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SYNOPSIS: A ten meter high retaining wall made by sands reinforced with continuous fibers was constructed in 1988. Thickness of the retaining wall was 1 m at the top and 2.5 m at the bottom, and the slope was 63° at the face and 71° at the back. Earth pressure acting on the wall, displacements of the face, settlements of the fill and acceleration of the retaining wall were measured. During the construction, around the third height of the wall was displaced 15 cm in a forward direction. At the time of an earthquake, the values of the maximum horizontal acceleration at the original ground surface and at the top of the retaining wall were recorded to be 95 gal and 200 gal respectively, and no damage was found. The relation between the increment of the earth pressure during earthquake and the movements of the wall and the fill is discussed.

1. INTRODUCTION

A four meter high retaining wall was constructed in 1987, by applying sands reinforced with continuous fibers for the wall material instead of concrete, reinforced concrete or masonry. This material was invented by Dr.Leflaive of France around 1976, and has been utilized for retaining wall and other soil structures successfully.

The retaining wall was damaged due to an earthquake on December 17, 1987 as shown in Fig.1. According to some report, the magnitude of the earthquake was 6.7, its epicenter was located about 50 km apart from the retaining wall and the maximum acceleration at the site of the retaining wall was assumed to be 140 to 200 gal.

Therefore, in order to study the stability on this type of retaining walls, a ten meter high retaining wall was constructed in 1988, various kinds of instrumentations were installed to observe the earth pressure acting on the wall etc., statically and dynamically.

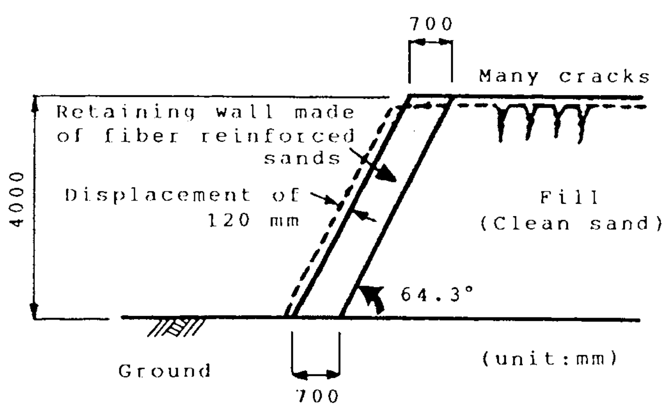

Figure 1. Example of Damage Caused by Earthquake

2. SANDS REINFORCED WITH CONTINUOUS FIBERS

The wall was made of the sands reinforced with continuous fibers. Properties of the sand used for the wall material are summarized in Table 1. The sand was selected in accordance with the specifications of the machinary to be employed.

The fibers are made of polyester, 30 filaments of which are bundled up with non-twisting. Properties of the fibers used in the wall are summarized in Table 2.

The fiber reinforced sand is produced by mixing the fibers and the sands at random in the air. At that time, the fibers are delivered with water jet and the sands are supplied with compressed air. Proportion of mixed fibers is approximately 0.2 % to the

Table 1. Properties of Sand

Specific Gravity		2.73
Maximum Dry Density (kN/m^3)		16.2
Optimum Water Content (%)		17.8
Sieve Passing Weight	2.0×10^{-3} m	99.1
(%)	4.0×10^{-4} m	82.5
	7.4×10^{-5} m	2.7

Table 2. Properties of Fiber

Material	Polyester
Thickness (D;Denier)	150
Tensile Strength per Denier (mN)	43.5
Number of Filaments	30

Table 3. Properties of Fiber Reinforced Sand

Unit Weight (kN/m^3)	17.1
Water Content (%)	18.7
Cohesion c_u (kN/m^2)	F(ϕ)
Angle of Internal Friction ϕ u (Degree)	30

ϕ : Angle between the plane in which mixture is placed and the imposed shear plane.

