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**THE APPLICATION OF EQUIVALENT LINEAR
METHODS FOR PREDICTION OF
SEISMIC GROUND MOTIONS**

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The Application of Equivalent Linear Methods for Prediction of Seismic Ground Motions

by

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Synopsis

Earthquake ground motions recorded at three different array sites (Sagara, Numazu and Matsuzaki) were evaluated using equivalent linear wave propagation analysis methods. Recorded base rock and rock outcrop motions and measured soil shear wave velocities and densities were used as the source of input data for the analyses. Calculated and measured displacement time histories, acceleration time histories, peak accelerations and acceleration response spectra were compared. The effect of varying soil properties was evaluated. It was found that equivalent linear soil properties and the assumption of vertically propagating shear waves appeared to be a reasonable representation of the behavior at the beginning of the strong motion, but did not represent the behavior particularly well at later times. Agreement between measured and calculated displacement time histories was generally good, however, for acceleration time histories, the agreement was good in some cases and bad in others. Reasons for the disagreement are unclear. The differences in calculated and measured peak accelerations and acceleration response spectra were substantial in almost all cases. Variation in soil properties changed the maximum amplitudes in calculation, but did not affect much the frequency characteristics and waveforms.

Key words : Seismic ground motion, equivalent linear soil properties, topography, shear waves.

要 旨

高密度強震観測が実施されている3地区（相良、沼津および松崎地区）における地震動特性を土の非線形性を等価線形化手法で考慮することにより評価した。解析の入力としては、各地区において1地震による実測の基盤地震動および露頭地震動記録、並びにせん断

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波速度を用いた。変位時刻歴波形、加速度時刻歴波形並びに加速度応答スペクトルについて計算結果と実測値の比較を行った。比較に当たっては、土の非線形性曲線を種々変化させて、その影響について検討した。

本研究により、等価線形化手法およびせん断波の鉛直伝播の仮定は、強震動の先頭部分については比較的良い近似を与えるものの、後半部分については必ずしも十分な精度を示さないことが明らかになった。そのため、加速度応答スペクトルについては計算結果と実測値に差異が認められた。また、土の非線形性曲線を変化させることにより、地震動の最大値は変化するが、振動数特性並びに時刻歴波形はあまり変化しないことが明らかになった。

キーワード：地震動、等価線形化手法、地形、せん断波

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1. INTRODUCTION

Equivalent linear methods of seismic ground motion evaluation are used to a very large extent in engineering practice in both the United States and Japan. Since the time the methods were first introduced in the 1970's, there has been debate in the engineering community about the reliability of the methods to predict ground motion. Thus, in order to gain greater understanding of the reliability of equivalent linear methods, recorded seismic ground motions were used to help evaluate them. The goal was to evaluate the applicability of equivalent linear methods for ground motion prediction and soil sites when rock outcrop or base rock motions are known.

This was done by using a one dimensional wave propagation computer program with an equivalent linear soil model. By comparing calculated and measured motions, an assessment of the ability to predict displacement time history, acceleration time history, acceleration response spectrum, and peak acceleration was made.

2. SITES STUDIED

The three sites were distinct from one another and could be classified as shown in Table 2. 1.

Table 2. 1 Sites studied

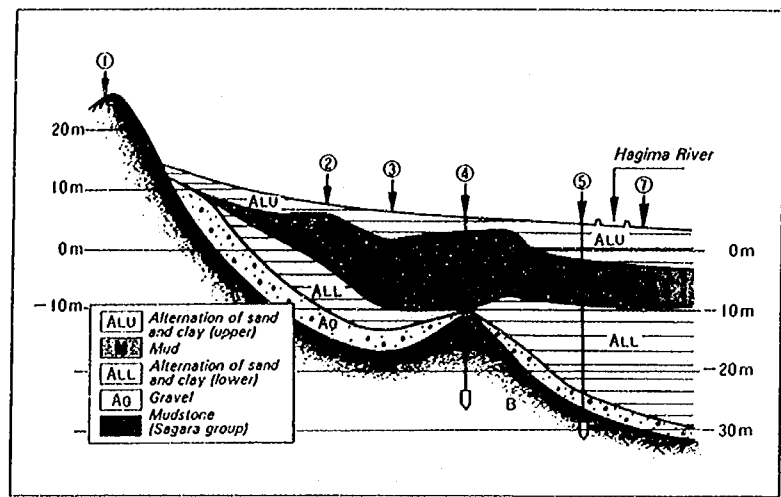
Site	Characteristics	Locations analyzed
Sagara	Mostly soft clay No topography	3 , 4 , 5
Numazu	Mix of sand and gravel topped with soft organic layer No topography	3 , 9 , 10
Matsuzaki	Mix of sand, gravel and clay (all soils fairly stiff) Significant topography	6 , 9 , 11

Simplified soil profiles for each of these sites are presented in Fig. 2. 1. Three dimensional soil profiles are shown in Fig. 2. 2 for each of the sites. Air photos of the sites are shown in Fig. 2. 3. Detailed soil profiles for the locations at which more detail was known are shown in Fig. 2. 4.

