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ANALYSIS ON PHASE VELOCITY OF GROUND MOTION WITH USE OF ARRAY RECORDS

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SUMMARY

This paper presents the result of analysis on the predominant direction and phase velocity of ground motion propagation using the array records obtained at the Public Works Research Institute, Tsukuba, Japan. The predominant direction of ground motion was identified by the cross correlation analysis of two orthogonal components of recorded data. It becomes clear that the predominant direction of ground motion and the direction of epicenter coincide fairly well. The phase velocity of ground motion propagation was calculated from the phase lag of records obtained at two observation points which are located on the horizontal plane with a distance of 100 m. The phase velocity estimated in this analysis is considerably large as compared with the shear wave velocity at the site and the reason of this result is indicated.

INTRODUCTION

The dynamic behavior of structures embedded in the ground, such as submerged tunnels, petroleum pipelines, is governed by the deformation of the ground during an earthquake, because the density of these structures is smaller than that of the ground. Based on this characteristic, the seismic deformation method, which considers ground deformation induced by an earthquake as seismic effect instead of inertia force, was developed and is now in practical use for the seismic design of extended structures embedded in the ground(Ref. 1). In this design method, the deformation of structures is calculated on the assumption that seismic wave propagates horizontally through the ground. Though the velocity of wave propagation is one of essential factors to assess appreciate seismic effect, actual state is that an adequate value is assumed for practical design, mostly due to the lack of measured data.

This paper presents an analysis on phase velocity of the ground motion taking account of propagating direction with use of array records obtained at the Public Works Research Institute. The records of 10 events with peak acceleration of 30 to 150 gals on the ground surface were considered in this analysis(refer to Table 1).

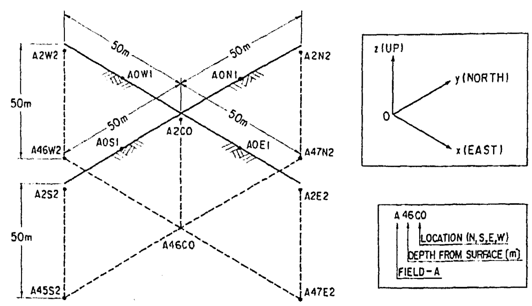
LOCAL LABORATORY ARRAY AT PUBLIC WORKS RESEARCH INSTITUTE

Two local laboratory arrays were installed at the Public Works Research

Table 1 Earthquake Records used for Analysis

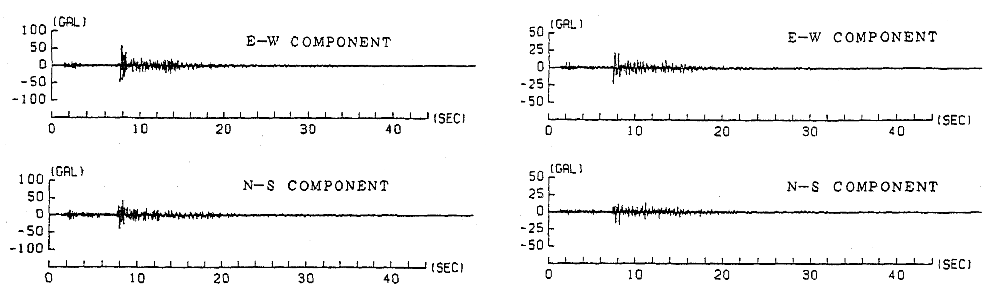
No.	Date	Epicenter			Depth	Epicen Dist	JMA
		Region	E Long	N Lat	[km]	[km]	Mag
EQ-13	1980. 9. 25	Central Chiba Pref	140°13'	35°31'	80	69	6.1
EQ-16	1981. 9. 2	Off Ibaraki Pref	141°08'	35°48'	40	102	5.8
EQ-21	1982. 3. 7	Kashima-Nada	140°39'	36°28'	60	64	5.5
EQ-22	1982. 7. 23	Off Ibaraki Pref	141°57'	36°11'	30	169	7.0
EQ-28	1983. 2. 27	S Ibaraki Pref	140°09'	35°56'	72	22	6.0
EQ-31	1983. 7. 2	Off Fukushima Pref	141°07'	36°54'	50	127	5.8
EQ-34	1983. 10. 28	SE Ibaraki Pref	139°59'	36°13'	60	13	5.2
EQ-39	1984. 1. 1	S off Kinki	136°59'	33°16'	400	425	7.4
EQ-44	1984. 2. 21	SE Ibaraki Pref	140°06'	36°06'	70	3	5.2
EQ-45	1984. 3. 6	Near Torishima	139°08'	29°28'	460	745	7.9

Fig.1 Array Instrumentation at PWRI



Institute in 1979(Ref. 2). Subsurface geological condition around the Institute is almost uniform, i.e., diluvial sandy and silty deposits with approximate thickness of 50 m rest on gravel formations. Shear wave velocities of the diluvial deposits and gravel formations are approximately 250 m/sec and 400 m/sec, respectively.