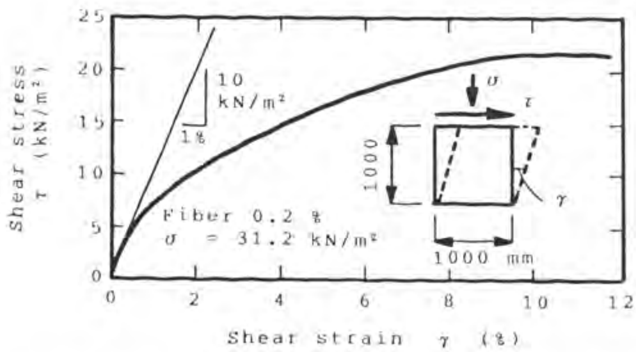

Figure 2. Typical Stress-Strain Curves From Simple Shear Test of Fiber Reinforced Sand

dry weight of the sands. Properties of the fiber reinforced sand used for the wall are summarized in Table 3, and a typical stress-strain curve from the simple shear test is shown in Fig.2.

The anisotropy in the strength of the fiber reinforced sand was pointed out by the inventor(Leflaive 1986). The strength and shear modulus varies according to the angle between the plane in which mixture is placed and the imposed shear plane. The closer the angle gets to a right angle, the larger the strength becomes(Khay 1990).

3. OUTLINE OF THE RETAINING WALL

The ten meter high retaining wall was constructed by using the fiber reinforced sand as wall material, and completed in December of 1988, at the testing yard of Science University of Tokyo, located approximately 40 km far from the downtown Tokyo.

General view of the retaining wall and its typical cross section are shown in Figs.3 and 4, respectively. The installation of five earth pressure cells and five accelorometers is indicated in Fig.4.

3.1 Design of the Retaining Wall

The front face of the retaining wall was given by the inclination of 1:0.5(63.4°) to be able to make planting on the surface of the wall to prevent from erosion due to a heavy rainfall, which would be one of the advantage of this method.

For the fill material behind the wall, a cohesive soil which is called as "Kanto

Figure 3. General View of Retaining Wall

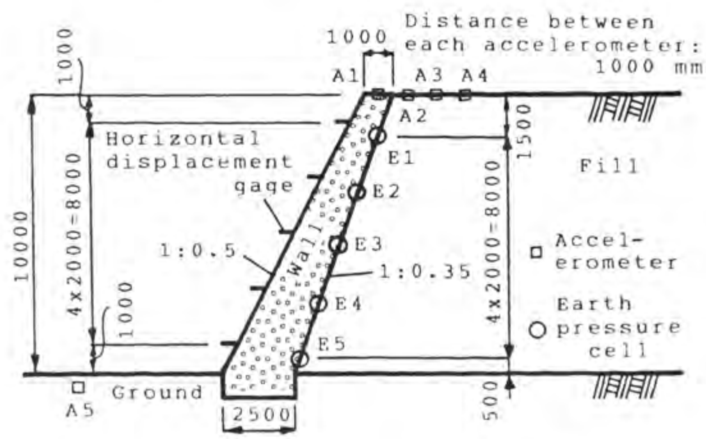

Figure 4. Cross Section of Retaining Wall and Arrangement of Gages

Table 4. Soil Properties of Fill

Unit Weight (kN/m^3)	15.9
Natural Water Content (%)	50.1
Triaxial Compression Test	
Cohesion c_u (kN/m^2)	6
Angle of Internal Friction ϕ_u (Degree)	18

loam" was used, because the soil is widely distributed around the metropolitan area. The properties of the soil are summarized in Table 4. Though there was no experience in the height of 10 meter for the type of the retaining wall, coefficient of earth pressure for design was assumed to be 0.2 considering earth pressure measurements to other types of retaining walls by Fukuoka(1981).

The retaining wall was designed by conventional masonry wall design method. The internal failure of the wall itself was examined in consideration of the anisotropic strength of the material used for the wall (Khay 1990). The design required a bottom width of 2.5 m and a top width of 1 m, and the dimensions of the wall were determined as shown in Fig.4.