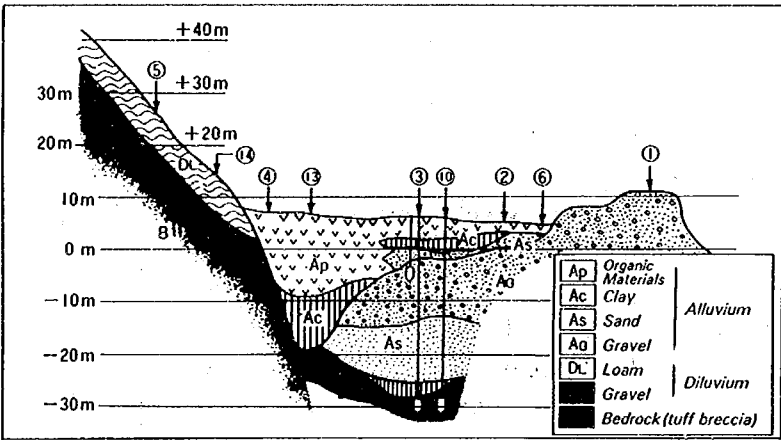
It should be noted that the simplified soil profiles in Fig. 2. 1 have exaggerated vertical scales which make the topography appear to be greater than it actually is. If plotted to true scale would be seen that only the Matsuzaki site has any significant topography. The other sites are flat for all practical purposes and the bedrock boundaries are nearly horizontal.

Both the Sagara and Numazu sites have a layer of particularly soft soil. At Sagara it is the

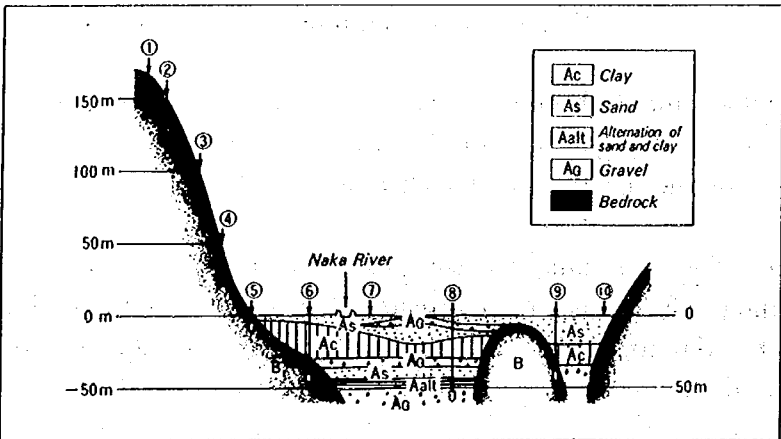
roughly 12m layer of mud. At Numazu it is the roughly 6m layer of organic material. At Matsuzaki, the soils are relatively stiff at all depths.



(a) Sagara

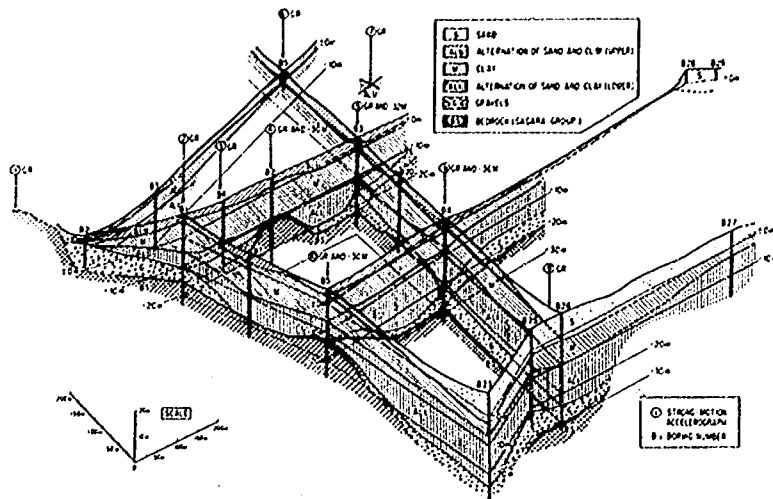


(b) Numazu

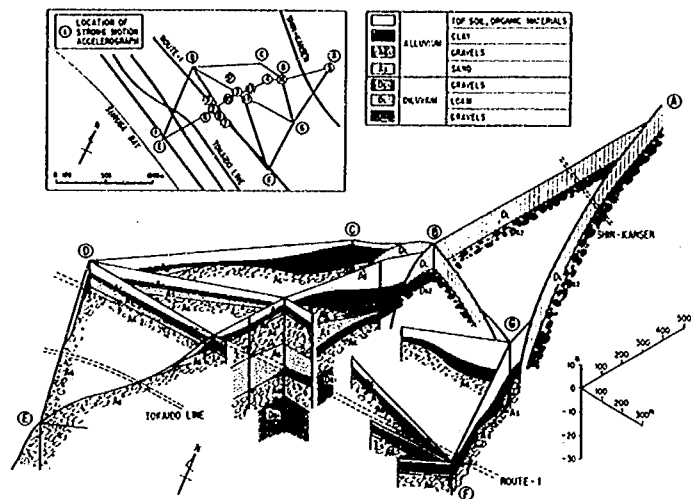


(c) Matsuzaki

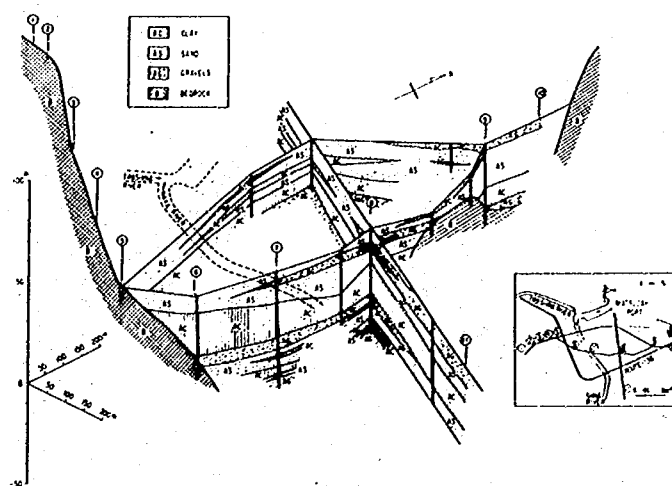
Fig. 2. 1 Cross sections



(a) Sagara



(b) Numazu



(c) Matsuzaki

Fig. 2. 2 Three dimensional soil profiles

SAGARA No.4

DEPTH [m]	PROFILE	SHEAR WAVE VELOCITY [m/s]	UNIT WEIGHT [g/cm ³]	SHEAR MODULUS [kg/cm ²]
2.0	A _c	200	1.50	884
7.6	A _c	76	1.75	103
10.9	A _c	115	1.75	236
15.5	I	395	1.85	2945
30.0	I	▽	1.85	2945
▽ACCELEROMETER				

