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Importance of strong motion in the design of earth reinforcement

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ABSTRACT: In the design of earth reinforcement structures in a seismic area it is important to understand the nature of the strong motion arriving at the site. It is known that the propagation of the stress waves through the soil strata overlying the bed rock will alter the characteristics of the bed rock motion. The recording of strong motion traces at different depths in the reclaimed area of Port Island during the Kobe earthquake provides us an opportunity to study the changes in the bed rock motion as it travels to the soil surface. This paper concerns itself with the analysis of the data recorded at this site and concentrates on the implications of strong motion modulation in the design of earth reinforcement structures.

It was observed that there is significant attenuation of the peak ground acceleration in the upper strata of soil at this site. The N-S component and the E-W component during this earthquake are 180° out of phase as the strong motion reaches the soil surface. Lissajous figures of these two components were constructed at all the four depths. These figures suggest that the strong motion polarizes in the N-E and S-W direction as it approaches the soil surface. These findings suggest that the orientation of the soil reinforcement within the soil structure will determine the efficacy of the soil reinforcement during an earthquake event. Also the arrival times of stress waves at the soil surface were compared between the U-D components induced by the P waves and the horizontal components induced by the shear waves. As expected the P waves arrive earlier than the shear waves at the soil surface. Frequency analyses were carried out for strong motion recorded in both N-S and E-W directions. These analyses suggest a strong attenuation of high frequency components while selective discrete frequencies are amplified. This suggests that there is a need to understand the behavior of a reinforced earth structure at discrete frequencies. Also it has strong implications on the type of input motion that may be used while modeling the dynamic behavior of a reinforced earth structure in a geotechnical centrifuge.

1 INTRODUCTION

The earthquake of 17 January, 1995 near Kobe city in Japan has provided strong motion records at several locations. The earthquake measured 7.2 on the Richter scale and inflicted significant damage to the city of Kobe. There were extensive liquefaction induced failures in the reclaimed areas and sea-front sites. On the other hand reinforced earth structures have performed satisfactorily overall at most of the locations. With the improvements in the understanding of the reinforced earth structures, in general, it is likely that these structures will be used in more seismic zones given there excellent performance during the Kobe earthquake. This necessitates the study of the dynamic behavior of soil reinforced structures. In this connection it is imperative to understand the importance of the strong motion arriving at the site of the reinforced earth structure. The present paper concerns itself with the analyses of ground motions recorded at the Port Island site which is one of the reclaimed areas. The implications of the above analysis in the design of the reinforced soil structures will be considered. However, specific reinforcement systems will not be considered. It is known that the stress waves propagating from the epicenter undergo changes according to the medium in which they are propagating. The soil layers overlying the bed rock will modify the stress waves as they propagate towards the surface, and largely determine the type of ground motion felt at the soil surface. This will strongly influence the design of a reinforced earth structure located just below the soil surface. The effect of the modulation of the stress waves by the soil layers must be delineated from the dynamic behavior of reinforced earth structure as an identical structure in different locations may perform differently based on the ground motion it receives. Also understanding the nature of the ground motion received by the reinforced earth structure will influence its design.

Strong motion records at different observation sites in Kobe were recorded by CEORKA (the Committee of

Earthquake Observation and Research in the Kansai Area). The data recorded at Port Island was unique in the sense that strong motion was recorded at different depths enabling us to study the modulation of stress waves as they propagate to soil surface at this site.

The soil conditions at all of the CEORKA sites are presented in Table 1 with the latitude, longitude and the altitude of each recording station. Note in this table that the soil type at the Port Island site is reclaimed land. This would mean that the analysis carried out for this site may be applicable to earth reinforced structures in similar reclaimed areas.

2 PORT ISLAND SITE SPECIFICATIONS

Port Island site was chosen for the present analysis as strong motion was recorded at different depths at this site. Accelerations were recorded at four different depths namely 83m, 32m, 16m below ground level and at the soil surface. The soil profile at this site is presented in Fig.1. The soil properties and the stress wave velocities in each of the strata shown in Fig.1 are presented in Table 2. At each of the depths the acceleration-time histories were recorded in the N-S (North-South) direction, E-W (East-West) direction and U-D (Up-Down) direction.

