

SEISMIC WAVE ENERGY EVALUATION IN SURFACE LAYERS FOR PERFORMANCE-BASED DESIGN

Takaji KOKUSHO¹, Ryu-ichi MOTOYAMA², Shogo MANTANI² and Hiroshi MOTOYAMA²

SUMMARY

Energy flow of seismic waves observed during the 1995 Hyogo-ken Nambu earthquake in vertical array sites is calculated by assuming vertical propagation of SH waves in surface layers. Wave energy flow in a 2-layers system is also investigated basically. The major findings are; (1) Upward wave energy generally tends to decrease as it goes up from the base layer to the ground surface, (2) A general perception that soft soil sits are prone to heavier damage may not be explained in terms of upward energy, because large damping ratio tends to cancel energy storage effects by resonance if it ever occurs. (3) The wave energy, which is directly related with induced strain in superstructures, can play a key role for the performance-based design. For that purpose, design seismic motion should also be defined in terms of wave energy.

Key Words: Seismic wave energy, SH wave, Impedance ratio, Damping, Performance-based design

INTRODUCTION

Conventional seismic design has been based on inertia force given by acceleration or seismic coefficients. Historically this force-based design method has long been used to date. In performance-based design methods increasingly employed recently, the degree of structural deformation is a target to evaluate rather than the safety factor against ultimate failure. It has been recognized increasingly that acceleration may not be an appropriate parameter not only for deformation evaluation but also for seismic damage evaluation in general. More and more strong

2. Ex-graduate student, diito

^{1.} Professor, Chuo University, Tokyo, Japan, Email: kokusho@civil.chuo-u.ac.jp

accelerograms exceeding 1 G have been obtained in recent years without any significant damage at all such as in Tarzana during 1994 Northridge earthquake, in Hokkaido during 2003 Tokachi-oki earthquake, etc. Velocity is increasingly used in place of acceleration because it is believed to closely connected with energy. Then why don't we directly use wave energy in seismic design?

In the first part of this paper, energy flow of seismic waves observed during the 1995 Hyogo-ken Nambu earthquake (sometimes called as the Kobe earthquake) in vertical array sites is calculated. Accumulated wave energy, energy flow rate and its dissipation in surface layers are calculated from vertical array records by assuming vertical propagation of SH waves in surface layers. Then, 2-layers systems with variable impedance ratios and damping ratios are studied for better understanding on energy flow and dissipation mechanism. Performance-based design using the wave energy is finally proposed based on the analytical results.

WAVE ENERGY EVALUATION BY VERTICAL ARRAY RECORDS

It is well recognized since the pioneering work by Kanai [1] that the major portion of a seismic response of a ground can be evaluated with a simple one-dimensional model in which SH wave is postulated to travel only vertically. Based on the postulate, the energy can also be assumed to propagate vertically. A wave energy increment E transmitted vertically by the SH-wave through a unit area in a time increment t is expressed as;

$$E = E_k + E_e = \rho V_s t \left(\frac{du}{dt}\right)^2 \tag{1}$$

where $\rho = \text{soil density}$, $V_s = \text{wave velocity and } du/dt = \text{particle velocity of the soil}$. Note that the wave energy E is shared 50% by kinetic energy E_k and 50% by strain energy E_e . Let us define the time derivative of the energy

$$\overline{E} = E/t = dE/dt = \rho V_s \left(\frac{du}{dt}\right)^2$$
(2)

and name it energy flow rate. If a time interval for a seismic motion to go through a point is $t = t_1$ t_2 , the accumulated energy is expressed as

$$E(t = t_1 \quad t_2) = \rho V_s \int_{t_1}^{t_2} \left(\frac{du}{dt}\right)^2 dt$$
(3)

Note that du/dt in Eqs.(1) and (2) is the particle velocity not directly of a recorded motion but of traveling wave in one direction. Therefore it is essential to separate a measured motion at a point into upward and downward waves in order to evaluate the individual energies.