3.2 INSTRUMENTATION

The wall was made of the fiber reinforced sands. Its rigidity is much lower than that of conventional concrete walls, so that the cracks shown in Fig.1 due to the earthquake seemed to be induced by the flexibility of the wall. In order to measure differential movement caused by earthquakes, four accelerometers(A1, A2, A3 and A4; refer to Fig.4) were installed at 1 m spacing on the top of the structure. An accelerometer(A5) was set on the original ground of 5 m apart from the retaining wall to measure acceleration at the ground.

5 earth pressure cells (E1, E2, E3, E4 and E5) were installed on the back face of the wall at heights of 0.5, 2.5, 4.5, 6.5 and 8.5 meters above the original ground surface to measureearth pressure acting on the wall. The diameter and thickness of the earth pressure cells were 200 mm and 25 mm respectively, and the capacity was 200 kN/m².

A set-up with these accelerometers and earth pressure cells was provided in order to monitor and record their dynamic responses synchronously during earthquake which is larger than 10 gal in acceleration at the top of the retaining wall.

3.3 Construction Method

Construction of the retaining wall was divided into six stages. In each stage, a 1.5 to 3 m high fill was shaped, then the wall was executed by spraying the sands and the fibers on the slope of the fill and compacting them until the planned shape was formed.

4. RESULTS OF STATIC MEASUREMENTS

Figure 5 demonstrates the records or measured values, i.e. (a) the construction progress of the fill and the wall in height, (b) the earth pressure acting on the wall and (c) the horizontal displacement at the several elevations of the wall, which were measured statically at a certain interval, during 100 days after starting the construction. No earthquake occurred during the period. H=1m, H=3m, H=5m, H=7m and H=9m described in Fig.5(c) denote the elevation of the earth pressure gages above the original ground surface, respectively.

According to Fig.5, the wall began to move forward at the time when the fill reached about 5 m high. Until the fill reached 8.5 m high, both the earth pressure and the forward horizontal displacement turned larger as the wall and the fill became higher . After that, the upper part of the wall(H=7m and H=9m) moved backward, while the lower part(H=1m, H=3m and H=5m) moved forward.

The maximum forward horizontal displacement of about 150 mm was observed at height of 3 m above the original ground surface, and the maximum backward horizontal displacement of about 20 mm was observed at height of 7 m above the original ground surface. These magnitude and direction of displacements would be unusual in comparison with conventional type of retaining walls.

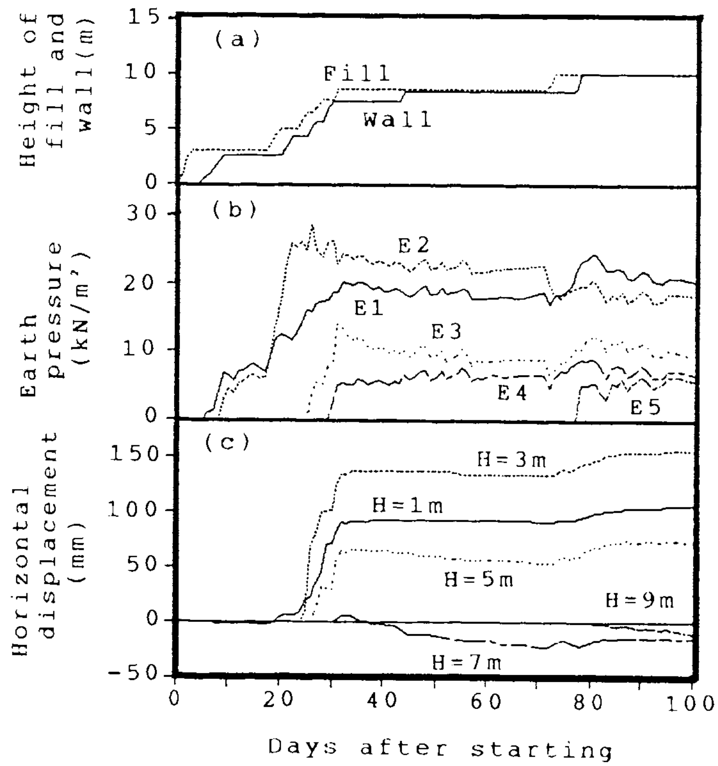

Figure 5. Progress of Fill and Wall, Earth Pressure and Horizontal Displacement During and After Construction.