Table 1 Location and Soil Conditions of all CEORKA sites

Site	Latitude	Longitude	Altitude	Soil Conditions
Kobe Univ.	N34.725	E135.240	110m	Mesozoic granite
Kobe	N34.725	E135.281	25m	Late Pleistocene fan deposit
Amagasaki	N34.718	E135.408	0m	Thick Holocene deposits
Fukushima	N34.687	E135.474	0m	Thick Holocene deposits
Morigawachi	N34.680	E135.572	1m	Thick Holocene deposits
Yae	N34.680	E135.612	3m	Thick Holocene deposits
Toyonaka	N34.801	E135.5[illegible]1	55m	Pliocene deposit
Sakai	N34.564	E135.462	2m	Thin Holocenel deposits
Tadaoka	N34.480	E135.408	12m	Thin Holocenel deposits
Chihaya	N34.439	E135.659	280m	Mesozoic granite
Abeno	N34.6[illegible]6	E135.519	12m	Late Pleistocene deposits
Port Island	N34.670	E135.208	4m	Reclaimed Land

Table 2 Soil information at the Port Island site

Depth (m)	Soil type	V_p (m/s)	V_s (m/s)	SPT (N)	Poisson Ratio
0~2.0	Gravel (Reclaimed)	260	170	5.2	0.127
2.0~5.0	Gravel (Reclaimed)	330	170	5.2	0.319
5.0~12.6	Gravel (Reclaimed)	780	210	6.5	0.461
12.6~19.0	Sand with Gravel (Reclaimed)	1480	210	6.5	0.490
19.0~27.0	Clay	1180	180	3.5	0.488
27.0~33.0	Sand	1330	245	13.5	0.482
33.0~50.0	Sand with Gravel	1530	305	36.5	0.479
50.0~61.0	Sand	1610	350	61.9	0.475
61.0~79.0	Clay	1610	303	11.7	0.482
79.0~86.0	Sand with Gravel	2000	320	68.0	0.487

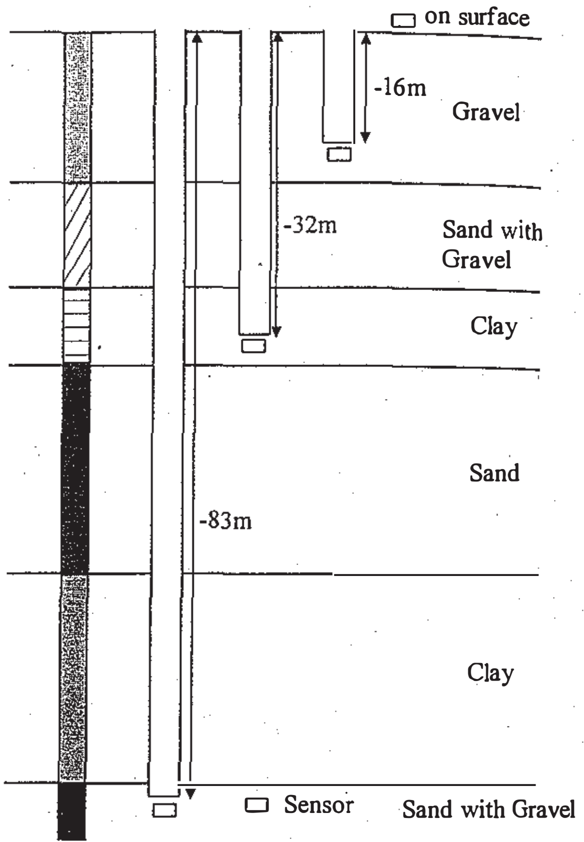

Fig.1 Schematic diagram showing the soil profile and the location of the acceleration sensors

3 STRONG MOTION RECORDS

The acceleration-time histories recorded at the Port Island site in the N-S direction, E-W direction and U-D direction are presented in Figs.2 to 4. In each of these figures the acceleration-time histories at different depths are presented. Also the frequency analysis of each of these traces in the range of 0 to 10 Hz is shown on the right hand side. These figures show the modulation of the strong motion as it travels towards the soil surface. In Fig.2 the strong motion in the N-S direction show a reduction of high frequencies as they travel towards the soil surface. Also the amplitude of the acceleration decreases significantly in the soil strata lying between the ground surface and 16m depth. Looking at Fig.3 we can draw a similar conclusion that the high frequency components of the ground motion in the E-W direction are attenuating as the waves travel to the soil surface and the amplitude of the acceleration is decreasing markedly in the top 16m of the soil strata. One of the reasons for this may be due to partial liquefaction resulting in a partial loss of soil stiffness. This will result in a lower transmissibility of the stress waves thus resulting in smaller peak accelerations near the soil surface. However, no pore pressure measurements were