If a site consists of a set of horizontal soil layers and the soil behaves as a linear material, upward and downward propagating waves at any point can be calculated based on the multiple reflection theory [2] from which the flow of the energy there is readily evaluated. However, if the soil experiences

strong nonlinearity due to strain-dependency or liquefaction during destructive earthquakes, such a linear model no longer holds. The seismic motions are very much influenced by the soil nonlinearity exhibited near the surface. Because a lot of energy has already been lost on the way when the seismic wave arrives at the surface, it is hard to evaluate the energy from the surface record. In a vertical array system, seismic motions in a deeper ground are available. It has already been demonstrated that the deeper the soil is, the more soil behaves as a linear material even during strong earthquakes [3]. If the upward and downward wave components can be separated from seismic records at some deeper level where the seismic wave is less contaminated by soil nonlinearity, the energy flow can be evaluated more reliably [4].

A harmonic SH wave with an angular frequency,
$$\omega$$
, is expressed as

 $u = Ae^{i(\omega t + kz)} + Be^{i(\omega t - kz)}$ (4) where, *u* is displacement in the horizontal direction, *t* and *z* is time and vertical axis positive in the downward direction, respectively, and , *A* and *B* are constants. The first and second terms correspond to upward and downward components, respectively. The constant *k* is the wave number given by

$$k^{2} = \frac{\rho\omega^{2}}{G^{*}} = \frac{\rho\omega^{2}}{G + iG'}$$
(5)

where G + iG' is a complex shear stiffness of soil. Here the soil damping is assumed as non-viscous as in geotechnical engineering practice. As shown in Fig.1, the one-dimensional soil model consists of a set of horizontal soil layers numbered from 1 to n. The m'th layer has the thickness, h_m , the soil density, r_m , the complex stiffness, G_m^* , the wave number, k_m , the constants A_m , B_m and so on. Taking a local coordinates z downward from the upper boundary for the m'th layer, the following recursion formula on A_m , B_m can be obtained based on the agreement of deformation and stress at the boundary between m'th and (m+1)'th layers.





$$\hat{\mathbf{I}}_{B_{m+1}}^{A_{m+1}} \hat{\mathbf{F}}_{\mathbf{F}} = \underbrace{\underbrace{\underbrace{k_{m+1}G_{m+1}^{*} + k_m G_m^{*}}_{2k_{m+1}G_{m+1}^{*}} e^{ik_m h_m}}_{\mathbf{K}_{m+1}} \underbrace{\underbrace{k_{m+1}G_{m+1}^{*} - k_m G_m^{*}}_{2k_{m+1}G_{m+1}^{*}} e^{-ik_m h_m}}_{2k_{m+1}G_{m+1}^{*}} \hat{\mathbf{F}}_{m+1}^{*} e^{-ik_m h_m} \underbrace{k_m H_m^{*}}_{2k_{m+1}G_{m+1}^{*}} e^{-ik_m h_m}}_{2k_{m+1}G_{m+1}^{*}} \hat{\mathbf{F}}_{m+1}^{*} e^{-ik_m h_m}} \underbrace{k_m H_m^{*}}_{2k_{m+1}G_{m+1}^{*}} e^{-ik_m h_m}}_{2k_{m+1}G_{m+1}^{*}} e^{-ik_m h_m}} \underbrace{k_m H_m^{*}}_{2k_{m+1}G_{m+1}^{*}} e^{-ik_m h_m}}_{2k_{m+1}G_{m+1}^{*}} e^{-ik_m h_m}} \underbrace{k_m H_m^{*}}_{2k_{m+1}G_{m+1}^{*}}} e^{-ik_m h_m}}_{2k_{m+1}G_{m+1}^{*}} e^{-ik_m h_m}} \underbrace{k_m H_m^{*}}_{2k_{m+1}G_{m+1}^{*}}} e^{-ik_m h_m}}_{2k_{m+1}G_{m+1}^{*}} e^{-ik_m h_m}} \underbrace{k_m H_m^{*}}_{2k_{m+1}G_{m+1}^{*}}} e^{-ik_m h_m}}_{2k_{m+1}G_{m+1}^{*}} e^{-ik_m h_m}} \underbrace{k_m H_m^{*}}_{2k_{m+1}}} e^{-ik_m h_m}}_{2k_{m+1}} e^{-ik_m h_m}} \underbrace{k_m H_m^{*}}_{2k_{m+1}}} e^{-ik_m h_m}}_{2k_{m+1}} e^{-ik_m h_m}} \underbrace{k_m H_m^{*}}_{2k_{m+1}}} e^{-ik_m h_m}} \underbrace{k_m H_m^{*}}_{2k_{m+1}} e^{-ik_m h_m}} \underbrace{k_m H_m^{*}}_{2k_{m+1}}} e^{-ik_m h_m}} \underbrace{k_m H_m^{*}}_{2k_{m+1}}} e^{-ik_m h_m}} e^{-ik_m h_m}} \underbrace{k_m H_m^{*}}_{2k_{m+1}}} e^{-ik_m h_m}} e^{-ik_m h_m}$$