Fig. 1 shows instrumentations at one of the two local laboratory arrays, where thirteen three-components accelerometers are installed, i.e., three on the ground surface, five at the depth of 2 m, and five at the depth of about 50 m which corresponds to the top of gravel formations, along a cross-shaped configuration with each length of 100 m. The direction of the cross configuration as well as the direction of accelerometers is oriented along N-S and E-W directions. Signals of each accelerometer are simultaneously transmitted by cable to the central data processing room, where the signals are dizitized with a time interval of 1/100 second by 12 bits AD converter. An example of acceleration records is shown in Fig. 2.



(a) A2C0 (b) A46C0

Fig.2 Example of Recorded Acceleration (EQ-34)

PREDOMINANT DIRECTION OF GROUND MOTION

Assuming that the ground motion propagates horizontally in a predominant direction, the cross correlation between the two components of a recorded ground motion in this predominant direction and in the direction perpendicular to this direction is thought to be minimum.

Two components of ground motion along rectangular coordinate axes X-Y of arbitrary direction θ, expressed as $a_X(\theta,t)$ and $a_Y(\theta,t)$, are calculated from E-W component $a_x(t)$ and N-S component $a_y(t)$ of the recorded data as

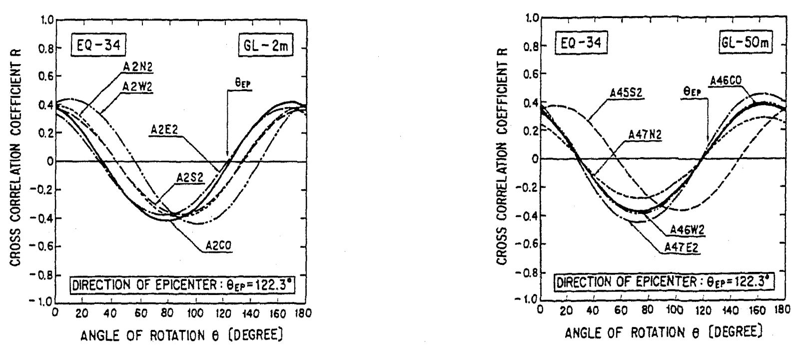
$$a_X(\theta,T) = a_x(t)\cos\theta + a_y(t)\sin\theta \tag{1}$$

$$a_Y(\theta,t) = -a_x(t)\sin\theta + a_y(t)\cos\theta \tag{2}$$

where the angle θ is measured counterclockwise from the x-axis (East). The cross correlation coefficient of $a_X(\theta,t)$ and $a_Y(\theta,t)$, $R(\theta)$ is obtained as

$$R(\theta) = \frac{\int_0^T a_X(\theta,t)\, a_Y(\theta,t)\, dt}{\left\{ \int_0^T a_X^2(\theta,t)\, dt \cdot \int_0^T a_Y^2(\theta,t)\, dt \right\}^{1/2}} \tag{3}$$

where, T denotes the duration time of recorded data. Since equations (1) and (2) apparently lead that $a_X(\theta+180,t)=-a_X(\theta,t)$ and $a_Y(\theta+180,t)=-a_Y(\theta,t)$, then the relation, $R(\theta+180)=R(\theta)$ is reduced. Fig. 3 shows an example of the cross correlation coefficient, in which θ is varied every 10 degrees from 0 to 180 degrees. The ground motions obtained at the points of 2 m below the ground surface (A2CO, A2N2, A2S2, A2E2, A2W2) and at the points of 50 m below the ground surface (A46CO, A47N2, A45S2, A47E2, A46W2) during the earthquake of EQ-34 are used in this figure.



