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Influence of Rigidity of the Surface Layer on Liquefaction during Earthquake

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Abstract: A new hypothesis clarifies the phenomenon of liquefaction of saturated sandy soil during large earthquakes. It is based on the multi-reflection theory and dynamic response calculation using FEM. The results using the hypothesis applied to soil at Hachinohe Port during the 1994 Far—Off Sanriku Earthquake ($M=7.5$) in calculating, showed good correspondence with the observed phenomena associated with this earthquake. The method was applied to other areas that had liquefied in the past and confirmed within acceptable limits the mechanism of liquefaction.

The Fukui Earthquake (June, 1948, $M=7.1$) occurred at depth of 15 km at the center of the Fukui basin and caused widespread damage and 5 300 casualties. The earthquake induced large-scale liquefaction everywhere and covered rice field over a wide area with sand and gravel. However, regardless of very strong acceleration several parts of the basin did not liquefy.

Using the hypothesis, we analyzed differences in surface layer under the same conditions. As a result, we found that the liquefaction depends on the size of strain caused by the rigidity of the surface layer and that the hypothesis accurately corresponds to what happens in practice.

Key words: **Liquefaction**; **Multi-reflection theory**; **Response calculation**; **Seismic wave**

地表刚性对地震液化作用的影响

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摘 要:一种新的假说阐述了在大地震中饱和沙土的液化现象。这是建立在多反射理论和 FEM 动力反应计算的基础上的。计算中应用了在 1994 年三陆外海 $M7.5$ 地震时对八户港土层的假设,其结果与观测到的地震现象十分符合。这种方法也被应用于其他曾经发生液化的地区并被证实是在液化机理可接受限度内。

富井地震(1948 年 6 月,$M=7.1$)发生在福井盆地中央,深度为 15 km,引起了大范围的破坏,伤亡人数达到 5 300 人。这次地震在各处引起大面积的液化,导致大范围的稻田被砂石所覆盖。但是,尽管加速度很大,盆地的几部分没有被液化。

应用这种假说,我们分析了在相同情况下地表层的差异。结果发现液化的产生取决于地表层刚性引起的应变大小,假设与实际情况一致。

关键词:液化作用;多反射理论;反应计算;地震波

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0 Introduction

The phenomenon of liquefaction is observed in saturated sandy soils during large earthquakes. Generally, liquefaction is described as originating from excess pore water pressure and diminishing effective stresses among grain structures, by repeated strong acceleration waves.

However, some significant differences exist between the natural phenomena observed and the above mentioned mechanism. The main differences are as follows: (1) while observed under laboratory conditions, large acceleration has not been observed in natural liquefied soil, and structural devastation caused by acceleration is rare; (2) liquefaction occurs and continues after the main shock of an earthquake and waves with small acceleration and long periods are often recorded for a prolonged period; (3) liquefaction is also seen in gravel and silt soils as well as sand; and (4) sometimes, large displacement is observed without sand boils being apparent.

The main reason seems to depend on the soft and flexible layer beneath the liquefied sandy soil. This means it is necessary to clarify the influence of this soft layer using response calculations [1].

To resolve the disparities described, a series of dynamic response analyses was 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 mechanism of liquefaction than 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 to predict the actual liquefaction [2-3].

The influence of the rigidity of the surface layer to the response of seismic waves is examined with reference to application to the 1948 Fukui Earthquake.

1 Geological background

Japan has a long history of recorded incidents of liquefaction. Geological surveys of areas that have been liquefied by recent large earthquakes, found without exception that clay, silt and other soft layer with a high susceptibility to strain or very thick soft rock to a depth of several km, were distributed the under the liquefied sand layer [1].

The following hypothesis has been formulated to account for the fact that shear deformation introduces excess pore water pressure and diminishes effective stresses among grain structures.

Generally, waves are easily transferred from a hard to a soft medium but rarely from a soft to a hard medium. The waves are reflected at the boundary and accumulate in the soft medium. Therefore, seismic waves transferred from the hard crust tend to accumulate in the relatively soft near-face formation. During a large earthquake, the soft formation absorbs a great deal of energy and eventually begins to vibrate at its own predominant periods.