The matrix in Eq.(6) is denoted here as \mathcal{F}_{m+1} is. Seismic responses are given at the top of the m'th and n'th layers, at Point B and C in Fig.1 as

$$u_m = U_m e^{iwt} = (A_m + B_m)e^{iwt} , \quad u_n = U_n e^{iwt} = (A_n + B_n)e^{iwt}$$
(7)

The separation of upward and downward waves becomes possible based on the multiple reflection theory. Based on Eq.(6), Eq.(8) can then be derived correlating the constants A_m , A_n and B_m , B_n in the two layers.

$$\begin{cases} A_n \\ B_n \end{cases} = [T_n][T_{n-1}]\dots[T_{m+1}] \begin{cases} A_m \\ B_m \end{cases} = [T_{n,m+1}] \begin{cases} A_m \\ B_m \end{cases}$$
(8)

The 2 by 2 matrix in Eq.(8) is expressed here as

Then, by using Eqs.(7) to (9), the following equation can be derived.

$$\hat{\mathbf{I}}_{U_{m}}^{U_{n}} \hat{\mathbf{y}}_{\mathbf{y}}^{i} = \hat{\mathbf{\xi}}_{11}^{T_{11}} + T_{21} \quad T_{12} + T_{22} \quad \hat{\mathbf{y}}_{1}^{A_{m}} \hat{\mathbf{y}}_{\mathbf{y}}^{i} = \hat{\mathbf{\xi}}_{n,m+1}^{p} \quad \hat{\mathbf{y}}_{1}^{A_{m}} \hat{\mathbf{y}}_{\mathbf{y}}^{i} \\
D_{m} \hat{\mathbf{y}}_{1}^{i} = \hat{\mathbf{\xi}}_{11}^{i} \quad 1 \quad \hat{\mathbf{y}}_{11}^{i} B_{m} \hat{\mathbf{y}}_{11}^{i} = \hat{\mathbf{\xi}}_{n,m+1}^{i} \quad \hat{\mathbf{y}}_{11}^{i} B_{m} \hat{\mathbf{y}}_{11}^{i}$$
(10)

Consequently, A_m and B_m can be obtained by the equation;

$$\hat{\mathbf{I}}_{B_{m}}^{A_{m}} \hat{\mathbf{y}} = \hat{\mathbf{g}}_{n,m+1}^{p} \hat{\mathbf{u}}_{1}^{1} \hat{\mathbf{I}}_{U_{m}}^{p} \hat{\mathbf{y}}, \qquad \hat{\mathbf{I}}_{B_{n}}^{A_{n}} \hat{\mathbf{y}} = \hat{\mathbf{g}}_{n,m+1}^{p} \hat{\mathbf{u}}_{n,m+1}^{p} \hat{\mathbf{u}}_{1}^{1} \hat{\mathbf{I}}_{U_{m}}^{p} \hat{\mathbf{y}}$$
(11)

Eq.(11) gives the amplitudes for a harmonic motion with the angular frequency, w. In order to obtain the response to irregular seismic motions, a recorded motion is expressed as a superposition of harmonic waves with different angular frequencies by using the complex Fourier series. Then the Fourier series are incorporated together with Eq.(11) to compute time histories (Schnabel et al. 1972) of the upward and downward components. Wave energies or energy flow rates can be calculated from the velocity time histories by Eq.(2) or Eq.(3). On the other hand, the upward energy at a ground surface (Point A in Fig.1) can be calculated by substituting a half of the velocity time history into $\frac{du}{dt}$ in Eq.(2) or (3).