5. ANALYSIS OF STATIC BEHAVIOR BY F.E.M.

An analysis was carried out by applying F.E.M., assuming the soil characteristics to be elastic. The input data for F.E.M. are summarized in Table 5.

Table 5. Input Data for F.E.M. analysis

Fiber Reinforced Sands	
Young's Modulus (kN/m²)	2600
Poisson's Ratio	0.3
Unit Weight (kN/m³)	18
Fill	
Young's Modulus (kN/m²)	690
Poisson's Ratio	0.4
Unit Weight (kN/m³)	16

The results of analysis are plotted in Fig.6, compared with the observed values of horizontal displacement, earth pressure acting on the back face of the wall and settlement of the fill. The computed values could be distributed similarly to the observed values in tendency, while comparatively large deviations were found between some of observed and computed values, especially in the earth pressure.

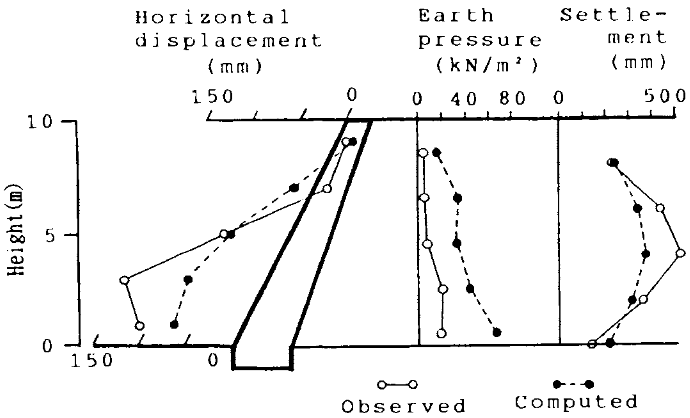

Figure 6. Comparison Between Observed and Computed Values

6. OBSERVED RECORDS OF EARTHQUAKE ON FEBRUARY 19, 1989

Since the completion of the retaining wall, earth pressure and acceleration during earth quake were recorded more than 15 times.

On February 19, 1989, an earthquake of magnitude 5.7 in Richter scale occurred in Tokyo area. Epicenter was approximately 15 km apart from the site of the retaining wall.

At that time, the maximum horizontal acceleration at the original ground surface (A5; refer to Fig.4) was recorded to be 95 gal at the direction perpendicular to the length of the wall, i.e. the same direction of the earth pressure. At the top of the retaining wall(A1~ A4), the accelerations were amplified more than double. Figure 7 shows the observed

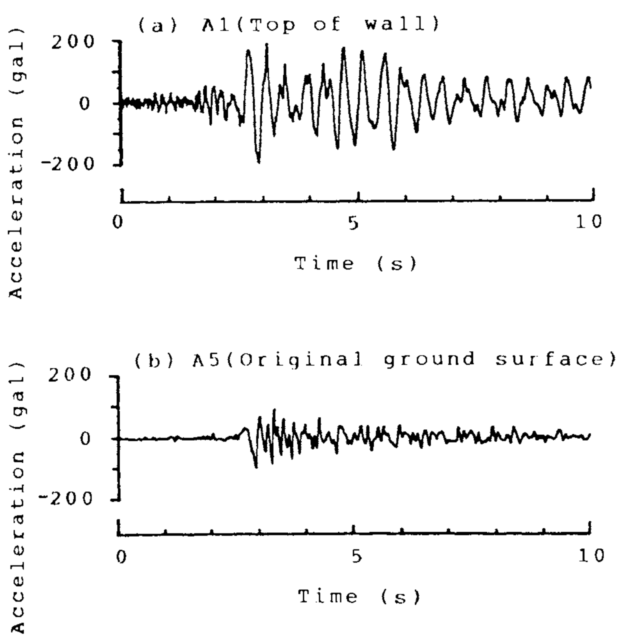

Figure 7. Acceleration Records (A1 and A5)