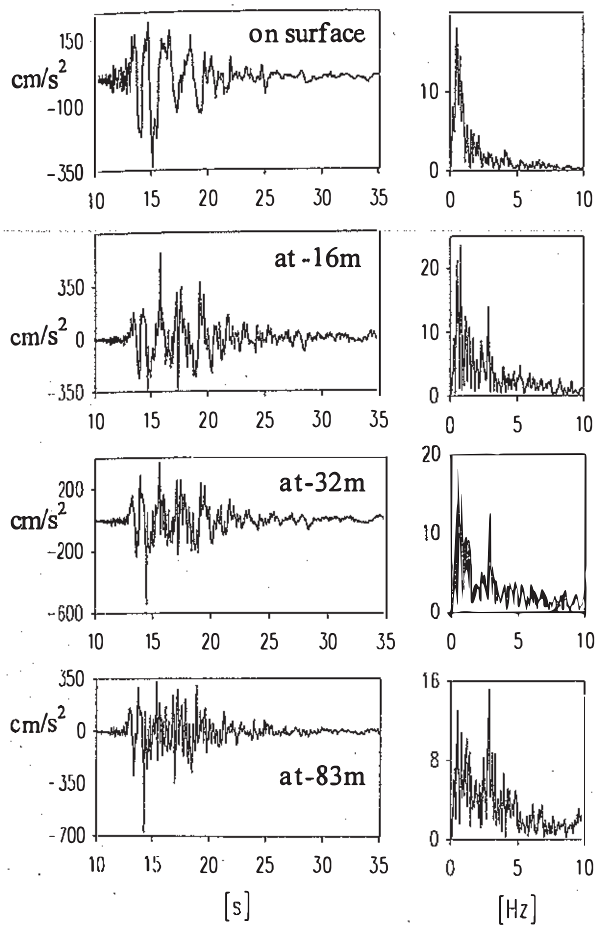

Fig.2 Accelerations in the N-S direction at different depths

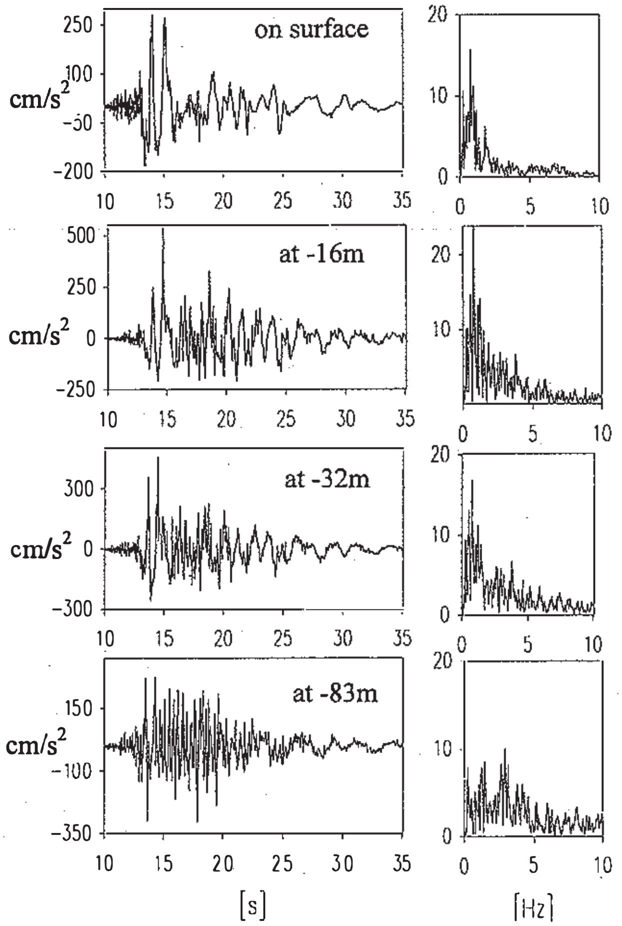

Fig.3 Accelerations in the E-W direction at different depths

made at the site to confirm the partial liquefaction hypothesis. Fig.4 also shows attenuation of high frequency components in the U-D direction as the vertical accelerations travels to the soil surface. Also the vertical accelerations show a remarkable amplification as they approach the soil surface. In Table 3 the peak accelerations in each direction are tabulated. This table summarizes the observations made in the above paragraph on the attenuation of amplitude of the accelerations as the strong motion approaches the soil surface.