Vertical array records used in the analysis were obtained in Port Island in Kobe city (PI), Research Institute of Kansai Electric Power Company [KEPCO] in Amagasaki city (SGK), KEPCO power plant in Takasago city (TKS) and KEPCO transformer station at Kainan-ko in Wakayama city (KNK). PI is just next to the causative fault, SGK is about 20km and KNK is about 65km far from it. In Fig.2, the soil profiles of the 4 sites are shown together with the seismograph installation levels. Three to four seismographs are installed between the ground surface and the deepest level of 84 to 100 m. In the same charts, profiles of S-wave velocities (Vs) measured by S-wave logging tests are shown together with Vs and damping ratios (D) back-calculated from the main shock records. Details on the back-calculation are available in other literatures [3].

Acceleration records in two horizontal directions at the deepest (Point C) and the second deepest levels (Point B) shown in Fig.2 are utilized to evaluate the energy flow at the second deepest level. In the analysis, soil properties between these two levels, where soil nonlinearity is less pronounced than in the surface layer, are used. The degree of soil nonlinearity exhibited in the vertical array sites during the main shock was already back-calculated by the inversion technique [3]. The



Fig.2 Borehole log and profiles of measured or back-calculated Vs and damping ratio at 4 vertical array sites for 1995 Hyogoken Nambu earthquake.

back-calculated S-wave velocity decreased by 50 to 80% of the initial values in PI, while *Vs* below Point B changed by less than 20% even in PI. In other sites the nonlinearity was less pronounced than in PI in deeper part in particular. In the energy evaluations, the back-calculated S-wave velocity and damping ratio indicated in Fig.2 are assigned to the soil properties between Points B and C, and also at Point A. The soil density is estimated from the soil type and the ground water level shown in the soil profile.

The vertical array records used in the analysis were already corrected for seismograph installation errors detected by the maximum coherence analysis [5]. In PI, the horizontal acceleration records converted to the major principal axis (in which the largest acceleration occurs) and the minor principal axis are used, while, in other three sites, records in NS and EW directions are used. Acceleration records at the ground surface and the two deeper levels are transformed into frequency spectra by the FFT technique. The low frequency portion of the spectra (f<0.1Hz) is then cut off to remove a long period drift based on the assumption that the energy contribution for the frequency lower than 0.1Hz may be negligible.

ANALYTICAL RESULTS AT 4 SITES

Figs.3 to 6 show analytical results in the major principal direction in PI and in NS direction in other 3 sites. In each figure, the top chart indicates time-histories of energies and the second to fourth charts represent velocity time histories of upward and downward waves at Points A, B and C, respectively. The energy time histories are drawn for upward energies at Points A, B and C, downward energies and their differences at Points B and C. All energies are in KJ/m^2 corresponding to the amount of seismic wave energy passing through a unit area of 1 m².

As shown in Fig.3 for the major principal axis of PI, the upward energies E_u remarkably increase within the first two cycles of strong acceleration until t=6.3 s. The final value of E_u at the deepest level (Point C; GL-83.4m) amounts to 305 kJ/m² as a scalar sum of the energies in the major and minor principal axes. This is equivalent to the energy given by the drop of a mass of one ton from the height of 31 m once in every square meter. At GL-32.4 m (Point B), E_u , which shows an almost identical time-dependent change, is about 80% of Point C. At the ground surface (Point A), the upward energy E_u is about 20% of Point C, indicating a clear decreasing trend of upward energy with decreasing depth.

It is noted that E_u and E_d show monotonic increase because they are the cumulative energy transported by one-directionally propagating waves. In contrast, the difference $(E_u - E_d)$ indicates the energy balance in the soil layers above a given level and hence shows both increase and decrease. The decrease in $(E_u - E_d)$ implies that the energy temporarily stored in the surface layers returns back to deeper ground. With some small fluctuations, $(E_u - E_d)$ tends to climb up to a final value, indicating that the energy dissipation in the surface layers is dominantly large compared to the energy storage effect at PI site. The time history of $(E_u - E_d)$ rises to 75% of the final value in less than two cycles in the major seismic motion. It has been demonstrated that during this interval the surface soil actually



Fig.3 Time-histories of energy (top) and particle velocities (bottom) at PI site.

liquefied by means of an identification analysis in time domain using the same vertical array records [6]. Therefore, this rapid rise in $(E_u - E_d)$ at GL-32.4 m seems to reflect the energy loss by the liquefaction in the surface soil as well as that by the soil nonlinearity of clay and alluvial sand above that level. The value $(E_u - E_d)$ reaches to a final value at t=17 s, which is identical with the dissipated energy in the surface layers, E_w . This amounts to 155 kJ/m² at GL-32.4 m in the two directions and about 65% of the corresponding upward wave energy, E_u at the same level.