acceleration records at the original ground surface(A5) and the top of the wall(A1), plus denotes that direction of inertia force is forward. The accelerometer(A5) located on the original ground surface was provided and installed in a set-up for the other experiment at that time, so that the record of A5 is difficult to be synchronized with others(A1 ~ A4).

Figure 8 demonstrates the power spectra obtained by analysing the acceleration records of A5 and A1 shown in Fig.7. It is found that the vibration frequency of the original ground surface(A5) and that of the top of the wall(A1) predominate over 2 to 10 Hz and 2.5 Hz respectively. The microtremor frequency of the wall also predominates over 2 to 3 Hz, so that the natural frequency of the retaining wall would be around 2.5 Hz (Fukuoka 1990).

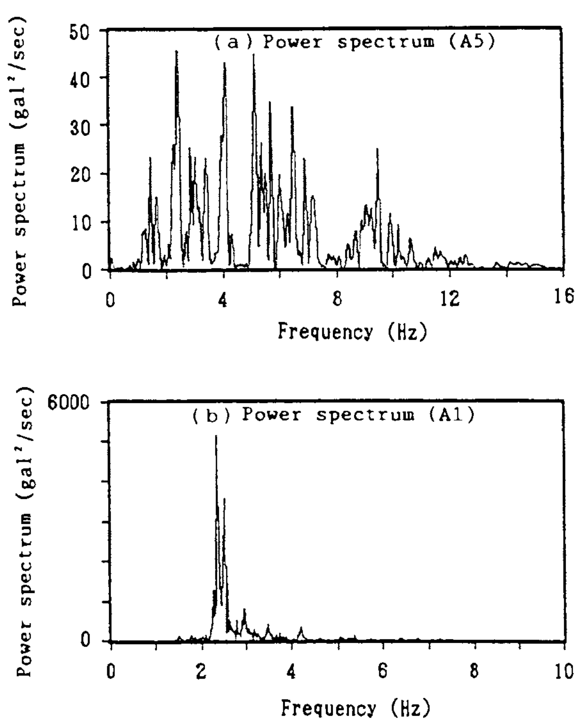

Figure 8. Power Spectra of Acceleration Records (A1 and A5)

Figure 9 shows the records of the earth pressure acting on the wall during the earthquake. In Fig.9, the earth pressure until about 2.5 s could be the one in the static condition. The earth pressure in static condition had decreased by the time of the earthquake, in comparison with the value immediately after the completion.

The amplitude of the earth pressure wave at the upper records(E3, E4 and E5; refer to Fig.4) was observed to be larger than that of the lower records(E1 and E2). This means that the increment or decrement of the earth pressure due to the earthquake was larger at the upper portion of the wall, while the earth pressure in static condition was smaller.

