# Seismic design based on response analysis of basement rock

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**ABSTRACT:**
This paper indicates that a realistic seismic design should be based on a response analysis of the basement rock. The different seismic waves change from the input waves on the basement rock as they pass through the various strata on their way to the surface, causing damage to structures and the like on the ground. When transmitted through multiple intermediate soft layers, waves with low acceleration and relatively long periods develop and generate particularly large deformation on the ground surface, resulting in liquefaction of saturated sandy layers. Waves transmitted through hard intermediate layers, however, have high acceleration and short periods when they reach the surface, generating a powerful force and these are likely to have a significant impact on structures. The seismic design of important structures on soft ground should take account of deformation and displacement and those on hard ground should mainly consider stress and ductility based on dynamic analyses. An analysis for seismic design should be performed from hard basement rock with a shear velocity of greater than 2 km/sec.

**KEYWORDS: SEISMIC DESIGN, RESPONSE ANALYSIS, SEISMIC WAVE, BASEMENT ROCK, LIQUEFACTION, SHEAR WAVE VELOCITY**

## 1. INTRODUCTION

Damage to sedimentary ground is brought about by the different seismic waves changed through the various layers between the basement rock and the surface. From the process to clarify the mechanism of liquefaction generated at Hachinohe Port in Aomori Prefecture in the 1994 Far-Off Sanriku Earthquake (Figure 1), it was found that the original waves on the basement rock changed to long period waves through the upper sedimentary layers, causing liquefaction of sandy soil at the ground surface. This is in accordance with the principle that waves transfer easily from a hard layer to a soft layer but do not transfer easily from a soft layer to a hard layer (Figure 2). The waves from the basement rock rise to the surface repeating reflection and refraction at the boundary faces of strata, and in doing so their own characteristics change. This phenomenon is explained by the multi-reflection theory. In particular, the wave energy concentrated in soft layers amplifies the vibration of the layer according to the low dimensional modes.