Similar results for SGK site in the NS direction are shown in Fig.4. The total upward energy at GL-97m adding the NS and EW direction is 83kJ/m² at t=15s, only 27% of that at GL-83.4m in PI site. The upward energy E_u at GL-25m (Point B) and at the surface (Point A) evaluate about 90% and less than 20%, respectively, of E_u at GL-97m (Point C), indicating again the clear decreasing trend of upward energy with decreasing depth. The value E_u obviously increases until t=25 s, while $(E_u - E_d)$ shows rapid increase until t=15 s and stays almost constant with small fluctuations after that. Considering a low possibility of liquefaction in this site judging from the soil condition, this increase seems to reflect the hysteretic energy dissipation due to a nonlinear stress versus strain relationship in non-liquefied soils during strong After t=15s, the increasing rate of shaking. $(E_u - E_d)$ becomes minimal, while E_u and E_d individually still keep rising with almost the same rate.



Fig.4 Time histories of energy (top) and particle velocities (bottom) at SGK site.



Fig.5 Time-histories of energy (top) and particle velocities (bottom) at TKS site.

The results of TKS site in NS directions are shown in Fig.5. At this site, E_u at the surface (Point A) is again much smaller than the deeper levels at GL-25 m (Point B) and GL-100 m (Point C) despite that the amplitude of the velocity time history is evidently larger at the surface. $(E_u - E_d)$ at GL-100 m approaches to an almost constant value at t=12.5 s while E_u and E_d rapidly increase thereafter. The value $(E_u - E_d)$ at GL-25 m shows a negative value in the latter part of the time history probably due to errors involved in soil modeling.

The results for KNK site in the NS direction are shown in Fig.6. A remarkable difference exists in this site in the velocity amplitude between GL-25 m and GL-100 m in both directions on account of the big difference in the impedance between the base rock of Vs=1630 m/s and the overlying soil layer as shown in Fig.2. The



Fig.6 Time histories of energy (top) and particle velocities (bottom) at KNK site.

upward or downward energy increases with a higher rate until t=17s or t=23s and then keeps constant or slowly increases after that. In a good contrast with the previous 3 sites, the upward energies E_u at GL-100 m (Point C), GL-25 m (Point B) and GL-0 m (Point A) are not so different to each other despite the aforementioned difference in wave amplitude. In this site, too, $(E_u - E_d)$ stops rising at t=14 s despite the sustained increases in E_u and E_d thereafter. The dissipated energy E_w is very small compared to E_u , and the ratio E_w/E_u is much lower than that in the previous three sites. This indicates that the seismic motion caused minimal nonlinearity even in the upper layer in this site, as was also demonstrated by the inversion analysis [3], resulting in a small energy loss in the surface layer and a large energy return into the deeper ground.

In most of the energy evaluations described above, the increasing trend in $(E_u - E_d)$ almost stops in the middle of the records despite that E_u and E_d are still increasing. The moment when $(E_u - E_d)$ seems to stop its increase is pointed out by the arrow mark in Figs. 4 to 6. It may be noted that, after the arrow marks, the velocity time histories in the upward and downward directions become almost identical in terms of the amplitude and seem to include longer period motion than before. These observations seem to imply that surface waves become dominant in the latter part of the records, in which the wave energy propagates horizontally. Up to that time, the wave energy may be assumed to propagate essentially in the vertical direction as the SH wave. Consequently, the accumulated energies are all calculated up to these points to be used in the latter energy analyses.

ENERGY FLOW AT 4 SITES

Fig.7 shows the energy flow rate per second at three depths in the principal axis of PI site calculated from the accumulated energy time histories indicated in Fig.3. The upward energy flow rates

 $\overline{E} = dE/dt$ are very variable with time comprising multiple peaks which correspond to the steeper gradients of the time history of cumulative energies and hence reflect wave form characteristics. The greater the depths, the higher the flow rate peaks and the earlier they appear. Fig.8 indicates the relationships between the cumulative value or maximum flow rate of upward energies versus the depth obtained by similar calculations at the 4 sites. The energies in the horizontal axis are expressed in the logarithmic scale indicating that there exists great difference in upward energies among the 4 sites. It should be noted that both the cumulative energy and the energy flow rate reduce drastically as they approach to the ground surface except in KNK site where the seismic shaking was milder without significant soil nonlinear effect.