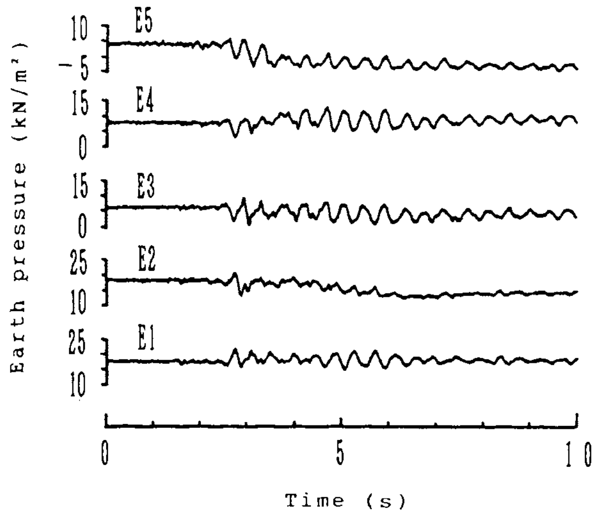

Figure 9. Observed Earth Pressure During Earthquake

The static earth pressure varied after the earthquake. The values of earth pressure at E2 and E5 gradually decreased with time during the earthquake, while that of E4 increased gradually. The earth pressure waves of E3, E4 and E5 generally have inverse phases of those of E1 and E2, so that the upper two third wall would vibrate in reverse direction to the lower third.

7. COMPARISON BETWEEN OBSERVED AND CALCULATED SEISMIC EARTH PRESSURE

Figure 10 shows a relation between the maximum increment of total earth pressure calculated by the Mononobe-Okabe formula and acceleration of earthquake. A relation between the observed maximum increment of total earth pressure and the observed acceleration at the original ground surface is also shown in Fig.10, including other observed earthquakes.

Figure 11 shows the earth pressures calculated by Coulomb's formula, Mononobe-Okabe formula and observed by the authors.

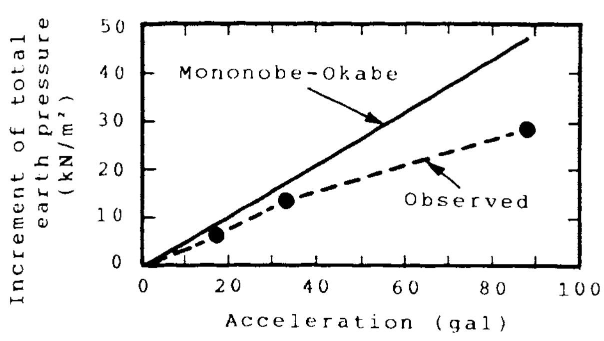

Figure 10. Increment of Total Earth Pressure due to Earthquake

The earth pressure in ordinary time calculated by Coulomb's formula is larger than the observed static earth pressure in the lower part of the wall. The amplitude of the observed earth pressure during the earthquake is larger in the upper part. The total earthquake earth pressure calculated by the Mononobe-Okabe formula is much larger than the observed one. The angle of internal friction and the angle of wall friction for the Coulomb's and Mononobe-Okabe formulae were assumed to be 30° and 15° , respectively.

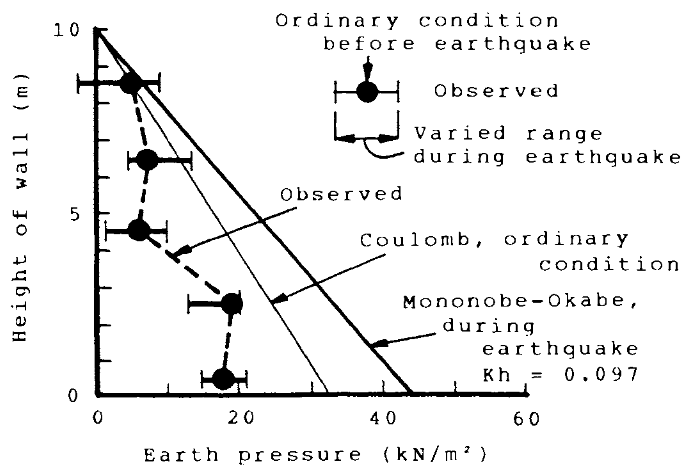

Figure 11. Earth Pressure Calculated by Coulomb's and Mononobe-Okabe Formulae, and Observed

8. RELATIVE DISPLACEMENT BETWEEN WALL AND FILL, AND EARTH PRESSURE DURING EARTHQUAKE

The records from the accelerometers at the top of the wall(A1) and the fill(A2), which are located 1 m apart from each other, are shown in Fig.12(a). A small gap is found in the phase between the acceleration wave of A1 and A2, the phase of A2 is later than that of A1. Such gaps exist also between the acceleration waves of A1, A2, A3 and A4. These gaps show that the top of the retaining wall moved differentially, and this differential movement may have been one of causes which have done damage to the top of the 4 m high retaining wall as shown in Fig.1.