(a) Sagara, No.4

SAGARA No.5

DEPTH [m]	PROFILE	SHEAR WAVE VELOCITY [m/s]	UNIT WEIGHT [g/cm ³]	SHEAR MODULUS [kg/cm ²]
1.0	A _c	200	1.50	135
9.4	A _c	94	1.75	158
10.0	A _c	156	1.75	435
14.0	A _c	190	1.80	663
19.5	O _G	294	2.10	1852
26.5	I	390	1.85	2871
32.0	I	▽	1.85	2871
▽ACCELEROMETER				

(b) Sagara, No.5

NUMAZU No.3

DEPTH [m]	PROFILE	SHEAR WAVE VELOCITY [m/s]	UNIT WEIGHT [g/cm ³]	SHEAR MODULUS [kg/cm ²]
1.0	A _c	200	1.50	111
5.5	A _c	85	1.75	129
8.0	A _s	170	1.95	575
10.0	A _G	280	2.00	1600
20.5	A _s	300	1.95	1791
28.0	A _c	280	1.85	1480
31.5	O _G	360	2.10	2777
▽ACCELEROMETER				

(c) Numazu, No.3

NUMAZU No.10

DEPTH [m]	PROFILE	SHEAR WAVE VELOCITY [m/s]	UNIT WEIGHT [g/cm ³]	SHEAR MODULUS [kg/cm ²]
3.5	A _c	200	1.50	279
5.5	A _c	135	1.75	325
10.0	A _G	270	2.00	1488
17.5	A _s	310	1.95	1912
30.0	O _G	360	2.10	2777
31.5	▽	▽		
▽ACCELEROMETER				

(d) Numazu, No.10

MATSUZAKI No.6

DEPTH [m]	PROFILE	SHEAR WAVE VELOCITY [m/s]	UNIT WEIGHT [g/cm ³]	SHEAR MODULUS [kg/cm ²]
1.0	A _c	200	1.50	185
8.5	A _s	110	1.80	413
13.5	A _c	150	1.80	413
20.0	A _c	210	1.75	402
30.0	A _G	210	2.00	900
32.0	I	370	2.30	3213
40.0	I	▽	2.30	3213
▽ACCELEROMETER				

(e) Matsuzaki, No.6

MATSUZAKI No.9

DEPTH [m]	PROFILE	SHEAR WAVE VELOCITY [m/s]	UNIT WEIGHT [g/cm ³]	SHEAR MODULUS [kg/cm ²]
2.0	A _s	200	1.60	198
5.0	A _G	110	2.00	247
10.0	A _s	200	1.85	755
22.5	A _c	270	1.75	714
30.5	A _G	270	2.00	1488
34.0	I	450	2.30	4753
38.0	I	▽	2.30	4753
▽ACCELEROMETER				

(f) Matsuzaki, No.9

Fig. 2. 4 Soil properties at various locations

3. APPROACH

3. 1 Earthquakes studied

One earthquake was selected for each site to be used for detailed study. The earthquakes selected were chosen for their relatively large ground motions recorded. They are shown in Table 3. 1

Table 3. 1 Earthquakes Studied

Site	Date	JMA Mag.	Depth (km)	Epicent. Distance (km)	PGA at site (gal)	Earthquake Identification Number
Sagara	3/16/83	5.7	40	55	71	2
Numazu	3/18/88	6.0	96	96	156	29
Matsuzaki	2/20/90	6.5	6	41	149	44

The sites have the accelerometer installation shown in Table 3. 2.

Table 3. 2 Accelerometer installation

Sagara		Numazu		Matsuzaki	
Location	Depth (m)	Location	Depth (m)	Location	Depth (m)
1	0	1	0	1	0
2	0	2	0	2	2
③	0	③	0, 10, 32	3	2
④	0, 30	4	0	4	2
⑤	0, 32	5	0	5	0, 5
6	0	6	2	⑥	0, 40
7	0	7	0	7	2
8	0, 36	8	0	8	0, 52
9	0	⑨	0	⑨	0, 38
10	0, 30	⑩	0, 32	10	2
		11	0, 32	⑪	0
		12	0		
		13	2		
		14	11		

① : Location analyzed

The locations of the sites and the epicenters are shown on Fig. 3. 1. It can be seen the all of the earthquakes have magnitudes between 5.7 and 6.5 with epicentral distances between 41 and 96 km.

It is believed that these earthquakes were representative of the characteristics of the ground motions experienced at these sites as there was a certain consistency of the ground motions for all of the earthquakes recorded at the sites. For instance, the Sagara site experienced four earthquakes which had peak ground accelerations measured at least one location greater than 33 gal. Of these four, the maximum recorded acceleration was at location 3 for three of the earthquakes. At Numazu, 13 of 16 earthquakes with more than 33 gal recorded, had the maximum acceleration at location 9 (E-W component). At Matsuzaki, six earthquakes had a maximum acceleration greater than 33 gal. For all of these, either location 1, 6 or 11 had the maximum acceleration at the site and in general all three of these locations had considerably greater accelerations than the others.

Thus, it is believed that the ground motions at all of these sites are relatively consistent and the earthquakes studied in detail are not unusual ones. Attempting to predict these ground motions then represents a reasonable test for the methods used. While only a limited number of earthquakes were studied, it is believed that had other earthquakes of similar magnitude and epicenter location been studied, similar conclusions to those listed in this report would have been drawn.