Let us then compare the surface energies E_s or dissipated energies E_w evaluated at Point B with the damping ratios in the corresponding sites. Here, the damping ratios in individual sublayers, which were back-calculated in a separate investigation by Kokusho et al. [3], are averaged by multiplying the weight of thickness of each sublayer shallower than Point B of Fig.2. In Fig.9, the energy ratios E_s/E_u are plotted versus damping ratios D with open symbols in the two directions at the 4 sites. It may well be assumed despite some data



Fig.7 Time histories of energy flow rate at PI site.



Fig.8 Distributions of accumulated energy and energy flow rate along depth at 4 sites.



Fig.9 Accumulated energy and energy flow rate versus optimized damping ratio at 4 sites.

scatters that the ratio of surface energy E_s to the upward energy E_u at Point B decreases with increasing averaged damping ratio as approximated by the thin curve. Almost the same trend can be recognized for the ratios of the energy flow rates plotted with the closed symbols in the same figure. In Fig.10, the energy ratios E_w/E_u are compared with the averaged damping ratios, where E_w and E_u are the dissipated energy in the surface layer shallower than Point B and the upward energy at Point B, respectively.



Fig.10 Dissipated energy versus optimized damping ratio at 4 sites.

The increasing trend of E_w/E_u with increasing damping ratio may be approximated by the thin line. The dissipated energy in the surface layer amounts to 70-50% of the upward energy at the base in the near-fault site PI, while it is around 20% or less in the remote site KNK, indicating that the rest of the upward energy returns to the deeper earth again.

The combination of Figs.9 and 10 indicates that, in a site with smaller shaking, dissipated energy is small and a large percentage of surface energy comes up to the ground surface. In a near-fault site with strong shaking, more than a half of the upward energy is lost by soil damping inside the surface layer and only a small portion arrives at the surface. Note that the energy ratio E_s/E_u or $\overline{E}_s/\overline{E}_u$ is much lower than 1.0 except in KNK, indicating that the surface energy tends to be lower than the upward energy at the base in those sites with stronger shaking and hence with larger soil damping.

ENERGY FLOW MECHANISM IN 2-LAYERS SYSTEM

In order to understand what mechanism controls the energy flow in layered ground under the assumption of one-dimensional propagation of the SH wave, a simple study on a 2-layers system has been carried out as depicted in Fig. 11. The thickness of the surface layer is H=30m and the soil density in the surface and base layers are $\rho_1 = \rho_2 = 2.0$ t/m³. These values are chosen so that the two-layers model can roughly represent the surface layer response in the vertical array sites. S-wave velocity in the base layer is kept constant as $Vs_2 = 330$ m/s while that in the surface layer Vs_1 is





parametrically varied from 330m/s to 30m/s. The impedance ratio $\alpha = \rho_1 V s_1 / \rho_2 V s_2$ correspondingly varies from unity to 0.0909. The damping ratio in the base layer is assumed $D_2 = 0$ while that in the surface layer is varied, $D_1 = 0.40\%$. The input motion shown in Figs.12(a) which is the same as the upward component in the principal axis in PI site is given at the base layer. The Fourier spectrum of the input motion shown in Fig.12(b) is compared with the transfer functions of the two-layers system shown in Fig.12(c),calculated for different Vs₁ with the damping ratio $D_1 = 5\%$. Note that the dominant frequency of the input motion is about 0.8 Hz although the spectrum has several peak frequencies around there.

Fig.13 shows the ratio of surface energy E_s to the upward energy E_u at the base in the vertical axis versus the impedance ratio α in the horizontal axis calculated from the parametric study described above. For $D_1 = 0$, E_s takes a maximum value when $\alpha = 0.182$ due to the resonant effect as indicated from Figs.12(b) and (c). However, the resonant effect diminishes as D_1 becomes larger, and E_s monotonically decreases as α decreases for $D_1 > 10\%$. In Fig.14, the flow rate of the upward energy dE_s/dt is taken in place of the accumulated energy in the vertical axis. In this case, too, the flow rate shows a monotonic decrease with decreasing impedance ratio for



Fig.12 Acceleration(a), Fourier spectrum(b) and spectrum ratio(c) used in the analysis.