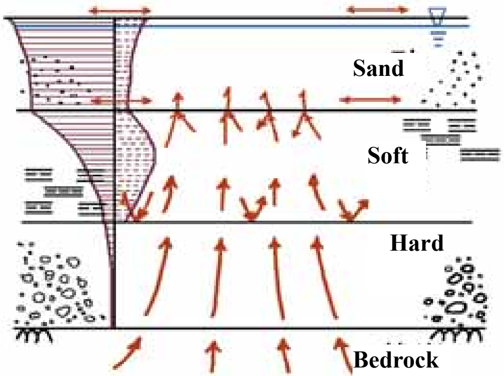

**Figure 2** Concept of mechanism of liquefaction

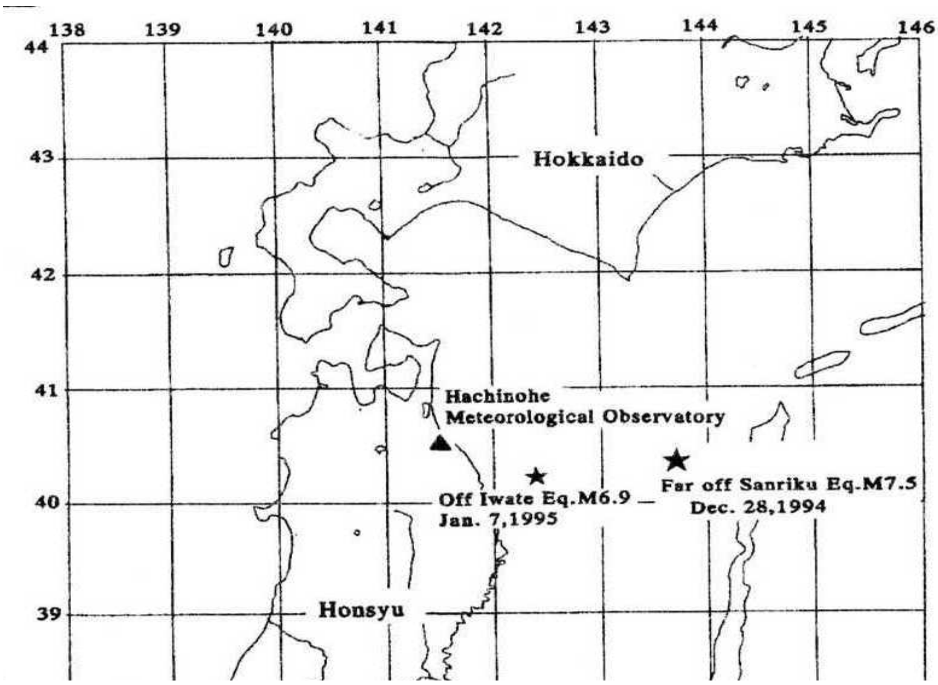

**Figure 1** The location of Hachinohe, the epicenters of the main shock and the maximum aftershock (Off Iwate Earthquake)

## 2. RESPONSE ANALYSES AT HACHINOHE IN THE 1994 FAR-OFF SANRIKU EARTHQUAKE

With a magnitude of 7.5 on the JMA (Japan Meteorology Agency) scale and a maximum acceleration of 675 gal, the1994 Far-Off Sanriku Earthquake caused extremely serious damage in the Hachinohe region, 200 km west of the epicenter on December 28, 1994 and great damage to the infrastructure, private buildings and housing. Large-scale liquefaction generated all over the harbor area and this gave rise to significant damage to harbor and industrial facilities. The geology at these areas consists of alluvium and diluvium deposits and basement rock of the Paleozoic sandstone lays 400 m deep. Figure 3 shows a model of the formation of sedimentary strata derived from response analyses performed using a two-dimensional finite element method (FEM) known as FLUSH and Figure 4 indicates the shear wave velocities of each strata.