3. 2 Method of analysis

For the one-dimensional equivalent linear analyses, the computer program SHAKE (1) was used. This program is also widely used in engineering practice in both the United States and Japan. The input consisted of recorded base rock ground motions in cases where a downhole instrument was installed at the location considered, recorded rock outcrop motions, or deconvolution from surface soil records to get base rock motions.

3. 3 Soil properties

Base cases of analyses were established by developing the soil properties from the method proposed by Iwasaki (2). In essence, Iwasaki gives equations for relating stiffness and damping to shear strain.

During the course of the analyses, the soil properties were varied considerably beyond what is described above in order to get a best fit. It was found that using Iwasaki's equations simply gave consistently good results. Varying the properties from these gave little improvement, if any and produced worse results in many cases. Thus, Iwasaki's method was used as a standard in the analyses.

A later section in this report describes in more detail the effect of varying the soil properties.

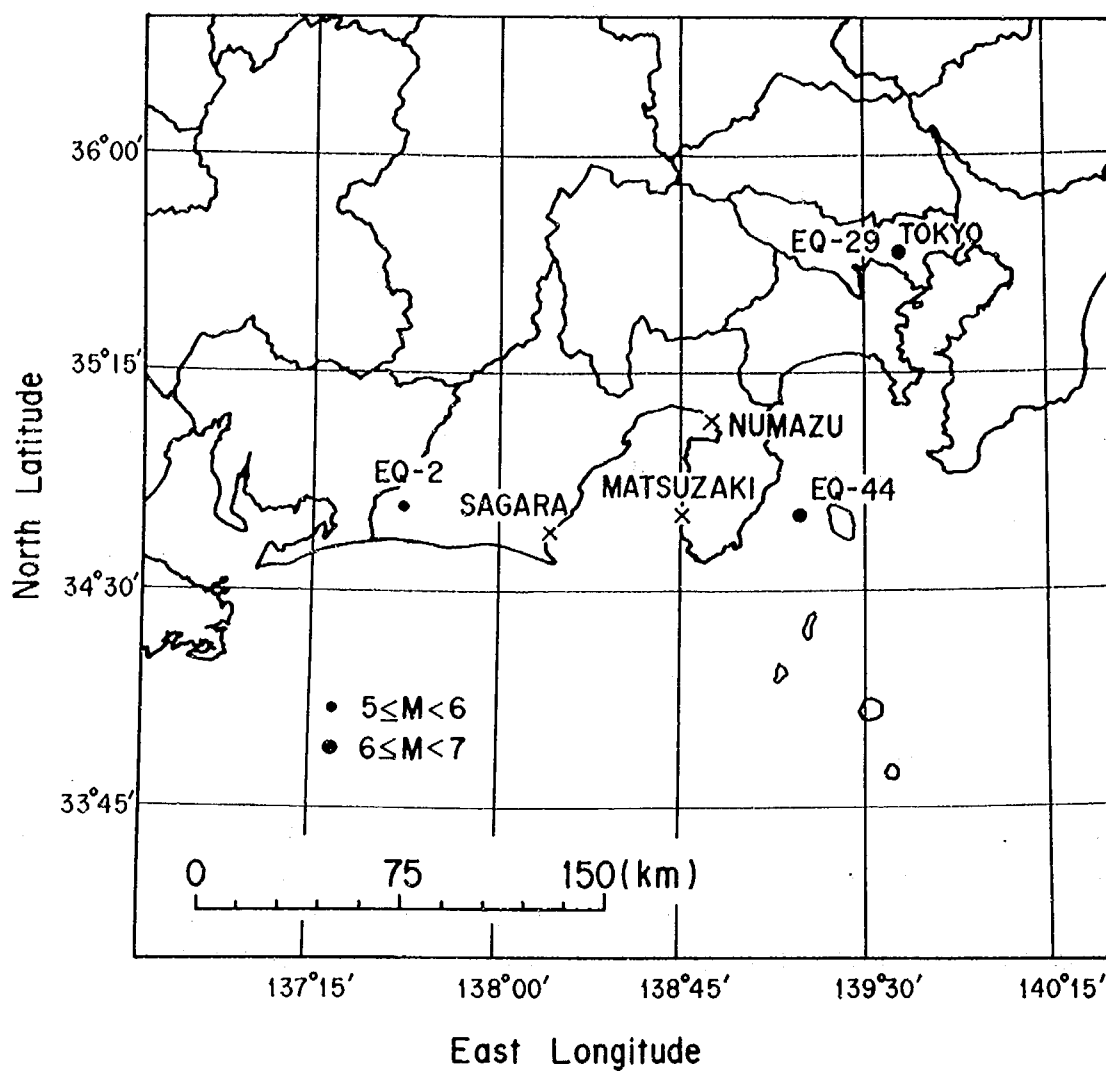


Fig. 3. 1 Map of earthquake epicenters and site locations

4. DISPLACEMENT TIME HISTORIES

4. 1 Sagara

The measured displacement is estimated by integrating the measured acceleration record twice in the frequency domain, where the lower and upper cut-off frequencies are selected as 1/5 Hz and 20Hz, respectively. The calculated and measured displacement time histories for locations 3 and 5 are shown in Figs. 4. 1 and 4. 2, respectively. Location 3 is the one which has consistently recorded the maximum acceleration at Sagara and thus was considered for further study.

In the analyses, for location 3, the input motion came from the recorded rock outcrop motion at location 1. For location 5 the input came from the recorded base rock motion at that location.

It can be seen that reasonably good agreement was obtained for both of these locations. The first three or four peaks of motion show an almost perfect match. Between 5 and 10 sec, the calculated and measured magnitudes of displacement appear to be different, however, the two are nearly in phase. After about 10 sec the two begin to get out of phase with one another.

