018, Hokkaido Iburi East Earthquake widespread mountainside collapses generated near the epicenter of the earthquake (Fig.24, Fig.25). The main cause of these slides on mountainous slope of volcanic ash is considered to be the excess pore water in a moment by vertical impact waves with very short period and high acceleration, differing from the liquefaction on the alluvium ground caused by the long period waves. The maximum value of an impact wave as a needle is higher than the gravity (Fig.26).

Generally, these vertical impact waves had made many shear failures of structures on relatively firm layers in the past. In this case, they extremely raise the pore water pressure in a moment in the volcanic ash on the slope. Then, the volcanic ash on the weathered slope may liquefy and fall down along the slope as shown in Fig.27. This liquefied volcanic ash (debris flow) ruins various objects except structures with reliable foundation (Fig.24) and covers the fields at the foot of mountain (Fig.28).

Fig.24 Collapses slopes and flowed earth

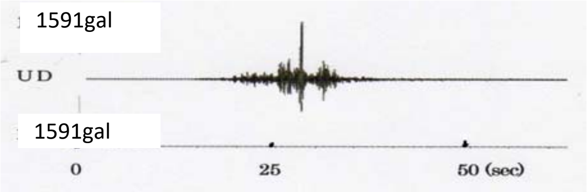


Fig.26 An impact wave in vertical acceleration wave

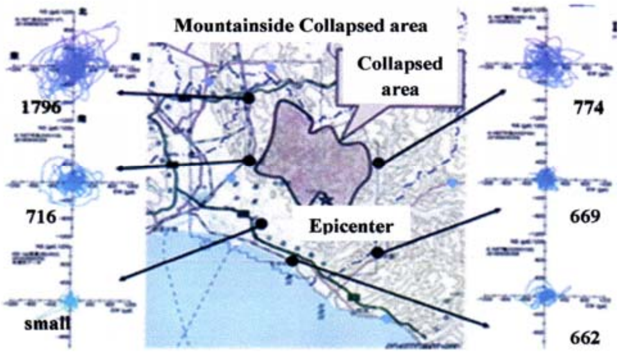


Fig.25 Concentrated area of slope collapse and observed maximum accelerations

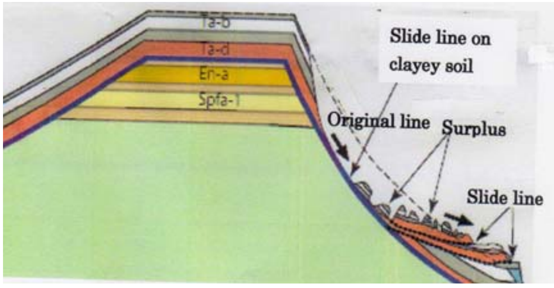


Fig.27 Assumed mechanism of hillside collapse

Fig.28 Liquefied volcanic ash (debris flow) from ravine

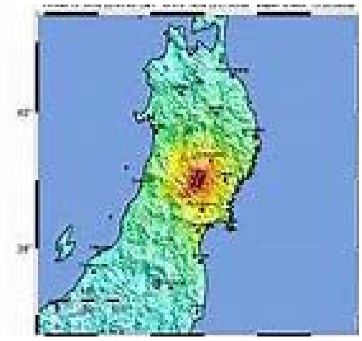


Fig.29 The 2008 Iwate Miyagi Inland Eq.

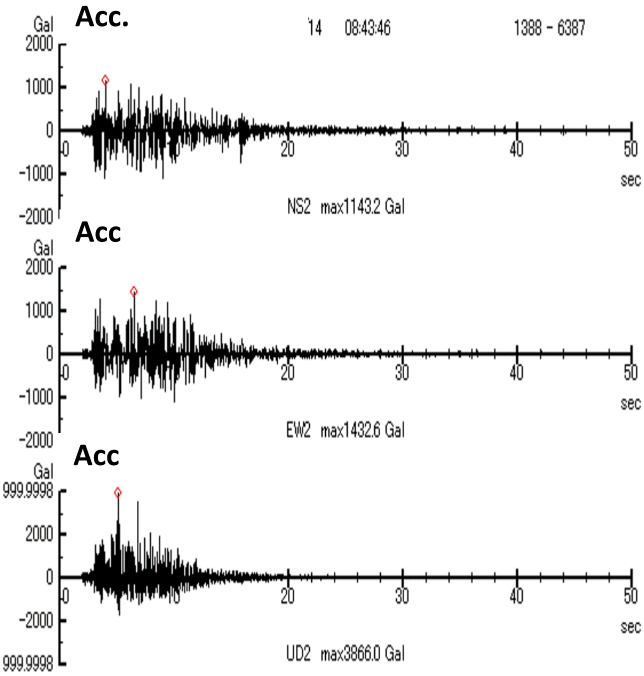


Fig.30 Records of acceleration (NIED)