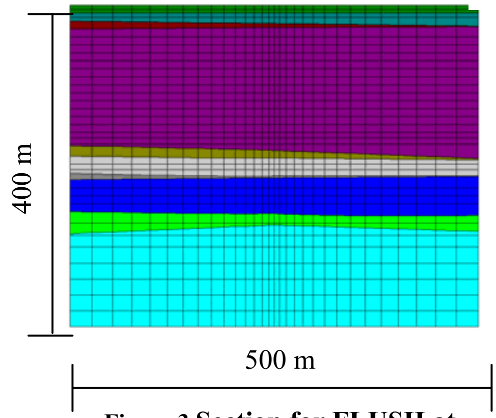

**Figure 3 Section for FLUSH at the 2nd port**

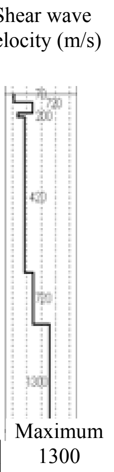

**Figure 4**
**Shear wave velocity at the 2nd Port**

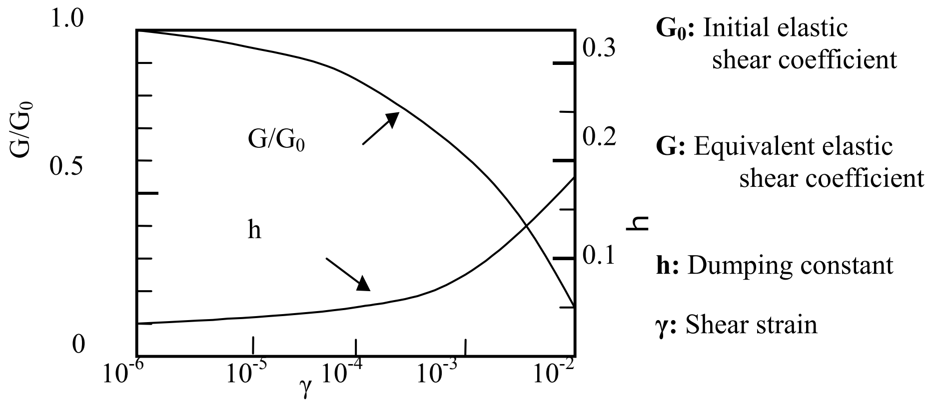

**Figure 5 Equivalent elastic shear coefficient G and dumping constant**

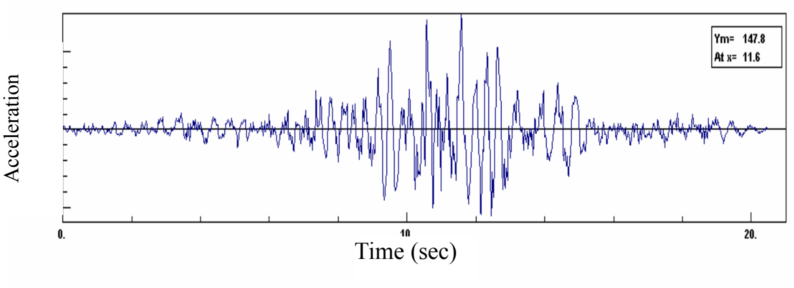

**Figure 6 Input wave observed at H.I.T.**

Figure 5 illustrates a model for equivalent elastic shear coefficients and dumping constants according to the value of the shear strain. Since the curves of these coefficients exhibit a narrow variation due to differing soils, the curve for these values fixed in one pattern for easy response calculation of FLUSH. Seismic waves with a magnitude of 147 gal, as shown in Figure 6, that were recorded in the hard Paleozoic mudstone below the Hachinohe Institute of Technology (HIT) were injected in the section of basement rock shown in Figure 3.

Figure 7 is part of the calculated results of the response analyses performed using FLUSH using Figures 3, 4, 5 and 6. The original waves injected in basement rock 277 m below the surface changed to long period waves in the process of propagation through intermediate layers, softening as they neared the surface, and wave energy easily accumulated in soft layers, as shown in Figure 8.