Considering this agreement, particularly at the beginning of the records, it is believed that this shows that the soil properties used in the analyses were reasonably well representative of the actual soil behavior at least for the first few cycles. In addition, it appears that the assumption of vertically propagating shear waves inherent in the one-dimensional analyses forms as a reasonable model for the behavior. However, it appears that either vertically propagating shear waves or equivalent linear soil properties are not a good representation as time progresses in the ground motion. Idriss (3) also found agreement at the beginning of the record, but not at later times in the analysis of Foster City ground motion in the 1989 Loma Prieta earthquake.

Location 4 was also studied at Sagara and the conclusions were similar.

4. 2 Numazu

The east-west component of site 9 at Numazu has consistently measured the peak acceleration at Numazu as described earlier and thus was chosen for more detailed study. The north-south component displacement time history is given in Fig. 4. 3 and the east-west in Fig. 4. 4. The input motion came from deconvolution of the measured surface motions at site 10.

In the north-south direction, the results are very similar to those for Sagara. That is, the beginning of the record agrees extremely well. At later times the magnitude and phase begin to differ, indicating that vertically propagating shear waves are not perfectly representative of the ground motions. These results indicate that it appears that the soil properties were reasonably well selected for the analysis.

The agreement for the east-west component, at first, appears to be equally good. However,

although it is difficult to see, several significant pulses between 8 and 9 sec are nearly completely missing from the calculated record. Strangely enough though, the agreement after 10 sec is probably better than that for the north-south component.

Given the agreement in the north-south direction, it is not believed that other soil properties would have given better results. Even if a more sophisticated soil model rather than an equivalent linear model were used, it is not believed that the significant pulses between 8 and 9 sec would have been included. Unfortunately, there was no downhole instrument at this location, so it is not possible to see whether these pulses were present in the downhole motions.

Deconvolution from site 3 was also done to get an input motion for the east-west component and the result was very similar to that shown. A visual inspection of other records also indicated that the pulses between 8 and 9 sec were not present at other locations at Numazu. Thus, it is unclear why they are included at site 9 and not at others. One possibility is that they came from other locations than the immediately underlying base rock. Another possibility is that they were really present in the base rock motion possibly due to some travel path effects. Although a detailed study has not been made, it appears that pulses such as these have been present in 13 of 16 earthquakes for this component of site 9.

Sites 3 and 10 were also studied at Numazu and the results were similar to those shown for Sagara.

4. 3 Matsuzaki

The Matsuzaki site 9 (north-south) and site 11 (north-south) displacement time histories are shown in Figs. 4. 5 and 4. 6, respectively. The input motion at site 9 came from the downhole instrument at that location. The input motion for the site 11 calculations came from those measured on the rock at site 5.

As for Sagara and Numazu, the agreement was very good at the beginning of the time history but broke down at later times. For Matsuzaki, this breakdown was considerably worse than at the other sites and it occurred more quickly in the time sequence. This was probably due to the presence of both above ground and underground topography which made the assumption of vertically propagating shear waves less appropriate than at the other sites. The agreement at the beginning of the records indicates that the soil properties are probably reasonably well represented in the analyses.

For site 11, a problem existed in the selection of the input motion. This was caused by the steepness of the hill and the many rock records. The difference between these records is not a subject of this study, however, at site 6 the input motion from different rock records were used. This resulted in substantial differences in the calculated displacement time histories. It was found that using the motion at site 5 as input gave the better agreement compared to using the motions at sites 1 and 3, and was nearly identical to that from using the recorded downhole motion at site 6 as input. Thus, site 5 was used as input for analyzing site 11. While no conclusion can be made

from this, it is believed best to select a rock record at roughly the same elevation as the desired record.

Since the Matsuzaki site had exaggerated topography compared to Sagara and Numazu and exaggerated differences in phase and amplitude in the comparisons between measured and calculated motions, the results hint that the differences between calculated and measured time histories at Sagara and Numazu (except location 9) may be due to underground topography despite the very little topography that exists. However, two-dimensional analyses with the computer program FLUSH (4) which included the slight topography at Numazu did not indicate that the effect was topographic in nature as the time histories calculated were nearly identical to those obtained by the one-dimensional analyses. These analyses, though, had the limitation that the base rock motion was the same at all locations.