Table 3 Peak ground accelerations at the Port Island site

Elevation	N-S direction (gals)	E-W direction (gals)	U-D direction (gals)
GL-00m	341.2	284.3	555.9
GL-16m	564.9	543.2	789.5
GL-32m	543.6	461.7	200.0
GL-83m	678.8	302.6	186.7

after Iwasaki (1995)

4 PHASE RELATIONSHIP BETWEEN THE N-S AND E-W COMPONENTS

In this section we shall investigate the phase relationship between the N-S component and E-W component of the ground motion. In Fig.5 these two components recorded at the surface are shown. From this figure it can be seen that the N-S component and E-W component are approximately 180° out of phase. This suggests that the peak acceleration in the North direction occurs at the same time as the peak acceleration occurs in the West direction. Similar figures for other depths are shown in Madabhushi (1995). To study this further Lissajous figure was constructed by plotting the N-S component along the x-axis and the E-W component along the y-axis as shown in Fig.6.

In Fig.6 the Lissajous figure constructed from the traces recorded at a depth of 83m shows a overall rounded shape for the duration of 10 to 35s suggesting that the N-S and E-W components are in almost in phase. The Lissajous figure for the depth of 32m indicates that the N-S and E-W components are polarizing in the N-E and

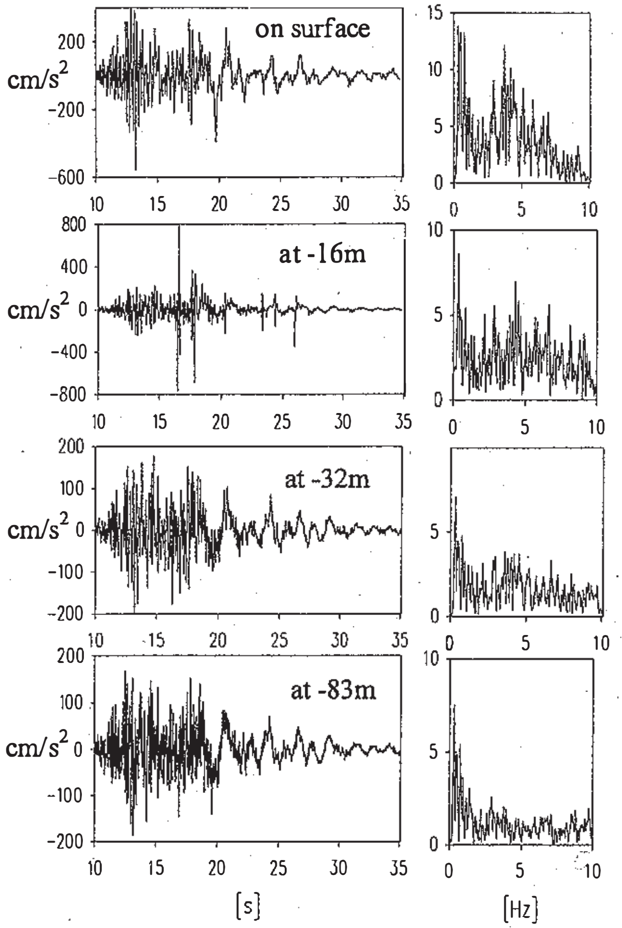

Fig.4 Accelerations in the U-D direction at different depths

S-W directions as there are more points in the Lissajous figure falling in this direction compared to the Lissajous figure at the depth of 83m. As we move up to the depth of 16m this trend of polarizing continues as shown by the Lissajous figure at this depth compared to the ones at the depths of 32m and 83m. The Lissajous figure at the soil surface shows almost complete polarization of the N-S and E-W components into N-E and S-W directions. This Lissajous figure is much narrower compared to the Lissajous figures at all other depths. One of the reasons for this may be the cross-anisotropy of soil strata closer to the surface. This can only be confirmed by more detailed determination of soil properties at the site.