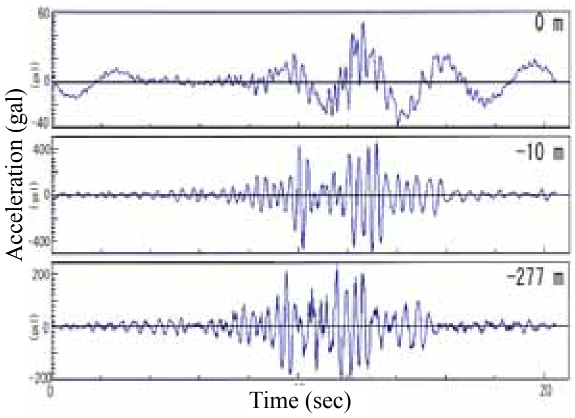

**Figure 7 Wave calculated by FLUSH**

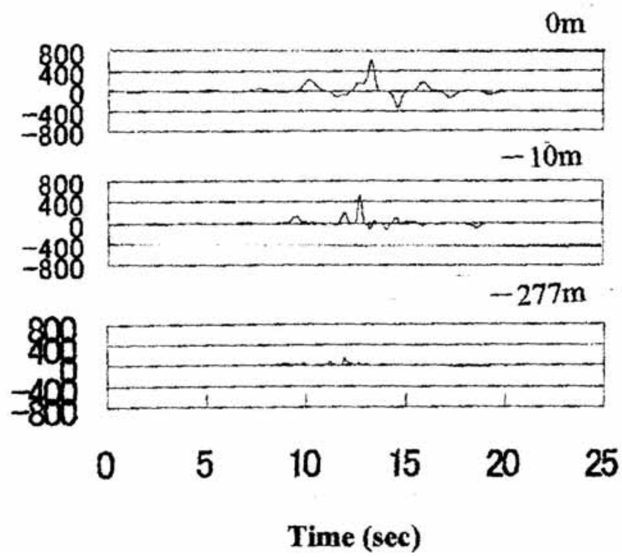

**Figure 8 Transition of seismic wave energy**

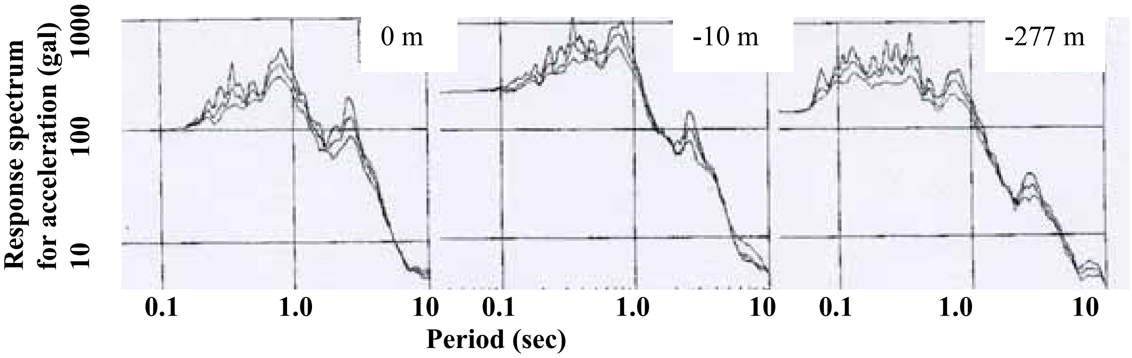

**Figure 9 Transition of response spectra for acceleration**

The response spectra for acceleration of waves in each depth are shown in Figure 9. The calculated maximum value of shear strain at stratum 10 m below the surface reached $0.6 \times 10^{-2}$, which is sufficient to liquefy the saturated sand layer above. Because the calculation adopted only one curve for the shear coefficients among various intermediate layers, the shear strain calculated with actual values for each layer is expected to be larger than that of this study.

Through a series of various response analyses, the following basic facts were revealed. (1) waves injected into the basement rock 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 under the ground surface may reach a high enough level to liquefy the upper saturated sand layer; (5) seismic energy increases progressively from the basement rock to the ground surface; (6) calculations using FLUSH probably produce more realistic results than those using SHAKE. The following additional facts were established; (7) the injection of input waves into the basement rock and estimation of the elastic shear coefficients of each layers are important; (8) linearization of shear modulus of soils is a practical concept for estimating liquefaction; and (9) a large amount of seismic energy is required to produce liquefaction.

## 3. THE INFLUENCE OF SURFACE LAYER RIGIDITY AND BASEMENT ROCK DEPTH

Fukui City is located in the middle of Honshu and on the edge of the Fukui basin on the Japan Sea side. As well as causing widespread damage and resulting in 5,300 casualties, the 1948 Fukui Earthquake, with a magnitude of 7.1 on the JMA scale, caused large-scaled liquefaction in the Fukui basin in June of 1948. The epicenter was at the center of the basin, 15 km deep. The damage sustained can be divided into two categories: a) the destruction of buildings and b) liquefaction, including that of the gravel layers.

The Fukui basin consists of horizontal alluvial and diluvium sedimentary layers upon a great shallow plate at a depth of 250 m. The upper three layers are alluvial, with the upper 10 m divided into two layers of 1.5 m and 8.5 m deep, underlain by a 24 m layer of sandy silt. The lower strata are divided into five layers as shown in **Table 1** and **Figure 10**. The groundwater table was almost at the ground surface due to the recent planting of rice.

The dynamic response calculation shown in **Figure 10** was performed with FEM and the input waves recorded at HIT. Two values were used for the elastic shear coefficient (rigidity) of the second layer to investigate its influence on the lower layer for damage to structures and the degree of liquefaction: a shear wave velocity of 720 m/sec indicating a hard layer on a relatively soft layer and one of 70 m/sec indicating a saturated loose sand layer. The results for the acceleration and displacement at each layer for these two cases are shown in **Figures 11 and 12** and the spectra of acceleration in **Figure 13 and 14**.