If a strong hard layer overlies the soft formation, the vibration mode is of the second order, or if a layer is loose, it is of the first order. A thicker soft formation allows the accumulation of a large amount of seismic energy, which brings about shear deformation in the upper saturated sand layer, resulting in liquefaction [2]. A model of the liquefaction mechanism based on this concept is shown in Fig. 1[3].

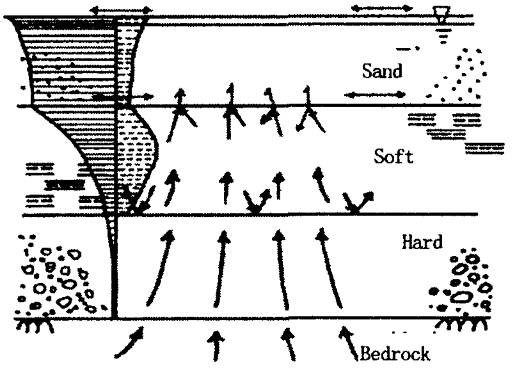


Fig. 1 Concept of mechanism of liquefaction.

By applying this concept, using the example of the 1994 Far -- Off Sanriku Earthquake as observed at Hachinohe Port, the mechanism of liquefaction has been verified.

2 Application to liquefaction at hachinohe port and others

Hachinohe City is located at the northern-east part of Honshu Island in Japan.

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 8, 1994 [4]. Liquefaction during this earthquake, which had a maximum acceleration of 675 gal, was concentrated chiefly in the harbor area and significantly damaged harbor facilities. However, the occurrence of liquefaction differed between the 1st Inustrial Port reclaimed in 1971 and the 2nd Industrial Port area reclaimed in the 1950s, shown in Fig. 2. Large and small sand boiling, subsidence of reclaimed land, displacement of quays and other damage were observed at the 2nd Port while tiny sand boiling alone was noted at the 1st Port.

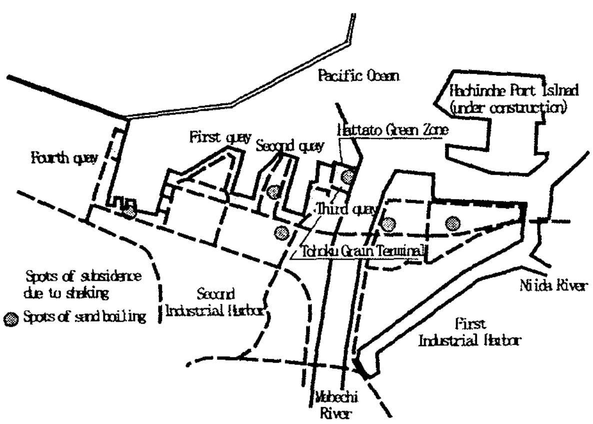


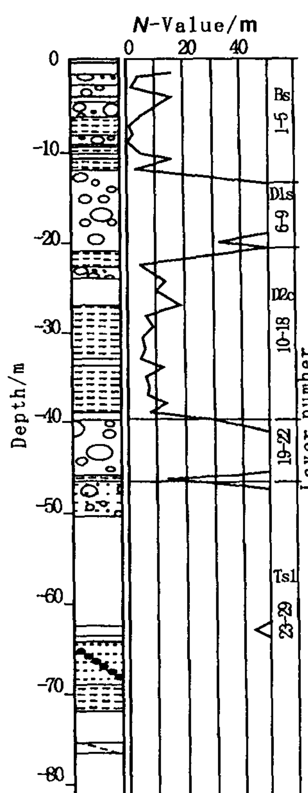
Fig. 2 Plan of Hachinohe port.

Columns representing the geology at the two ports are shown in Fig. 3 and 4. From seismic surveys, the bedrock of the 2nd Port area is estimated to lie about 400 m underground, but boring has only reached to a depth of 80 m. 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. The bedrock of the 1st Port is sandstone below 50 m and the upper sedimentary formation is mostly sand layers of Pleistocene origin.

As the first step in analysis comparing the characteristics of heavily liquefied and lightly liquefied soils, a one-dimensional calculation (SHAKE) based on the multiple reflection theory and the equivalent linearization method (Fig. 5) was performed. Then, as the second step, a two-dimensional FEM analysis (FLUSH) followed to ascertain the response of liquefied ground in more detail.