The polarization of the strong motion in the N-E and S-W direction near the soil surface suggests that the reinforcement in the soil structure that might be located at this site will be only effective if the its oriented in such a way that it will carry the tensile stresses in the soil created by the polarized strong motion. Also the amount of soil reinforcement required in the structure is dictated by the polarized strong motion arriving at the site.

5 ARRIVAL OF VERTICAL ACCELERATIONS RELATIVE TO HORIZONTAL ACCELERATIONS

The horizontal accelerations within the soil layer overlying the bed rock arise due to the vertically propagating horizontal shear waves (S_h waves). The vertical accelerations in the soil layer result from the Primary waves (P waves). In Table 2 the stress wave velocities for all the soil strata at the recording site are presented. The shear wave velocities are significantly lower than the primary wave velocities. From this it follows that the P-Waves must arrive at the surface earlier than the S_h waves.

In Fig.7 the U-D component recorded at the surface is superposed on the traces recorded in the N-S and E-W directions. In this figure the peak vertical accelerations occur significantly before the peak accelerations in the horizontal direction (both N-S and E-W). This confirms that the vertical accelerations are induced by the P-waves while the S_h waves cause the horizontal accelerations. The arrival of peak vertical accelerations ahead of the peak horizontal accelerations at the soil surface may have significant implications in the design of reinforced soil systems. As the peak vertical accelerations are separated in time from the peak horizontal accelerations the same reinforcement may be able to take the tensile stresses created by accelerations in both these directions. In other words, we may not have to design the reinforcement by considering the superposed effects of the vertical and horizontal accelerations. However, this aspect needs further research.

6 FREQUENCY ANALYSIS OF GROUND MOTION IN THE N-S DIRECTION

Frequency analyses were carried out by using the Discrete Fast Fourier Transform (DFT) method. In Fig.2 the frequency analysis of the N-S component and the actual time trace of the strong motion at different depths are presented. The frequency analysis of the strong motion recorded at the depth of 83 m shows significant components at various frequencies between 0 to 10 Hz as seen in Fig.2. Some of these high frequencies are filtered by the time the strong motion arrives at the depth of 32m. This is seen in Fig.2 which reflects the attenuation of the 2.8 Hz component and amplification of the 0.5 and 0.75 Hz components. As the strong motion travels upwards to the depth of 16 m the 0.5 and 0.75 Hz components show further amplification. As the strong motion reaches the soil surface there is some attenuation of the 0.5 and 0.75 Hz components. The 2.8 Hz component and all of the high frequency components suffer extensive attenuation in this region.

The effect of partial liquefaction was proposed as a possible reason for the attenuation of amplitude of the