If the second layer is hard, it can constrict the behavior of a lower soft layer and its acceleration amplifies to 251 gals, which may cause damage to weak structures. If the third strata are stronger than those given in Table 1, the value for the response of acceleration may increase. If the second sand layer is loose as a result of being geologically young, however, the value of the maximum acceleration reaches only 40 gals and long-period waves develop. A strain level of 1-3% is sufficiently large to generate large scaled liquefaction, including that of the gravel layers along the Kuzuryu River. The strain level for the former case is 0.08%, which corresponds to sand boil.

**Figure 13 and 14** suggest a concentration of wave energy in the surface ground that resulted in such serious damage and liquefaction that a **seismic intensity scale of 7** had to be created in Japan.

**Table 1 Geological strata of the Fukui Basin**

| number | geology | velocity of shear wave (m/s) | thick-ness (m) |
|---|---|---|---|
| 1 | sand | 70 | 1.5 |
| 2 | sand (Holocene) | 720<br>(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 | - |

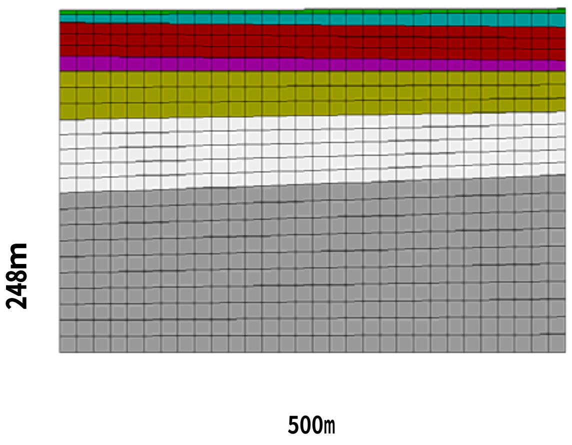

**Figure 10 Section for FLUSH at Fukui**

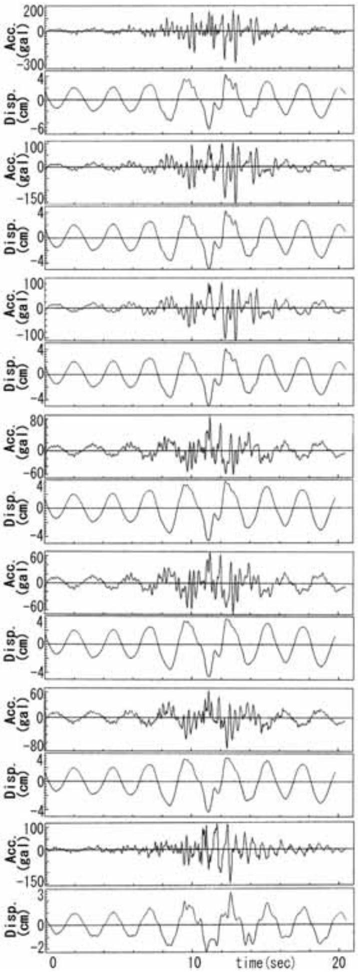

**Figure 11**
**Comparison of acceleration and displacement waves calculated in Fukui basin (hard layer)**

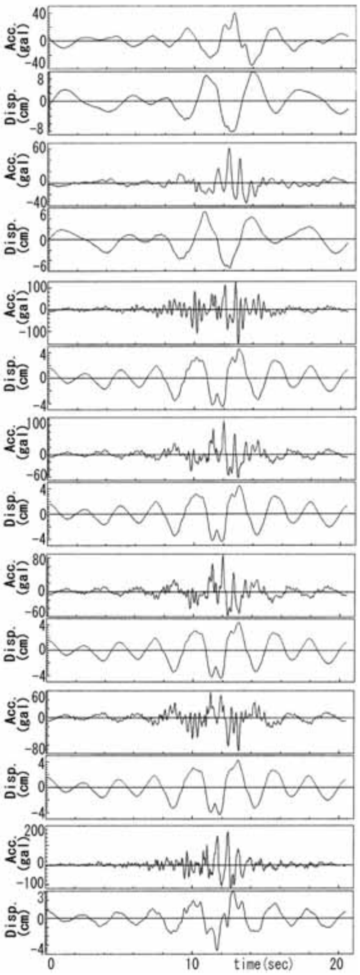

**Figure 12**
**Comparison of acceleration and displacement waves calculated in Fukui basin (loose layer)**

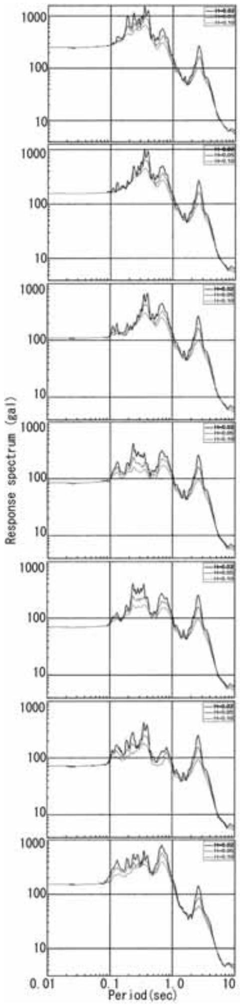

**Figure 13 Response spectra for acceleration in Fukui basin**

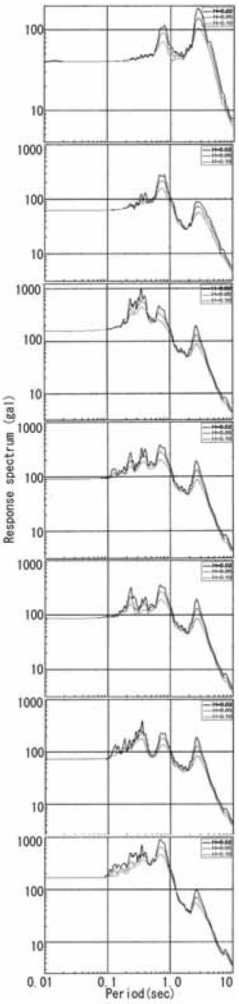