In the response calculations, seismic waves with a maximum acceleration of 147 gal (Fig. 6), recorded in the hard Paleozoic mudstone 20 m below Hachinohe Institute of Technology (HIT), were injected in the bedrocks at both ports, and the elastic shear coefficients (G) of each layer were derived from the shear wave velocity (V_S). The elastic shear coefficient (G) and dumping coefficient (h) of various geological strata change in a narrow curve width, according to shear strain (Fig. 5).

The maximum values of acceleration, velocity and shear strain from the response calculation for the soils of both ports are indicated in Fig. 7 and 8.



GL -83-180 (V_s=430 m/s, 30-39)
GL-180-360 (V_s=720 m/s, 40-48)
GL-360-380 (V_s=1 430 m/s, 49)

Fig.3 Soil profile at 2nd post.

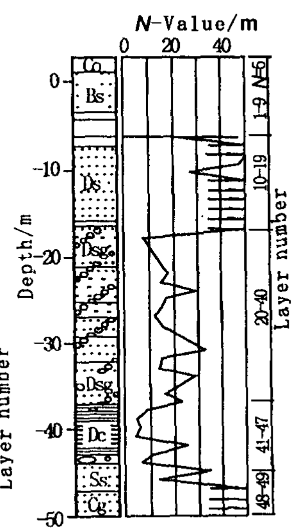


Fig.4 Soil profile at 1st post.

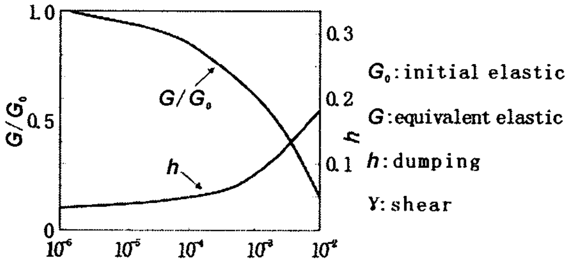


Fig. 5 Equivalent linearingation of elastic shear coefficient G and dumping constant h.

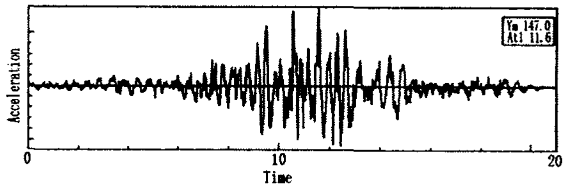


Fig. 6 Input wave observed at H. I. T.

At the 2nd Port, although the value of acceleration does not increase markedly, the velocity increases as the depth decreases and the shear strain increases rapidly at the cohesive layer near the surface, reaching a value high enough to cause liquefaction of the upper sand layer. At the 1st Port the properties of the injected waves did not increase markedly except for the shear strain in the lowest clayey layer. The shear strain of 0.8×10^{-3} at a depth of 10 m, is the limiting value for liquefaction to occur.

Fig. 9 shows the waves of shear strain at several depths at the 2nd Port and explains the tendency shear strain waves with a long period to amplify as progress toward the surface.

To verify these tendencies and to confirm the mechanism of liquefaction, two-dimensional FEM analysis (FLUSH) was performed using a soil model at the 2nd Port, as shown in Fig. 10(in plate 3) and 11(in plate 3). The seismic waves injected into the bedrock and curves of G and h in Fig. 5 are the same as the calculations of SHAKE, but the soil coefficients are modified to be consistent with the soil section. The calculated results for Fig. 10(in plate 3) by SHAKE are in Fig. 12 different from those of Fig. 7 divided bit by bit. The results calculated by FLUSH are shown in Fig. 13. In the case of FLUSH, only one directional waves were injected and the figures calculated are the values at the center. Fig. 14 shows the transition of seismic energy expressed in $1/2\ V^2$[3].

From the results obtained, it was fond that the influences of modeling, the value of coefficient, the differences between SHAKE and FLUSH, etc. are very important. However, the basic facts are: (1) waves injected into the bedrock amplify in flexible layers such as clay or silt; (2) waves reaching the surface through soft layers, tend to have an elongated period; (3) waves with a relatively long period continue for a long time after the main shock; (4) the shear strain of waves near the ground surface possibly reaches a level high enough to liquefy the upper saturated sand layer; (5) seismic energy increases progressively from the bedrock to the ground surface; (6) calculation using FLUSH probably produces more realistic results than that using SHAKE.