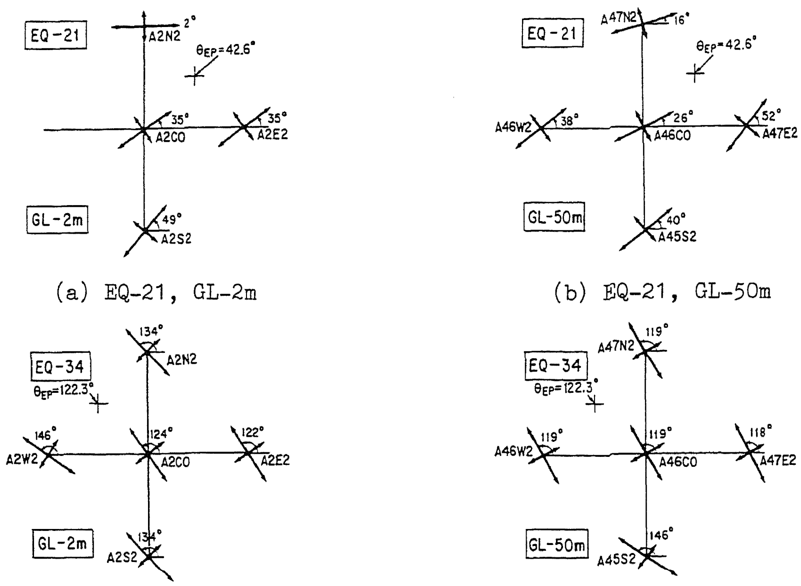
(a) GL-2m (b) GL-50m

Fig.3 Cross Correlation Coefficient (EQ-34)

It can be seen from Fig.3 that there are two angles at which the cross correlation coefficient is equal to 0 between 0 and 180 degrees. If it is assumed that the principal motion propagates along the predominant direction, the power of ground motion component along this direction is thought to be smaller than that of the component along the direction perpendicular to the propagation direction. So, the predominant direction axis "X" of ground motion was identified as the direction which satisfies the following equation.

$$\int_0^T a_X^2(\theta,t)\, dt < \int_0^T a_Y^2(\theta,t)\, dt \tag{4}$$

Examples of the predominant direction of ground motion for each observation point and the direction of epicenter are shown in Fig. 4. In this figure, longer one of two arrows drawn at each observation point indicates the predominant direction. Although there are some earthquakes of which the predominant direction does not coincide with the direction of epicenter, both directions coincide fairly well in not a few cases.



(a) EQ-21, GL-2m (b) EQ-21, GL-50m

(c) EQ-34, GL-2m (d) EQ-34, GL-50m

Fig.4 Predominant Direction of Ground Motion

PHASE VELOCITY OF GROUND MOTION

Basing upon the results mentioned above, the horizontal phase velocity of ground motion was calculated for the cases of which the predominant direction of propagation coincide with the direction of epicenter. The phase velocities of ground motion in the direction of epicenter i.e. radial component, and perpendicular to the direction of epicenter i.e. transverse component, were calculated respectively from the phase lag of records obtained at two observation points which are located on the horizontal plane with a distance of 100 m. The phase velocity calculated from the phase lag of records obtained at two observation points, which are located along a plumb line, is reported to coincide well with the shear wave velocity of the site(Ref. 3).

Denoting the radial components at points i and j in Fig. 5 $a_{i,X}(t)$ and $a_{j,X}(t)$ respectively, the cross correlation coefficient of $a_{i,X}(t)$ and $a_{j,X}(t)$, $R_{ij}(\tau)$ is represented as

$$Rij(\tau) = \frac{\int_0^T a_{i,x}(t)\, a_{j,x}(t+\tau)\,dt}{\{\int_0^T a_{i,x}^2(t)\,dt \cdot \int_0^T a_{j,x}^2(t)\,dt\}^{1/2}} \tag{5}$$

where, τ represents the phase lag. Let the phase lag, at which $Rij(\tau)$ becomes maximum value Rmax, be denoted by τ_{max} and the distance between two points projected to the direction of epicenter be expressed by l(refer to Fig.5), then the phase velocity v, is obtained as follows.

$$v = l \,/\, \tau_{max} \qquad (6)$$

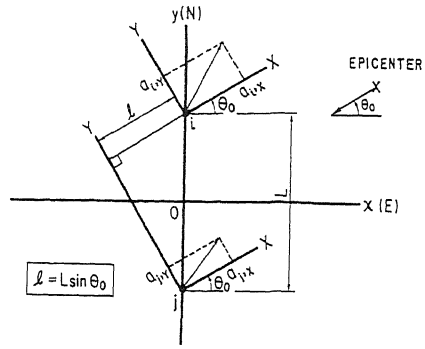


Fig.5 Notation of Coordinate

The phase velocity of the transverse component can be obtained similarly. Table 2 summarizes the calculated results for four sets of data at (A2N2, A2S2), (A2E2, A2W2), (A47N2, A45S2) and (A47E2, A46W2) as the combination of points (i, j). In this table, negative value means that the propagating direction is opposite to the apparent direction. Although the shear wave velocity around these points is some 250 m/sec for the strata from ground surface to the depth of 50 m, and 400 m/sec for deeper strata, the phase velocity estimated by the equation (6) is considerably large.