Fig.31 Various mountainside collapses

The similar phenomena have been observed at other places such as the 2008 Iwate-Miyagi Inland Earthquake (Fig.29), where the maximum value of impact waves reached at about 4 G in the vertical direction near the epicenter (Fig.30). There occurred such various mountainside collapses (Fig.31) as landslips, landsides and collapse of rock mass and a derived debris flow gave heavy damage along the ravine. The detailed shapes and periods of the measured impact waves are not clarified for the cause of collapse.

The impact waves with a very short period in the seismic waves are not yet certified because the current seismograph can only record the waves less than 50 Hz. It is expected that a new high frequency seismograph able to measure waves of some 1000 Hz shall be born for furthermore investigation of the performance by the impact waves in the earthquakes.

6. Prediction and countermeasure for liquefaction

Many people want to know the possibility and the countermeasure of liquefaction at his own site. It is permitted to use the response analysis method proposed in this paper.

Though the response analysis method from the bedrock to the surface can clarify the mechanism of liquefaction, it requires the stratum structure up to the bedrock and the mechanical properties of each stratum (Fig.32), to make the ground model for FLUSH or SHAKE. For the dynamic calculation it is necessary to decide the input seismic waves and their scale. The calculation for the nonlinear response analysis with the equivalent linearization method repeats until convergence within a level of error. Finally, the values of shear wave at each point indicate possibility and situation of liquefaction (for example, 10^{-3}:partially, 10^{-2}:wholly).

To provide the data of geology, various kinds of conventional geologic investigation and soil testing are applicable for the shallow depth. For the deep strata up to the bed rock, a few geophysical explorations, specially, the refraction method (Fig.33) or the reflection method can give depth, thickness, rigidity, inclination angle of each stratum, elastic wave velocity and so on. The travel time curve gained from the retraction method is shown in Fig.34〔5〕.:

Since the spindle shape of the curves of $G/G0\sim\gamma$ and the curve of $\eta\sim\gamma$ in Fig.4 and Fig.14 do not affect the results of calculation sensitively, their curves could set between $10^{-4}\sim10^{-2}$ of strain. For the input waves to the bedrock, any seismic waves recorded inside of the hard rock in deep depth may be applicable because the surface waves become its inherent waves depending on the intermediate stratum structure repeating multiple reflections and refractions. As the calculation method, FLUSH using FEM or SHAKE based on the multiple reflection theory is useful to get the shear waves near the surface for acknowledgement of liquefaction. The segmentation of geology model of these methods affects accuracy of calculation and the capacity of computer