**Figure 14 Response spectra for acceleration in Fukui basin**

The results of response analyses for sedimentary ground vary according to the depth of the basement rock. In a conventional seismic design, a response analysis is used starting from hard intermediate stratum. To perform a more accurate seismic design, we recommend that the response calculation be performed from a basement rock with a shear wave velocity of more than 2 km/sec, because seismic waves rapidly propagate within the hard crust from the epicenter, rising vertically to the sites. The acceleration of waves in the basement rock is not so strong but it grows to a large value as it rises through intermediate layers repeating reflection and refraction on its way to the surface and accumulates seismic energy toward weaker strata near the surface. These phenomena generate seismic damage to structures, geotechnical hazards and so on.

Figure 15 is a comparison of accelerations calculated using response analysis at different depths. The soil condition, as shown in Figure 16, is firm diluvium stratum deeper than 50 m. The response calculations start from two points of the same formations 60 m and 162 m deep. In Figure 15, the values of the acceleration curves do not differ substantially up to a depth of 10 m but at the surface the amplified values can be clearly distinguished. Four curves shallower than 50 m show how the responses differ according to the changing soil properties and they have similar tendencies.

To follow this method, it is necessary to know the thickness, unit weight and shear modulus of the intermediate layers down to the basement rock, which can sometimes be a few thousands meters deep. Use of geological data from a physical survey for their estimation is recommended because the shear strain in deep strata is usually less than $10^{-4}$