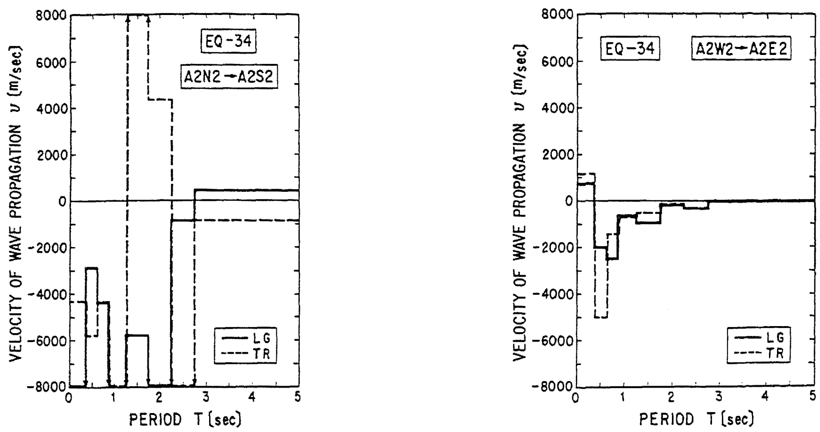
Table 2 Phase Velocity of Ground Motion

No.	Direct of Epicen	Observ Points	Propagat Distance L[m]	Comp[1)]	Maximum Correlat R_{max}	Phase Lag τ_{max}[s]	Propagat Veloci[2)] v[m/s]
EQ-21	43°	A2N2 → A2S2	64.3	LG	0.577	0.01	6430
				TR	0.613	0.00	∞
		A47N2 → A45S2	64.3	LG	0.374	-0.05	-1286
				TR	0.497	-0.05	-1286
		A47E2 → A46W2	76.6	LG	0.536	0.01	7660
				TR	0.753	0.00	∞
EQ-22	3°	A47E2 → A46W2	100.0	LG	0.796	0.00	∞
				TR	0.834	0.00	∞
EQ-34	122°	A2N2 → A2S2	86.6	LG	0.398	0.00	∞
				TR	0.657	-0.02	-4330
		A2W2 → A2E2	50.0	LG	0.209	0.05	1000
				TR	0.528	0.035	1429
		A47N2 → A45S2	86.6	LG	0.261	0.52	167
				TR	0.506	0.01	8660
		A46W2 → A47E2	50.0	LG	0.497	-0.02	-2500
				TR	0.623	-0.02	-2500
EQ-39	228°	A45S2 → A47N2	76.6	LG	0.477	-0.01	-7660
				TR	0.609	-0.02	-3830
		A46W2 → A47E2	64.3	LG	0.670	-0.01	-6430
				TR	0.724	-0.01	-6430
EQ-45	264°	A2S2 → A2N2	100.0	LG	0.850	0.00	∞
				TR	0.877	0.00	∞

Note: 1)LG:Direction of Epicenter TR:Perpendicular to LG
2)Negative velocity means that the propagating direction is opposite to the apparent direction

Next, the phase velocities of the treated records, obtained by band path filtering the original records in frequency domain, were calculated for each period by the same procedure mentioned above. Fig. 6 shows an example of the results of this calculation, which is for the case of EQ-34. It is reduced from the analysis on the phase velocity of various periods as follows;

1)The apparent velocity of the ground motion in any period is generally larger than the shear wave velocity of the site.
2)There are no apparent relations between the period and the phase velocity as far as the range up to 5 seconds of period which was examined in this analysis. However, it seems that the phase velocity generally becomes smaller in longer period.



(a) A2N2 to A2S2 (b) A2W2 to A2E2

Fig.6 Phase Velocity of Various Periods

It is concluded from the above mentioned results that the apparent phase velocity of ground motion in the horizontal plane is considerably large for the data analyzed here, because the ground motion propagates vertically around the ground surface.

CONCLUSION

From the analysis on array records of 10 events, followings are concluded.
1)The predominant direction of ground motion and the direction of epicenter coincide fairly well.
2)The apparent horizontal velocity of ground motion is considerably large for the data analyzed here. The reason of this result is thought to be that the ground motion propagates vertically around the ground surface.

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