The relative displacement between the wall and the fill at the top can be computed by using these acceleration records. In the process of computation, a high and low pass filter was employed to eliminate noise and error. By this method, the relative displacement between the wall and the fill at the top is computed at ± 5 mm as shown in Fig.12(b).

The earth pressure record at the place 1.5 m below the top(E5) shown in Fig.9 is also shown in Fig.12(c), synchronized with the acceleration records of A1 and A2(Fig.12 (a)) and the wave of the relative displacement computed from the acceleration records of A1 and A2(Fig.12(b)).

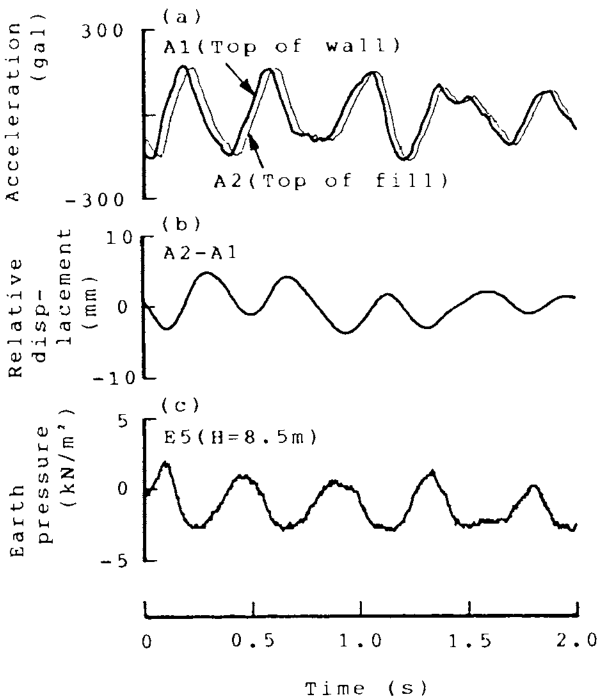

Figure 12. Movement of Wall and Fill, and Earth Pressure During Earthquake

The positive acceleration denotes that the direction of inertia force is forward, and the relative displacement is expressed to be positive when the distance between the point A1 and A2 becomes longer.

The earth pressure seems to be concerned with the gaps in the phases between the acceleration waves.

In case of leaning wall, including this retaining wall, earth pressure during earthquake seems to be dominated not only by acceleration but also by some other factors. For the stability of this type of retaining wall, appearing of a large earth pressure is not always dangerous. In case that inertia force of the wall is large, the maximum earth pressure sometimes occurs at the time when the wall is moving backward(Fukuoka 1984). Though it is generally thought that seismic earth pressure is mainly concerned by inertia force of backfill, it is also concerned by inertia force of wall.

12. CONCLUSIONS

Findings contributed in this paper would be summarized as follows;

a. The ten meter high retaining wall made by using sands reinforced with continuous fibers as the wall material was able to be constructed, while a horizontal displacement of 150 mm was found during construction, at about one third of the wall height.

b. The retaining wall was proved to be stable against an earthquake of about 100 gals at the original ground surface and about 200 gal at the top of the wall and fill. No crack was found on the top of the fill. The predominant frequency of the original ground surface was over 2 to 10 Hz.

c. The natural frequency of the retaining wall was estimated to be 2.5 Hz.

d. The upper two third wall and the lower third wall would vibrate in reverse directions during the earthquake.

e. The observed earthquake earth pressure obviously differed with computed one from the Mononobe-Okabe formula.

Further studies on the dynamic response analysis are recommended, compiling the measurement data which would be obtained in the future.

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