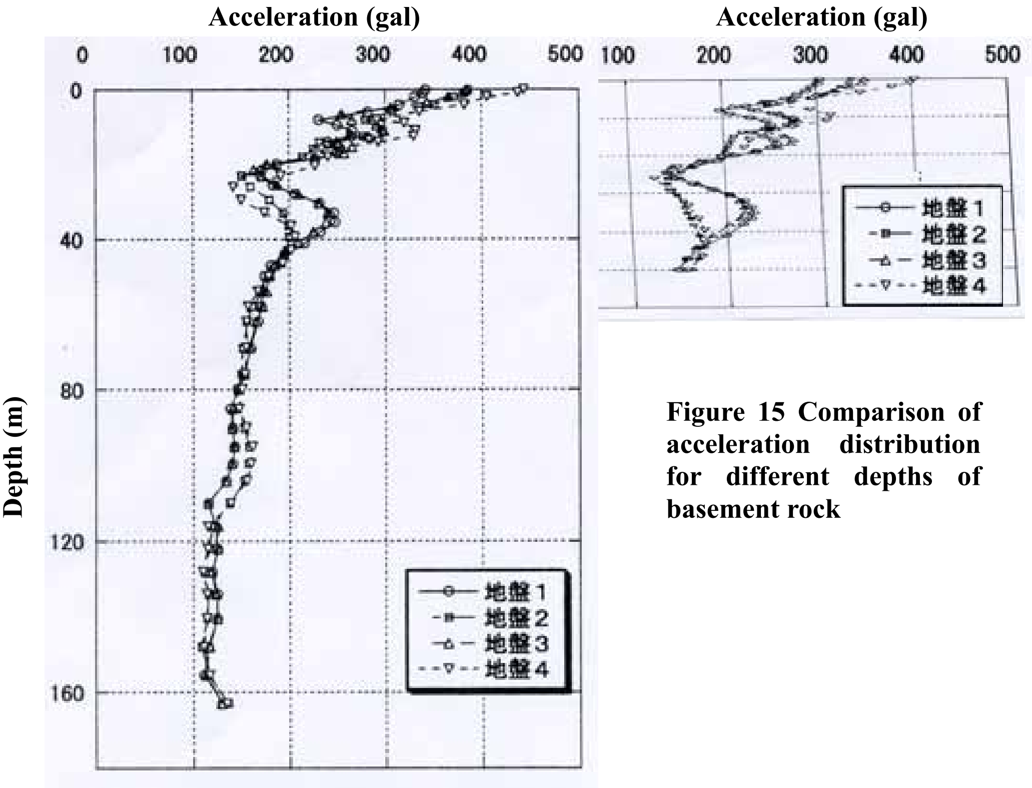

**Figure 15 Comparison of acceleration distribution for different depths of basement rock**

**Figure 16 Column of soil profile**

and the strain of elastic waves in a physical survey are at a level of about $10^{-6}$.The shear rigidity of the soils is almost constant between strain levels of $10^{-4}$ and $10^{-6}$. We can estimate approximate values for the thickness and shear modulus of each layer from the shear wave velocity.

The results of several studies in which this method was applied to locations that have been affected by liquefaction in the past have quantitatively explained the observed phenomena and suggested the possibility of forecasting liquefaction and appropriate countermeasures. Although these response analyses were calculated from the basement rocks using the input waves at HIT and curves in Figure 5, the results for the response at each location, with different long period waves changing from the input waves through own intermediate layers, fairly supported the recorded phenomena on liquefaction and revealed the contribution of soft layers under the liquefied sandy layer, as demonstrated in the 1948 Fukui Earthquake. With more accurate values and actual curves in Figure 5, we would be able to produce more reliable calculated values.

## 4. CONCLUSION

Based on a series of geological response analyses for earthquakes that have caused liquefaction, the authors wish to stress the necessity for response analysis to be conducted from the basement rock for an accurate and realistic seismic design.

Although it is difficult to determine the required physical constants of deep geological strata (such as the shear wave velocity, thickness of layers, etc) directly, it is possible to estimate them from the results of geophysical surveys. It is preferable that the shear velocity of the basement rock exceed 2 km/sec.

This method can deliver accurate values for the actual intensity of seismic waves, which amplified and synthesized through intermediate layers from the basement rock, for the design of structures and the study of surface liquefaction. Depending on the scale of the earthquake, the concentrated energy and the continuing vibration time can be estimated by response analysis. Important structures, at least, which are required to carry out their functions even during a very large earthquake, should be examined using this method.

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