Furthermore, (7) the injection of input waves to the bedrock and estimation of the elastic shear coefficients of each layers is important; (8) linearization is a practical concept for estimating liquefaction; (9) high seismic energy is required to produce liquefaction.

This hypothesis and the dynamic response calculation were applied to four areas liquefied by other large earthquakes to verify these concepts and the hypothesis. Regardless of the fact that all input waves to both bedrock were recorded at HIT, the calculated waves on the surface were reasonably consistent with the degree of liquefaction and damage experienced. This means that the surface waves that generate liquefaction depend on the composition and properties of the intermediate sedimentary layers, especially those near the surface.

3 Application to Fukui Earthquake

Fukui City is located in the middle of Honshu and on the edge of the Fukui basin on the Japan Sea side.

The 1948 Fukui Earthquake with a magnitude of 7.1 on the JMA scale caused widespread damage and 5 300 casualties as well as causing large-scaled liquefaction in the basin in June of 1948. The epi

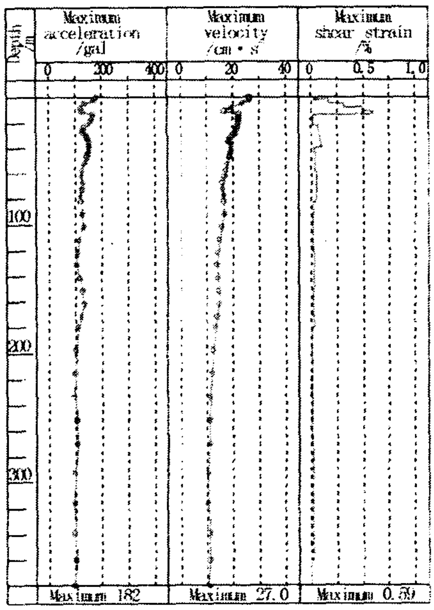


Fig. 7　Amplification of wave at the 2nd port.

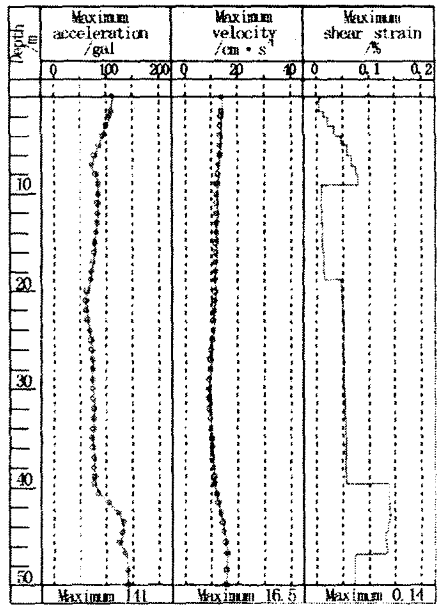


Fig. 8　Amplification of wave at the 1st port.

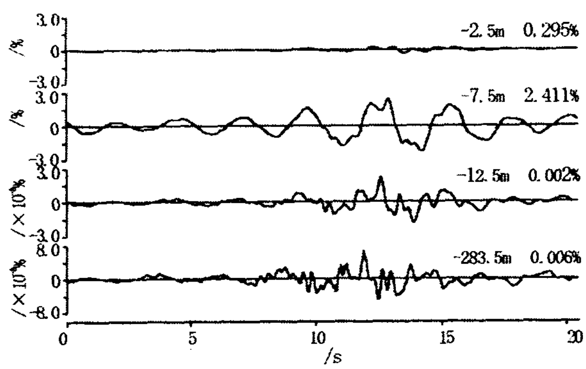


Fig. 9　Shear strains in depth at the 2nd port.

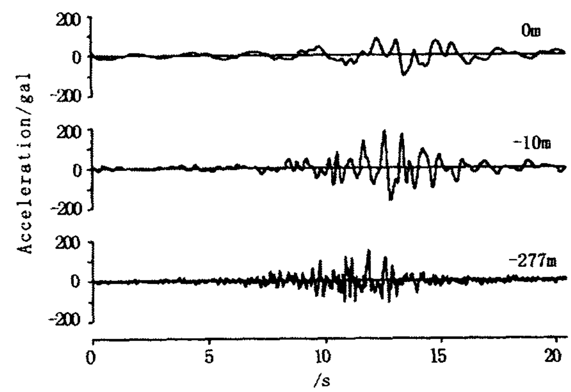


Fig. 12　Calculated waves by SHAKE.