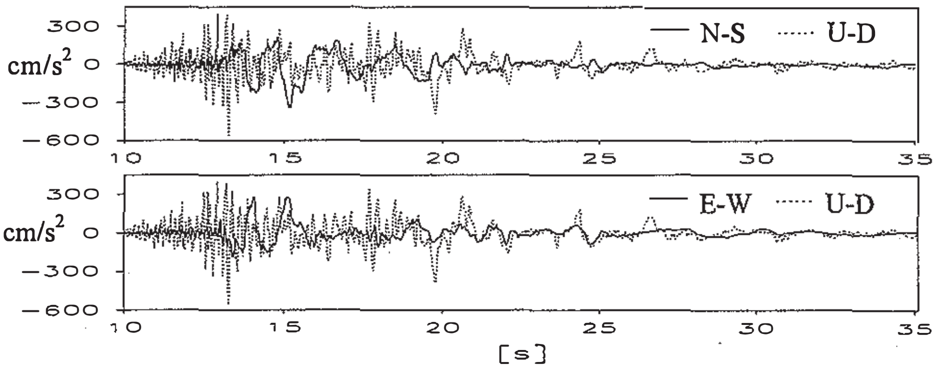

Fig.5 Difference in arrival time of the stress waves at the surface

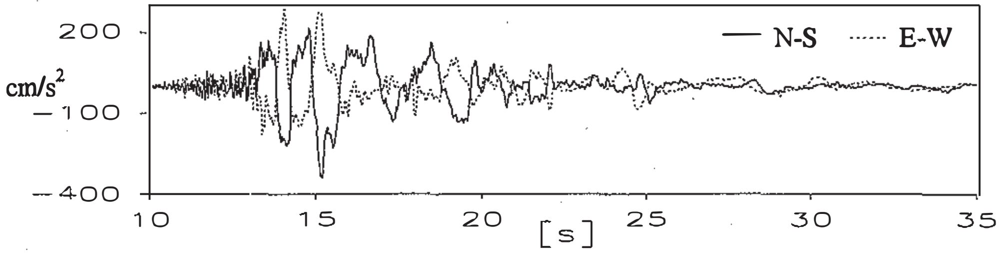

Fig.6 Phase difference between the N-S component and E-W component at the surface

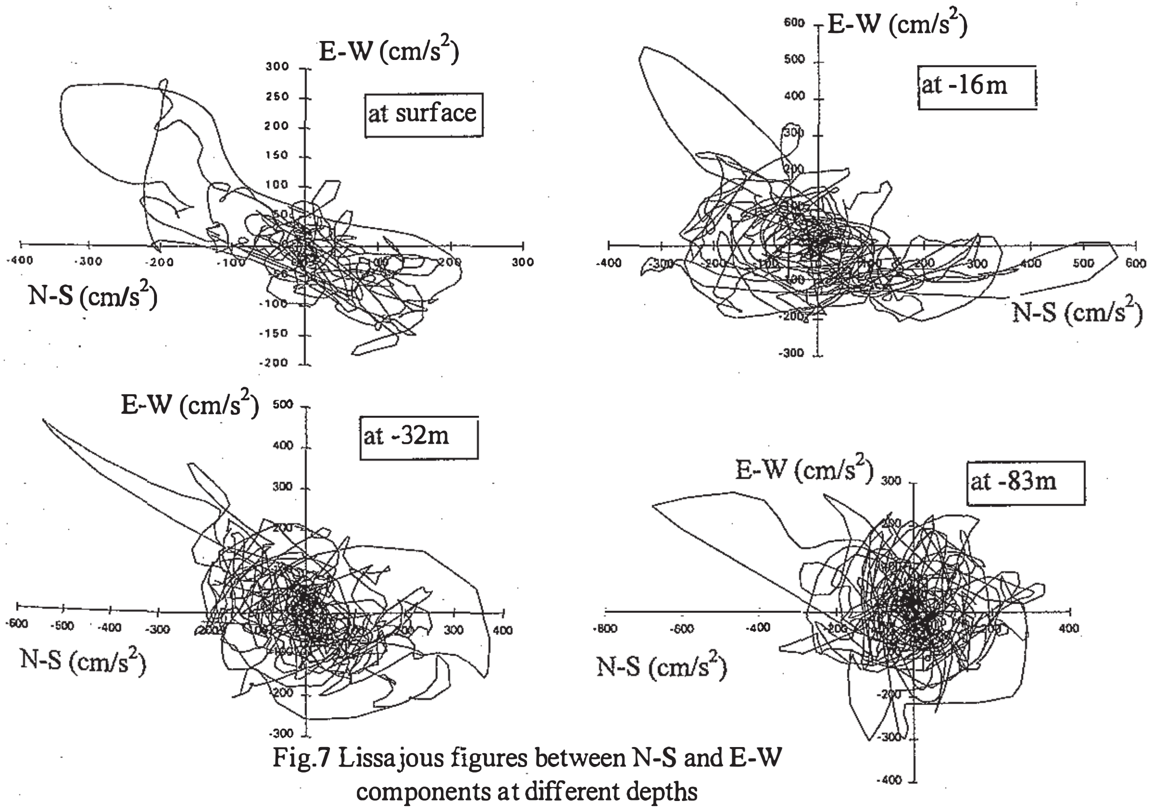

Fig.7 Lissajous figures between N-S and E-W components at different depths

ground motion in the upper strata at this site. It is clear from Fig.2 that this attenuation is not effecting all the frequency components in the same way. The 2.8 Hz components suffers extensive attenuation in the top 16m of soil strata bringing its magnitude from 0.15m/s^2 at 16 m depth to 0.02 m/s^2 at the soil surface (a reduction of 86.6%). The 0.5 Hz component suffers an attenuation from 0.22 m/s^2 to 0.18 m/s^2 in the same soil strata (a reduction of 22.2%). This analysis suggests that the design of soil reinforcement may be governed by the natural frequency of the resulting reinforced soil structure. If the stiffness of the reinforced soil structure (by virtue of the reinforcement) is higher the natural frequency will be higher drawing the structure away from any possible resonance. The above analysis prompts us to study the dynamic behavior of soil reinforced systems.