Fig.13 Surface energy versus impedance

 $D_1 \ge 10\%$. This indicates that the softer the surface soil, the smaller the energy or its flow rate becomes under high soil damping in the surface layer. Fig.15 depicts the ratio of dissipated energy E_w to the upward energy E_u at the base versus α obtained from the same parametric study. While $E_w = 0$ quite naturally for $D_1 = 0$, E_w takes the maximum value when $\alpha = 0.182$ under higher damping ratios because the more wave energy is trapped and dissipated in the surface soil due to the resonance effect.

According to Figs.13, 14 and 15, it may be said that the seismic wave energy at the ground surface is mostly smaller in soft soil sites than in stiff soil sites during destructive earthquakes, because the soil damping in the surface layer tends to be greater due to strong shaking particularly in soft soil sites. This view seems to disagree with widely accepted perception that earthquake damage is larger in soft soil sites. In discussing this problem, it is essential to distinguish geotechnical and structural aspects in earthquake damage. Needless to say, geotechnical damage tends to concentrate in soft soils. During the 1923 Kanto earthquake, larger number of wooden houses are said to have collapsed in down-town soft soil area than Pleistocene stiff soil area in Tokyo and triggered great fires killing many people. However, during 1995 Kobe earthquake on the contrary, wooden houses were damaged mostly in stiff soil area and little shaking damage of superstructures including wooden houses occurred in soft soil areas along the coast. In what follows, some considerations are made how the seismic wave energy is related to structural failures and on a possibility of the performance based design using the seismic wave energy.



Fig.14 Energy flow rate at surface versus impedance ratio for different damping ratios.



Fig.15 Dissipated energy versus impedance ratio for different damping ratios.

PERFORMANCE-BASED DESIGN BY WAVE ENERGY

Obviously, structural damage is directly related to induced strain in members of superstructure. Here, a superstructure is idealized by a shear vibrating system resting on a foundation ground as depicted in Fig.16. If the width of the structure is large enough, the interaction between the foundation ground may be approximated by the 2-layers system. Then, shear strain in the super structure is expressed as

$$\gamma = \left[\frac{4\sin k_{st}^{*}(H_{st} - z)}{\left(1 + \alpha_{st}^{*}\right)e^{ik_{st}^{*}H_{st}} + \left(1 - \alpha_{st}^{*}\right)e^{-ik_{st}^{*}H_{st}}}\right] \left(\frac{\alpha_{st}^{*}\overline{E}_{s}}{\rho_{st}Vs_{st}^{3}}\right)^{1/2}$$
(12)

where, H_{st} =height of superstructure, k_{st}^* =complex wave number in superstructure, α_{st}^* =complex impedance ratio, ρ_{st} =equivalent density of structure and Vs_{st} =equivalent S-wave velocity of structure. This equation indicates that the structural strain is proportional to the square root of the energy flow rate at the foundation ground, $\overline{E}_s = dE_s/dt$, and proportional to the square root of the impedance ratio between the structure and the foundation ground, $\alpha_{st} = \rho_{st}Vs_{st}/\rho_1Vs_1$. Eq.(12) indicates the energy flow rate at the ground



Fig.16 Two-layers shear-mode system approximating a structure resting on soil

surface \overline{E}_s directly controls the induced strain in the superstructure. In reality, superstructures are not so simple as idealized by uniform shear beams. They behave more like lumped mass-spring systems with limited width and vibrate in bending-shear modes. However, it may be possible to find equivalent parameters for the idealization which basically satisfies Eq.(12). The induced strain thus evaluated from the energy flow rate can be compared with yield strain and correlated with different steps of structural integrity to be used for the performance-based design.

For structures with high flexibility and low damping such as buildings and houses, shear strain induced cycle by cycle seems decisive for the failure of the structure. Consequently, the energy flow rate becomes a key parameter as indicated in Eq.(12) for the performance based design. In contrast, for structures with higher rigidity and higher damping ratio such as retaining walls, soil structures, slopes, etc., total strain accumulated by a number of loading cycles are essential for the structural performance. Therefore, the accumulated energy should be used in place of the energy flow rate in designing such structures.