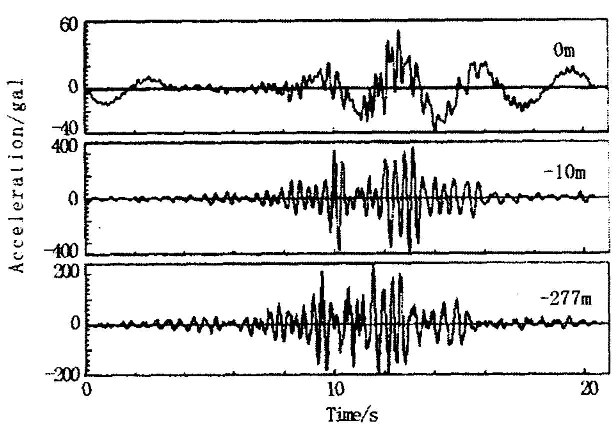


Fig. 13　Calculated wave by FLUSH.

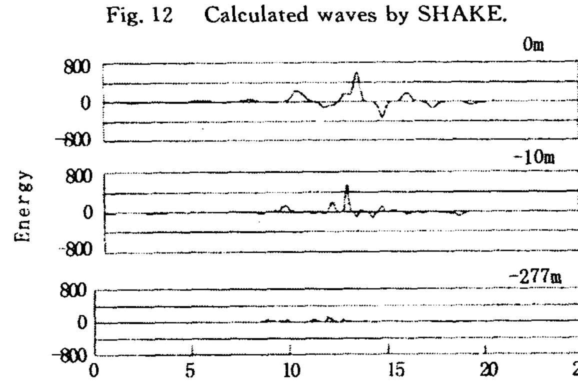


Fig. 14　Transition of seismic energy.

center was at the center of the basin, 15 km deep. Damage can be classified into two categories: a) destruction of buildings, and b) liquefaction including that of gravel layers.

The Fukui basin consists of horizontal Holocene and Pleistocene sedimentary layers upon the great shallow plate with a depth of 250 m. The upper 3 layers are Holocene and the upper 10 m divided into 1.5 m and 8.5 m deep layers, underlain by 24 m of sandy silt. The lower strata are divided

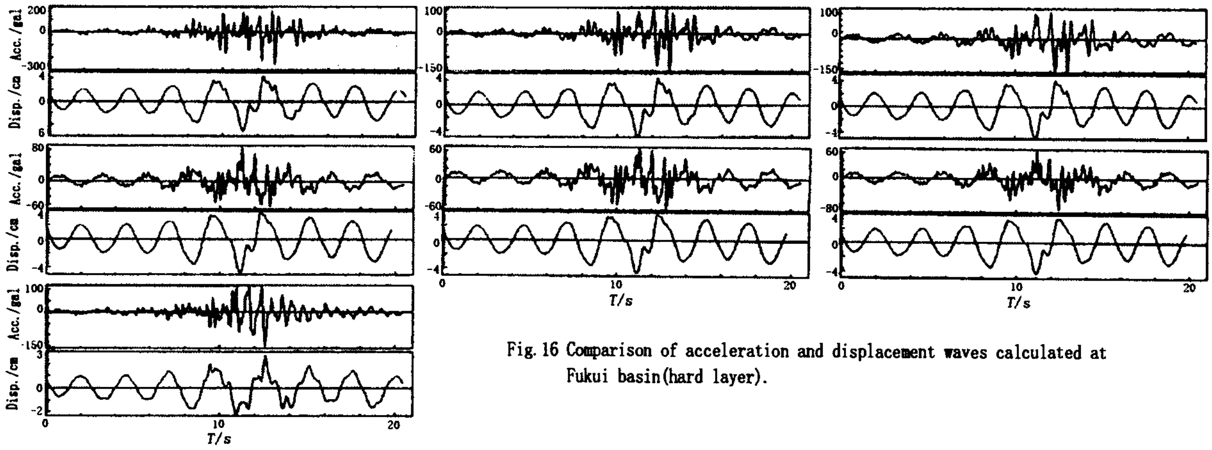


Fig. 16 Comparison of acceleration and displacement waves calculated at Fukui basin(hard layer).