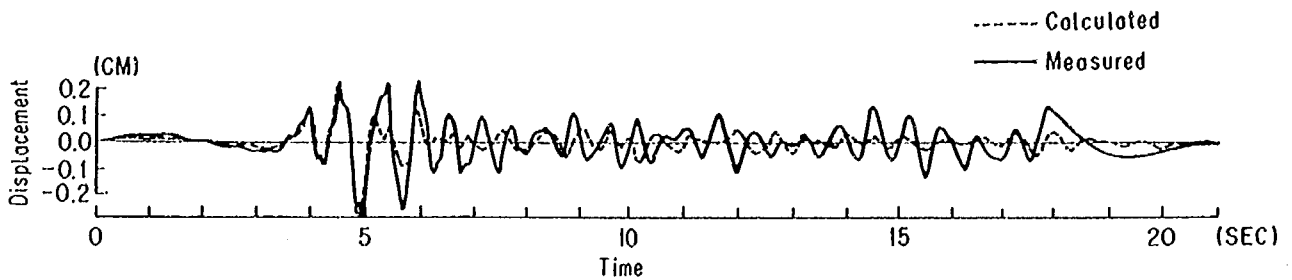


Fig. 4. 1 Sagara site 3, E-W displacement time history

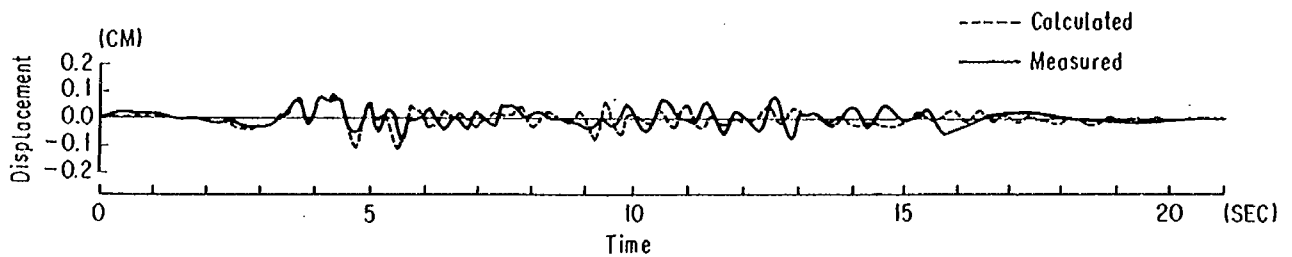


Fig. 4. 2 Sagara site 5, N-S displacement time history

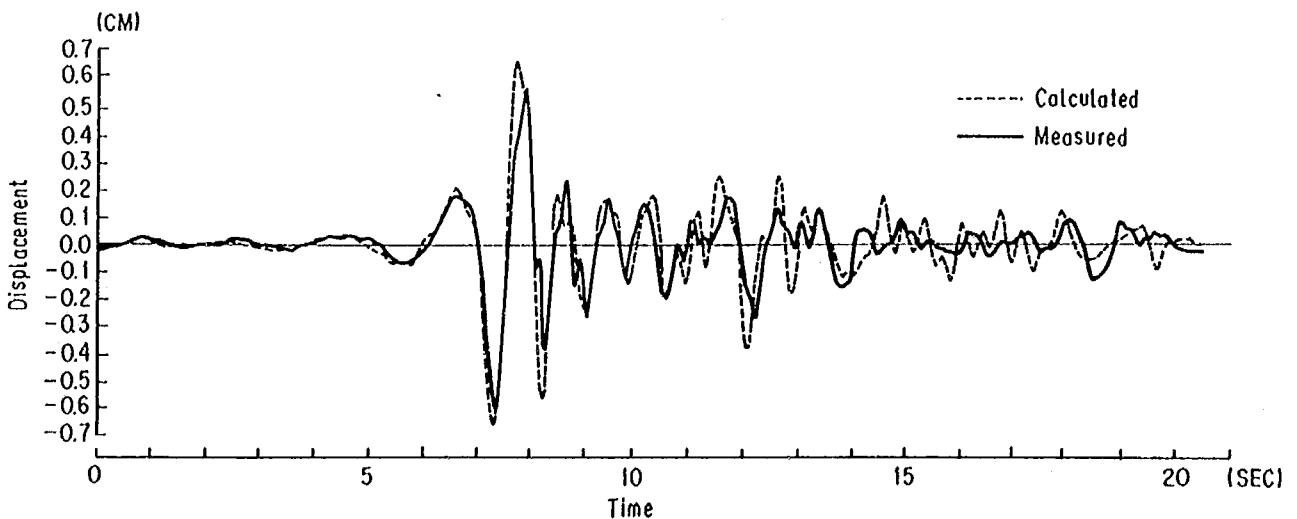


Fig. 4. 3 Numazu site 9, N-S displacement time history

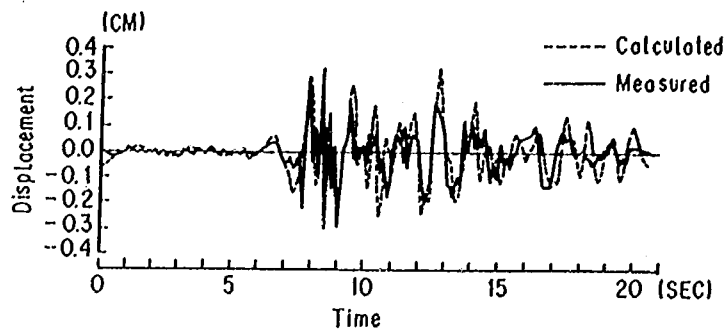


Fig. 4. 4 Numazu site 9, E-W displacement time history

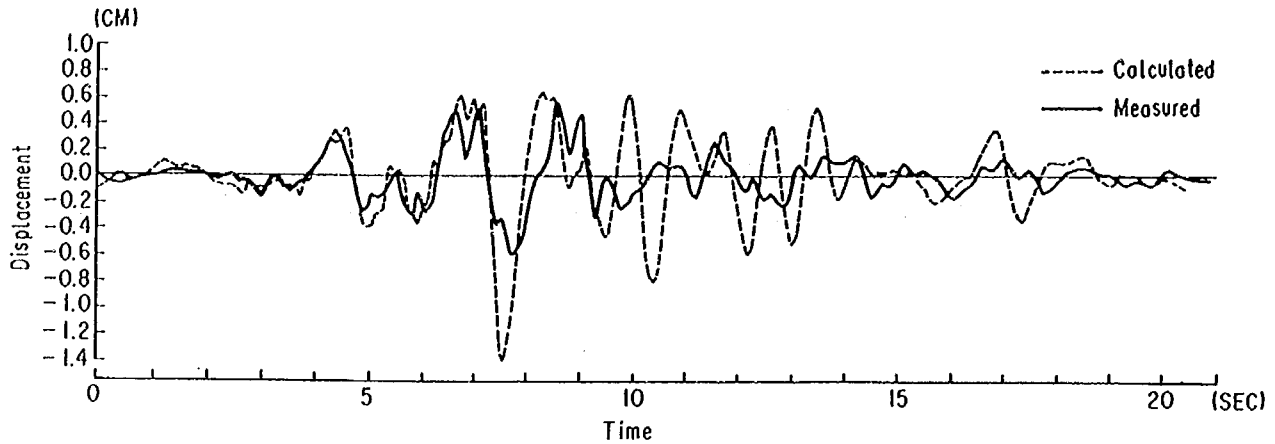


Fig. 4. 5 Matsuzaki site 9, N-S displacement time history

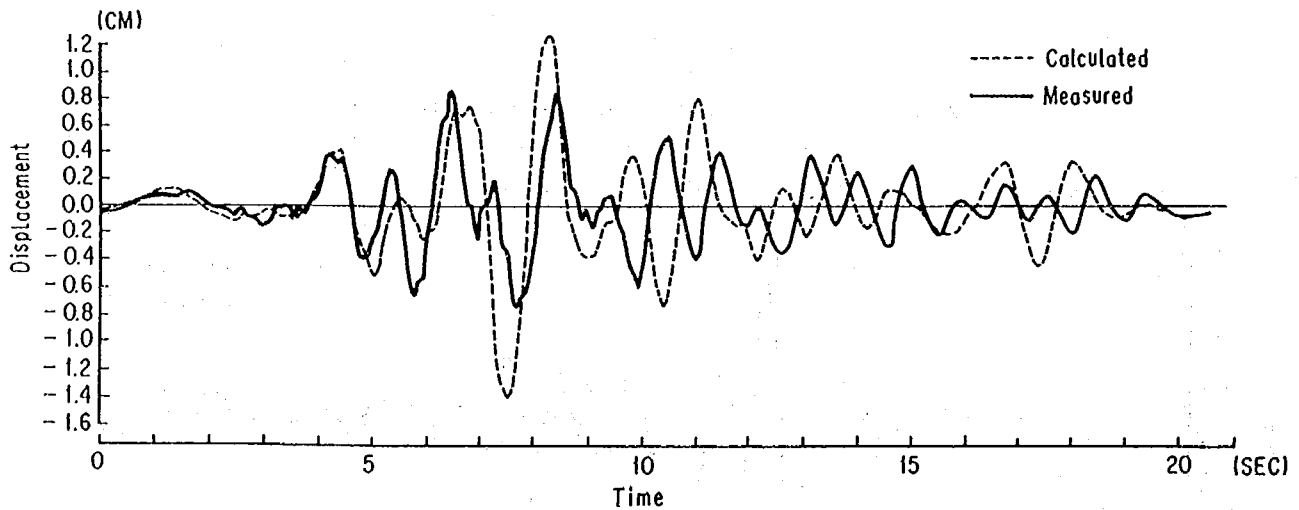


Fig. 4. 6 Matsuzaki site 11, N-S displacement time history

5. ACCELERATION TIME HISTORIES

The measured and calculated peak accelerations for the sites considered are shown in Table 5.1.

Table 5. 1 Measured and calculated peak accelerations

Site	Maximum acceleration (gal)		Difference from calculated value
	Measured	Calculated	
Sagara location 3	71	37	+92%
Sagara location 5	25	22	+14%
Numazu location 9, N-S	89	58	+53%
Numazu location 9, E-W	155	41	+278%
Matsuzaki location 9	108	107	+ 1 %
Matsuzaki location 11	112	46	+143%

A detailed description for each site is given below.

5. 1 Sagara

The calculated and measured acceleration time histories for locations 3 and 5 are shown in Figs. 5. 1 and 5. 2, respectively.

Location 3 has consistently recorded the peak acceleration at the Sagara site for a number of earthquakes. It can be seen that the peak acceleration is severely underestimated by the calculations (by 92%) even though the measured displacement time history was reasonably well represented by the calculated displacement time history. Also, both the frequency content and magnitudes of the peaks are substantially different between the calculated and measured accelerations.

At the location 5, which did not record the greatest acceleration in the Sagara site, the measured and calculated acceleration time histories agreed fairly well, as shown in Fig. 5. 2. Both the frequency content and the magnitudes of the peaks of the peaks were quite similar. However, it should be noted that the measured and calculated maximum peak accelerations still differed by 14%.