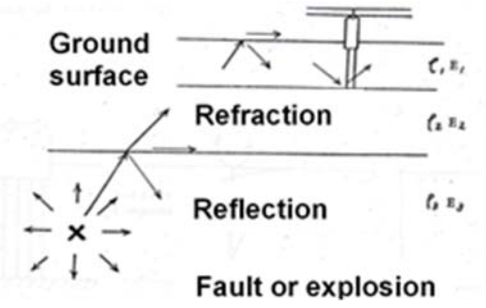


Fig.32 Route of seismic waves

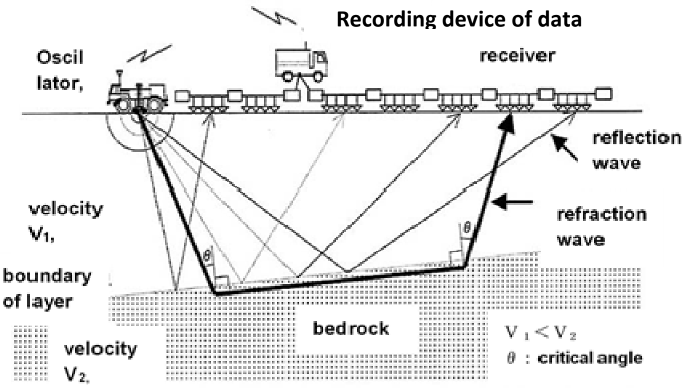


Fig.33 Primciple of refraction method

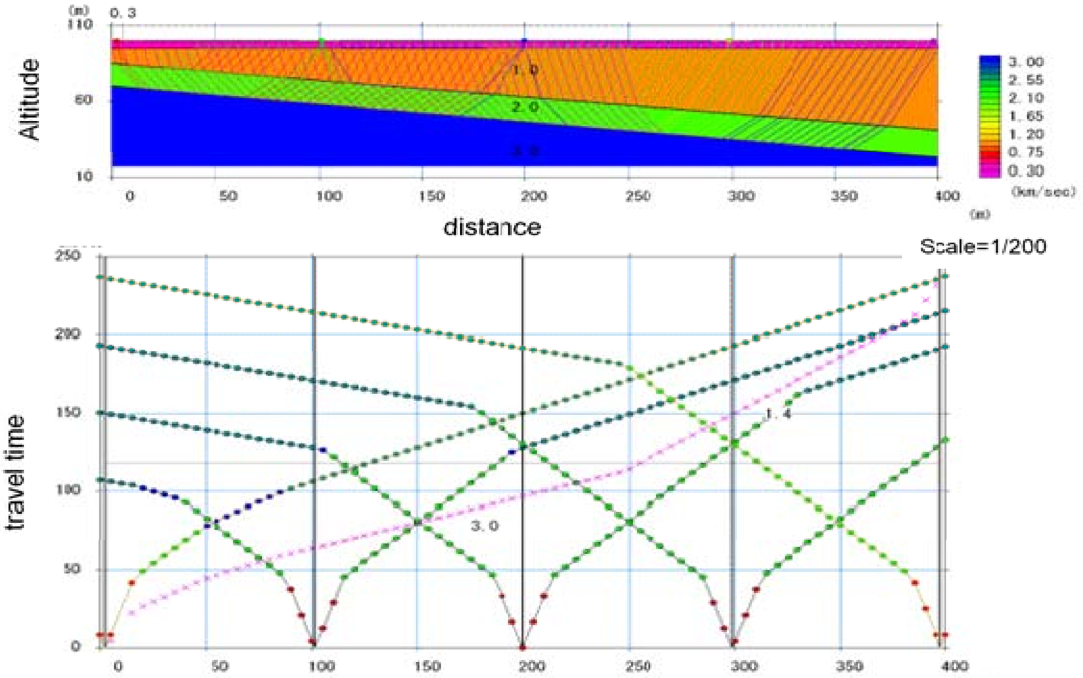


Fig.34 Example of travel time curve in case of refraction method

Thus, it is possible to evaluate occurrence and situation of liquefaction depending on the scale of earthquake, the stratum structure, the countermeasures and so on.

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

① (Mitigation of excess pore water pressure) As the measures to mitigate the excess pore water pressure in the sand layer, sand drain & sand compaction piles (Fig,35), gravel drain pile, paper drain and other methods are applicable.

② (Ground improvement & consolidation of surface layer) To endure the shear strain caused by the seismic waves, ground improvement (Fig.36) and the consolidation of surface layer are effective countermeasures. In case of spread foundation, the consolidation of surface layer is required to a certain depth and width.

③ (Restriction frame for soil shear strain) Sometimes, rigid frame walls (Fig.37) are adopted to restrict the shear strain in the saturated sand. They have been proved to prevent liquefaction effectively.

④ (Deep rigid foundation) On the grounds where liquefaction or debris flow might occur, the foundations with a proper rigidity should be built into the bearing stratum.

Furthermore, the measures are requested for the existent structures and houses. The following methods are proposed.

① (Reinforcing for foundation) Fig.38 shows reinforcement of pile foundation. Since the influence of liquefaction is limited in the shallow layers near the surface, the method to surround the existing foundation with sheet piles and to improve the soil inside of wall is ideal for the suitable rigidity of foundation. Then, the improvement of surrounding foundation is often proposed.

② (Drain of ground water & supply of rigidity) The rotary penetration steel pipe pile with strainers (Fig.39)