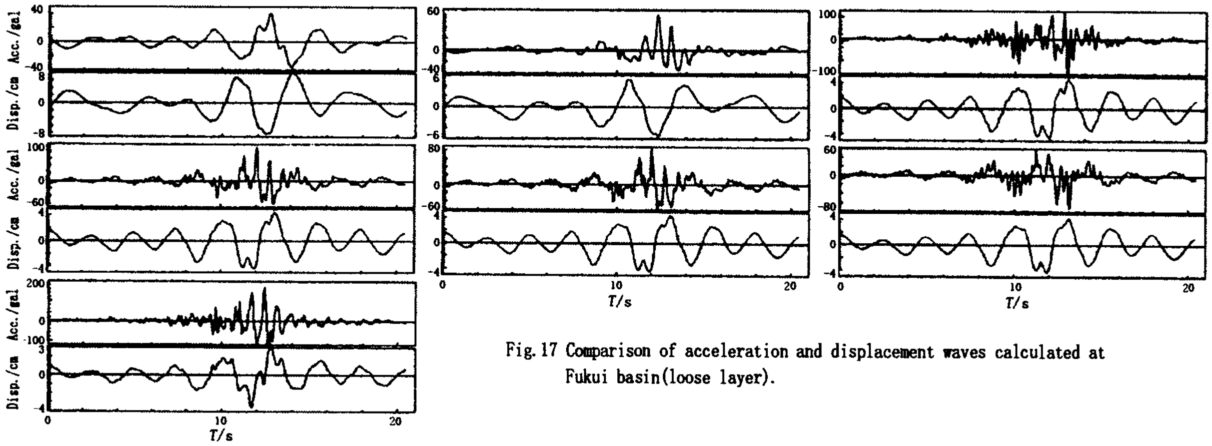


Fig. 17 Comparison of acceleration and displacement waves calculated at Fukui basin(loose layer).

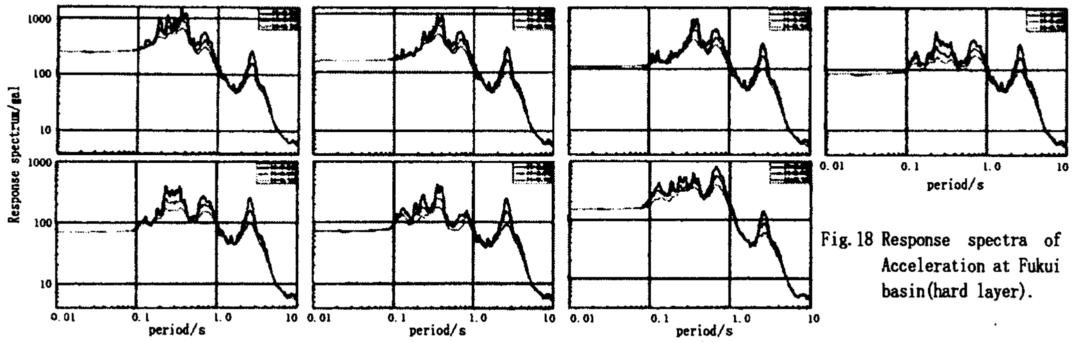


Fig. 18 Response spectra of Acceleration at Fukui basin(hard layer).

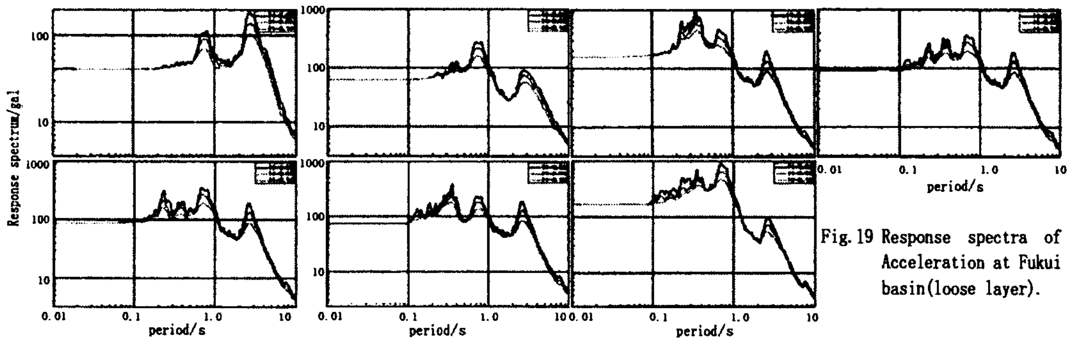


Fig. 19 Response spectra of Acceleration at Fukui basin(loose layer).