At location 4, which recorded only a moderate peak acceleration (as found for location 5), the agreement between measured and calculated acceleration time history was similar to that found for location 5. It was also found that if instead of the base rock motion being used for the source input motion the rock outcrop motion of location 1 were used as input, then the agreement was similar. Thus it appeared that no significant errors were introduced by using the rock outcrop motion instead of the base rock motion.

Unfortunately, the large acceleration at Sagara occurred at a location without a downhole instrument. This has made it unclear whether the cause of not being able to accurately calculate the surface acceleration is due to the assumptions of vertically propagating shear waves and equivalent linear soil properties or due to the outcrop motion being a poor representation of the base rock motion.

5. 2 Numazu

As described previously, the peak acceleration at Numazu was consistently recorded by the location 9 E-W instrument. This occurred at 13 of 16 earthquakes with an acceleration of 33 gal or greater. Because of this, location 9 was studied in detail including both the north-south (N-S) and east-west (E-W) components.

A comparison between the measured and calculated acceleration time histories for the N-S component is shown in Fig. 5. 3. It can be seen that reasonably good agreement exists at the beginning of the strong motion part of the record. At later times the agreement is less good but overall the agreement is not too bad. The frequency content is slightly different with the measured motions having slightly higher frequencies. This level of agreement, together with the agreement for the displacement time histories indicates that the soil properties appear to have been reasonably represented by the equivalent linear properties used for input.

However, as shown in Fig. 5. 4, the agreement between calculated and measured accelerations time histories was not very good for the E-W component. The large accelerations recorded for this component between 8 and 9 seconds is not even closely matched by the calculations. This difference appears to be primarily due to the lack of the pulses illustrated by the displacement time histories (Fig. 4. 4) in this same time period, as described earlier.