So far, in seismic design practice the seismic input has been defined by acceleration, velocity or their spectral values. In order to use seismic wave energy for the performance-based design, design wave energy should be defined in place of the conventional parameters such as acceleration or velocity. Not only the energy but also time histories or spectral data are necessary in order to compute energy flow or flow rate. Consequently the energy approach is similar to detailed dynamic analyses using seismic motions. However, the key of the energy approach is to define a design input motion in terms of energy, which enables different analytical results using design motions with different dominant frequency, different duration, etc. to compare on the same scale through the energy concept.

CONCLUSIONS

Energy analyses on recorded motions at 4 vertical array sites yield the following major findings;

- 1) It is possible to quantify energy flow in a surface ground by using vertical array records based on the assumption of the vertical propagation of the SH wave so long as the influence of surface waves is negligible.
- 2) The ratio of the upward energy at the ground surface to the upward energy at the base, E_s/E_u , is much lower than 1.0 in sites with strong shaking because of soil modulus degradation and increased soil damping, which almost cancels the energy storage effect in the surface layer by resonance even if it ever occurs.
- 3) The dissipated energy E_w in the surface layer amounts to 65% of the upward energy E_u at the base in the near-fault site with strong input motion PI, while it is around 20% or less in a distant site KNK in indicating that the rest of the upward energy returns to the deep earth.
- 4) The flow rate of upward energy is very variable with time comprising multiple peaks which correspond to the steeper gradients of the accumulated energies and hence reflect wave form characteristics.
- 5) The upward energy and the energy flow rate tend to reduce drastically as they approach to the ground surface in those sites experiencing strong motion attacks and hence significantly reflect soil nonlinearity effect.

Simple analyses on SH-wave propagation in 2-layers system with variable impedance ratio, in which a seismic motion is given at the base layer, indicate the following;

- 6) With increasing damping ratio in the surface layer, the surface energy decreases while the dissipated energy increases, respectively. The trends are very similar to those observed in the analytical results for the energy flow in the vertical array sites.
- 7) The surface energy or its flow rate which is expected to increase due to resonance in the surface layer cannot become so large because of exerted large soil damping in soft soil sites. If large damping ratio of more than 10% is assumed, the surface energy tends to decrease with decreasing impedance ratio.
- 8) Based on 5) and 7) above, the general perception that soft soil sites are more susceptible to heavier earthquake shaking damage than stiff soil sites may not be appropriate if the ground surface energy is the key parameter for structural failures by seismic shaking.

If a structure resting on a ground can be idealized by a two-layers system of shear-mode vibration, the induced strain in the structure is directly related to the seismic wave energy. Consequently, the performance-based design in which induced structural strain is compared with threshold strains for various structural performance may be recommended by using the seismic wave energy. The energy approach enables different analytical results using design motions with different dominant frequency, different duration, etc. to compare in the same energy principle.

ACKNOWLEDGMENTS

The Kansai Electric Power Company and the Kobe Municipal Office who successfully recorded the vertical array data and CEORKA (The Committee for Earthquake Observation Research in Kansai Area) who generously distributed them are gratefully acknowledged.

REFERENCES

 Kanai, K., Tanaka, T., Yoshizawa, S. "Comparative studies of earthquake motions on the ground and underground." Bulletin of the Earthquake Research Institute, Tokyo University, Vol.37, 1959: 53-87.
 Schnabel, P. B., Lysmer, J. & Seed, H. B. "SHAKE, A computer program for earthquake response analysis of horizontally layered sites." *Report EERC 72-12*, University of California Berkeley, 1972.

3. Kokusho, T., Matsumoto, M. and Sato, K. "Nonlinear seismic properties back-calculated from strong motions during Hyogoken-Nambu EQ." Proc. World Conference on Earthquake Engineering (Acapulco), 1996, CD-publication.

4. Kokusho, T. and Motoyama, R. "Energy dissipation in surface layer due to vertically propagating SH wave." *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, Vol.128, No.4, 2002: 309-318.

5. Kokusho, T. and Matsumoto, M: "Nonlinearity in site amplification and soil properties during the 1995 Hyogoken-Nambu Earthquake." *Special Issue of Soils and Foundations*, 1998: 1-9.

6. Elgamal,A.W., Zeghal,M. and Parra,E. "Identification and modeling of earthquake ground response." Proc. *1st International Conference on Earthquake Geotechnical Engineering*, Balkema, Rotterdam, The Netherlands, Vol.3, 1995: 1369-1406.