7 FREQUENCY ANALYSIS OF GROUND MOTION IN THE E-W DIRECTION

In Fig.3 the frequency analysis of the E-W component and the actual time trace of the strong motion at different depths are presented. The frequency analysis of the strong motion recorded at the depth of 83 m shows significant components at various frequencies between 0 to 10 Hz as seen in Fig.3. Some of these high frequencies are filtered by the time the strong motion arrives at the depth of 32m. This is seen in Fig.3 which reflects the marked attenuation of the 2.8 Hz component and amplification of the 0.2, 0.5 and 0.75 Hz components. As the strong motion travels upwards to the depth of 16 m the 0.5 and 0.75 Hz components show further amplification. As the strong motion reaches the soil surface there is some attenuation of the 0.5 and 0.75 Hz components. The 2.8 Hz component and all of the high frequency components suffer some attenuation in this region.

8 FREQUENCY ANALYSIS OF GROUND MOTION IN THE U-D DIRECTION

In Fig.4 the frequency analysis of the U-D component and the actual time trace of the strong motion at different depths are presented. The frequency analysis of the strong motion recorded at the depth of 83 m shows significant components at various frequencies between 0 to 10 Hz as seen in Fig.4. Significantly there are large components between 0 and 2.5 Hz. The frequency components between 2.5 to 5 Hz show amplification by the time the strong motion arrives at the depth of 32m. As the strong motion travels upwards to the depth of 16 m there is an overall amplification of all the frequency components. As the strong motion reaches the soil surface there is further amplification of the 0.5 and 0.75 Hz components. The pattern of amplification of the vertical accelerations is very different from that of the horizontal accelerations. This may be expected as they are induced by different kinds of stress waves namely the P-waves and S_h waves.

9 IMPLICATIONS FOR MODELING

Dynamic centrifuge modeling is being extensively used over the past decade in modeling of the seismic events in a centrifuge. There is a valid discussion on the type of strong motion that must be used to study the dynamic behavior of a reinforced soil system subjected to earthquake loading. Use of servo-hydraulic systems which simulate a 'realistic ground motion' observed in one of the past earthquakes is an approach followed by many universities in the USA like Caltech, RPI, UC Davis and Boulder. One of the difficulties of this approach arises from the fact that use of multi-frequency input may excite various modes of vibration in the mechanical actuators and centrifuge swings, the effects of which are hard to differentiate from the 'real' behavior of a reinforced soil system. An alternative approach used at the Cambridge University is to use a single frequency input to which the system (actuator and swing) response is known. A new earthquake system called the Stored Angular Momentum (SAM) actuator was commissioned which increases the versatility in dynamic centrifuge testing by giving the research worker the choice of frequency of the strong motion and the duration of the earthquake.

10 CONCLUSIONS

The strong motion traces recorded at different depths at the Port Island site during the Kobe earthquake were analyzed. Significant attenuation of the peak ground acceleration in the upper strata of soil at this site. The N-S component and the E-W component during this earthquake are 180° out of phase as the strong motion reaches the soil surface. Lissajous figures of these two components were constructed at all the four depths. These figures suggest that the strong motion polarizes in the N-E and S-W direction as it approaches the soil surface. This implies that the orientation of the reinforcement will determine its efficacy when a reinforced soil system is subjected to a polarized strong motion. The arrival times were compared between the U-D components and the horizontal components. As expected the P waves arrive earlier than the shear waves at the soil surface. As the peak accelerations in the vertical direction arrive ahead of those in horizontal direction the same soil reinforcement may be able to cope with the tensile stresses created by both of these waves. This aspect requires further research. Frequency analyses were carried out for strong motion recorded in both N-S and E-W directions. These analyses suggest a strong attenuation of high frequency components while selective discrete frequencies are amplified. This suggests that the dynamic behavior of reinforced soil systems must be investigated.

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