into five layers as shown in Table 1 and Fig. 15(in plate 3). The groundwater table was almost at the ground surface due to the recent planting of rice.

The dynamic response calculation performed with FEM is shown in Fig. 15. The input waves were recorded at HIT. The elastic shear coefficient (rigidity) of the second layer was allocated two values in order to investigate its influence on the lower soft layer and the degree of liquefaction. The calculated results of these two cases are shown in Fig. 16 and 17 for the accelerations and displacements at each layer, and in Fig. 18 and 19 for the spectra of acceleration.

Table 1 Geology at Fukui

Number	geology	velocity of shear wave /[m · s^{-1}]	thickness /m
1	sand	70	1.5
2	sand (Holocene)	70	8.5
3	sandy silt (Holocene)	420	24
4	gravel (Pleistocene)	800	10
5	gravel (Pleistocene)	1 000	32
6	sand (Pleistocene)	720	50
7	sand—silt	420	122
8	bed rock	1 700	—

If the second sand layer is loose as a result of being geologically young, the value of the maximum acceleration reaches only 40 gals and long-period waves develops. If the second layer is hard, however, it constricts the behavior of the lower soft layer and its acceleration amplifies to 251 gals. The strain level in the former case is 1%~3% corresponding to liquefaction and the latter case is 0.08% corresponding to sand boil.

This calculation supports the hypothesis presented above. We deduce that the maximum acceleration will increase considerably where there is no soft layer underlying the surface layer or where a soft layer is thin, such as near the edge of the basin.

4 Conclusion

Through a series of dynamic response calculation, the following conclusions were reached.

(1) A new hypothesis for the liquefaction mechanism has been formulated using practical methods.

(2) A rational assessment on whether liquefaction will take place depends on the dynamic response analysis from the bedrock.

(3) The surface waves causing liquefaction, are governed by the composition and properties of intermediate sedimentary layers, especially near the surface, and are not influenced significantly by the input waves into the bedrock.

(4) The rigidity of the surface layer over the next soft layer controls liquefaction, though depending on the energy of the earthquake.

(5) This calculation method is able to simulate and predict liquefaction at any chosen location.

(6) This concept and analysis will contribute to improvements in the method of seismic design for liquefaction.

Acknowledgment

The authors wish to thank Professor E. Yanagisawa, president of Hchinohe National College of Technology, for the valuable suggestions and Mr. K. Tani, Construction Institute of Technology (CIT), for the cooperation. This study is subsidized by CIT. The FLUSH calculations were performed in cooperation with Dr. Feng Yi and Mr. Weidon Sun, JCD Co. Ltd.

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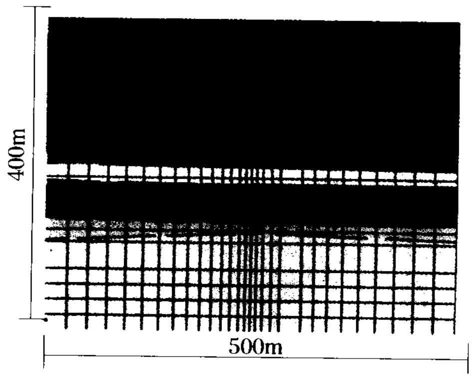


Fig.10 Section for FLUSH at the 2nd port.

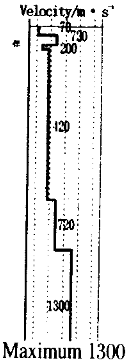


Fig.11 Shear wave velocity at the 2nd port.