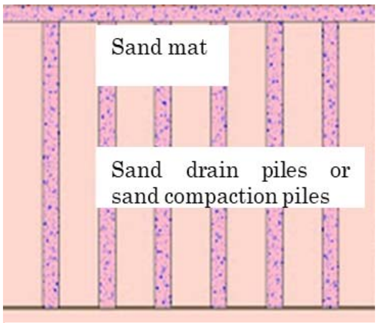


Fig.35 Sand pile & sand compaction pile

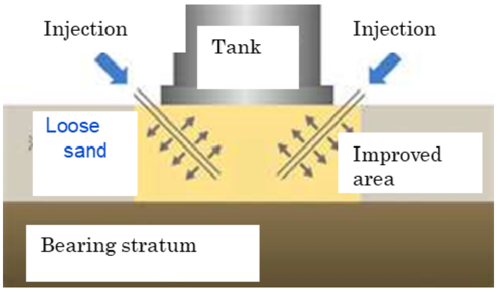


Fig.36 Ground improvement

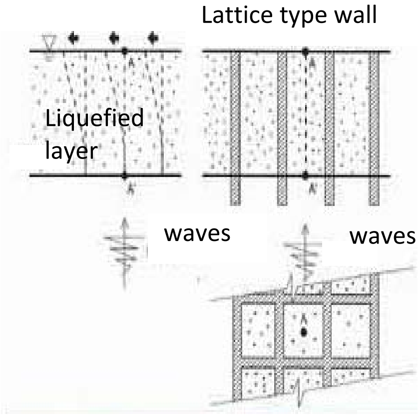


Fig.37 Rigid diaphragm wall

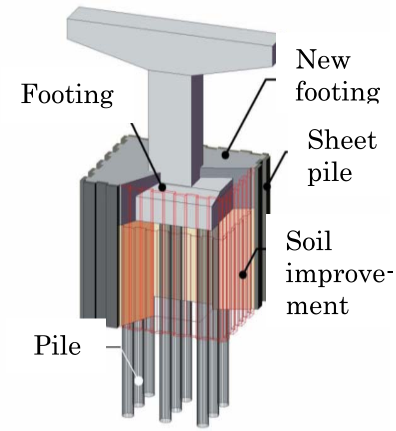
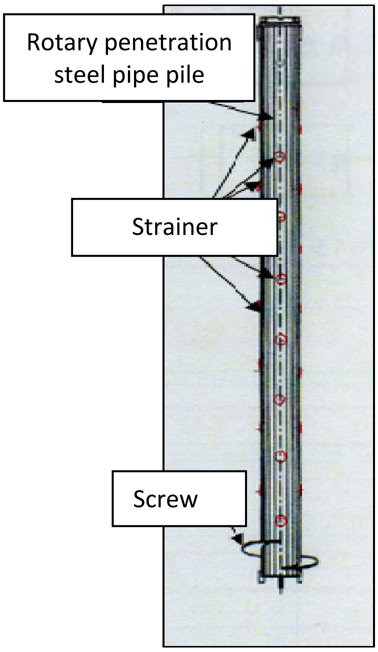


Fig.38 Sheet piles & soil improvement



Fig,39 Steel pipe pile to absorb excess pore water pressure with strainers is effective to extinguish excess pore water pressure around the pile and to increase the shear resistance of the sand layer together with the lateral rigidity of pile. At the residential area, the small pipe piles with a diameter of 100~300 mm in an interval around houses can effectively resist the deformation of ground and prevent liquefaction under the houses. For setting them, small rotary machine is used.

③ (Dewatering etc.) If the sand on the surface is not saturated, liquefaction will not occur. One proposal is to lower the ground water table with pumps. However, the maintenance costs of this proposal are significant and there is a fear to settle the surrounding area.

④ (Injection of agent) Injection of cement milk, water glass or other chemical agents exist to consolidate the surface layer. However, it is difficult to penetrate equally in the ground and their effects do not always apparent.

7. Conclusions

The following results on liquefaction are gained as the conclusions.

(1) The liquefaction on the loose saturated sandy ground generates by the excess pore water pressure due to the large strain of shear waves in the soft layer beneath.

(2) The seismic waves from the bedrock accumulated in the soft surface layer become the waves of small acceleration with elongated periods and continue to swing long time.

(3) The stored shear waves with long periods have the energy of high level enough to liquefy the upper saturated sandy layer and to continue liquefaction long time.

(4) The wave energy grows gradually through the intermediate layers from the bedrock.

(5) In case of hard surface layer, the seismic waves do not cause liquefaction and give the common earthquake motion to the structures on the surface.

(6) Liquefaction progress in the saturated sandy layer from the border of soft layer beneath. The phenomena of liquefaction in Hokkaido and the landslide by liquefaction in Indonesia are supposed to be depending on the rising shear waves.

(7) The debris flow is provoked by a large impact wave at the epicenter in mountainous area and ruins various objects except structures with reliable foundation.

(8) The data of geology at large depth unable to get by the conventional methods, required in the calculation of response analysis, can be gotten with a few geophysical explorations

(9) Several countermeasures to the liquefaction are given for the seismic design of structures and the protection for the existing structures and houses considering the mechanism of liquefaction.

(10) This paper states that the response analysis from the bedrock is practical for the assessment and the prevention of liquefaction.

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