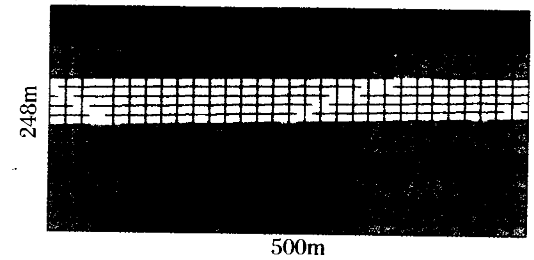


Fig.15 Section for FLUSH at Fukui.

张向红等：对宁夏中卫南F_{201}左旋逆走滑发震断层长度的确定

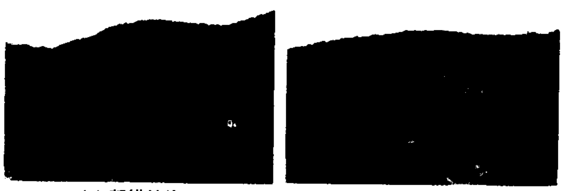
图 7 黄河黑山峡河段（深 10km 左右）视磁化率异常图

Fig.7 Map of apparent magnetic susceptibility anomaly in Heishanxia Gorge area (about 10km deep).

(a) 刘岗井（东段） (b) 小红山（西段）

图 4 1709 年地震陡坎地貌

Fig.4 Fault-scarps formed in 1709 earthquake.



(a) 断错纹沟 3m (b) 断错纹沟 2m

图 5 小红山 F_{201} 左旋断错纹沟

Fig.5 Gully left lateral displacement caused by the F_{201} fault at Xiaohongshan.

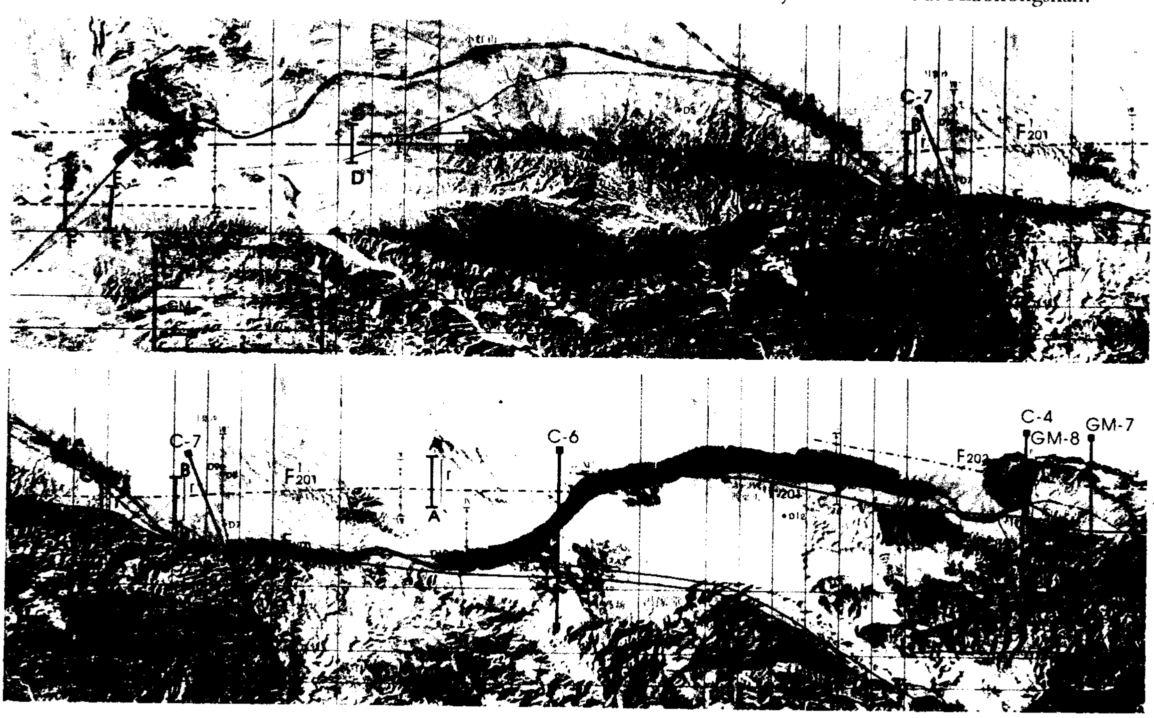


图 8 浅层电法勘探布线及综合成果图

Fig.8 Chart of shallow layer electrical prospecting wiring and comprehensive achievement.