Other equivalent linear soil properties were input into the analyses to see if better agreement could be obtained for the acceleration time history. However, no reasonable soil properties improved the agreement significantly. Reducing the damping to near zero caused the calculated accelerations to increase substantially for the entire record (not just between 8 and 9 seconds) and reduced the frequency content. Thus, although the peak acceleration showed better agreement using near zero damping, the rest of the record was unreasonable and therefore not a viable representation of the soil properties.

Given the agreement in the N-S direction, it is not believed that other soil properties will give a substantially better representation of the time history. It is believed that the main question is whether the significant pulses between 8 and 9 seconds are present in the base rock directly below location 9 or whether they come to the surface from other locations. Two-dimensional FLUSH (4) analyses seemed to indicate that the motions did not come to the surface from other locations since the topography was small. Thus, it is currently felt that the motions between 8 and 9 seconds were contained in the base rock possibly due to travel path or focusing effects which are not clearly understood at this time.

The influence of the base rock motions is shown in Fig. 5. 5. The bottom part of the figure shows the calculated base rock motions which, unfortunately, were not measured because there was no downhole instrument at this location. The dark line gives the base rock motions calculated by deconvoluting the measured surface motions from location 10 and the light line gives the base rock motions calculated by deconvoluting the measured surface motions from location 9. The displacement time histories for these two cases are nearly identical. They differ primarily in the few sharp pulses around 8 sec.

5. 3 Matsuzaki

The Matsuzaki acceleration time histories are shown in Figs. 5. 6 and 5. 7. At location 9, the measurements at the downhole instrument were used as input to calculate the surface motions. It can be seen that the agreement is reasonably good despite the strong topography at the Matsuzaki site. The peak acceleration agreed within 1% as shown in the table above. The frequency content was also quite reasonably represented by the calculations, however, after about 8 seconds the calculated acceleration does indicate somewhat higher frequencies than the measured values.

However, this agreement at location 9 can be contrasted with that shown in Fig. 4. 5 for the displacement time history which shows excellent agreement at the beginning of the record and much worse agreement after 8 seconds. This tends to indicate that the agreement for the acceleration time history after 8 seconds may be somewhat fortuitous. Calculations at location 6 which also had a downhole instrument indicated poor agreement between calculated and measured acceleration time histories.

Location 11, which did not have a downhole instrument, was also analyzed. In Fig. 5. 7 it can be seen that the calculated acceleration time history was not calculated as well as that for site 9. Part of the reason for this may be the use of the rock record at location 5 for input, however, the displacement time history shown in Fig. 4. 6 did not indicate that the calculated motion was particularly worse than at location 9 shown in Fig. 4. 5.

These calculations indicate that it is indeed possible to calculate reasonable representations of acceleration time histories using one-dimensional equivalent linear analyses even in the case of significant topography. However, the displacement time histories and acceleration time histories at other locations indicate that this agreement may be somewhat fortuitous. In general, it is unclear why in some cases it is possible to obtain reasonable estimates of acceleration time histories and in other cases it is not.

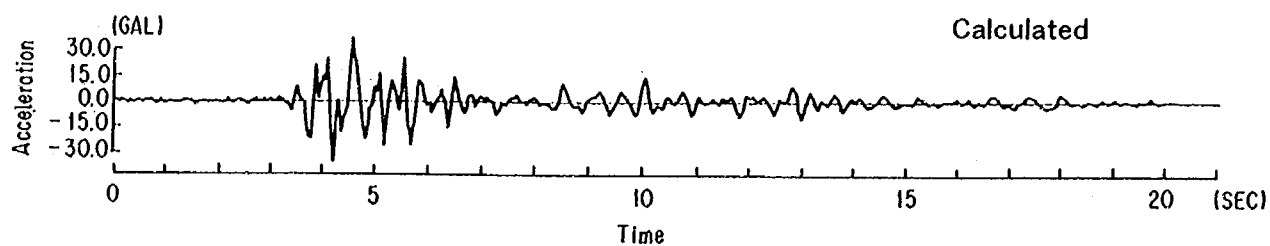
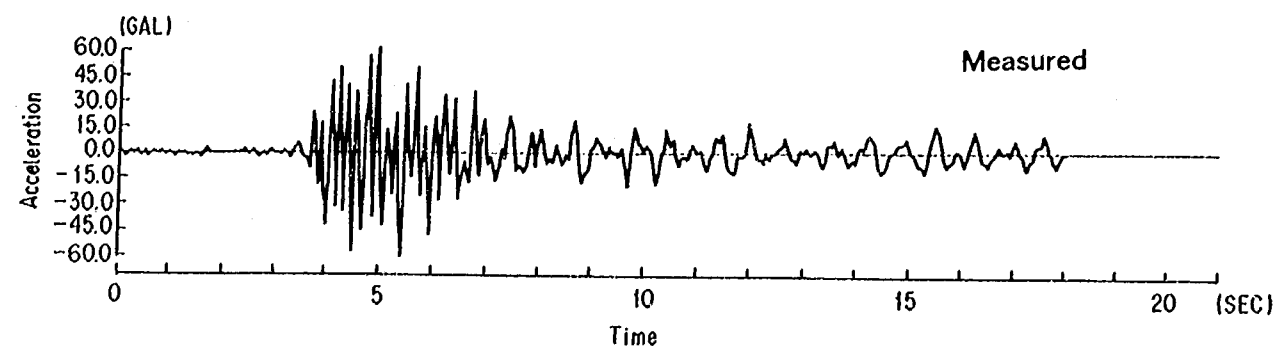


Fig. 5. 1 Sagara site 3, E-W acceleration time histories

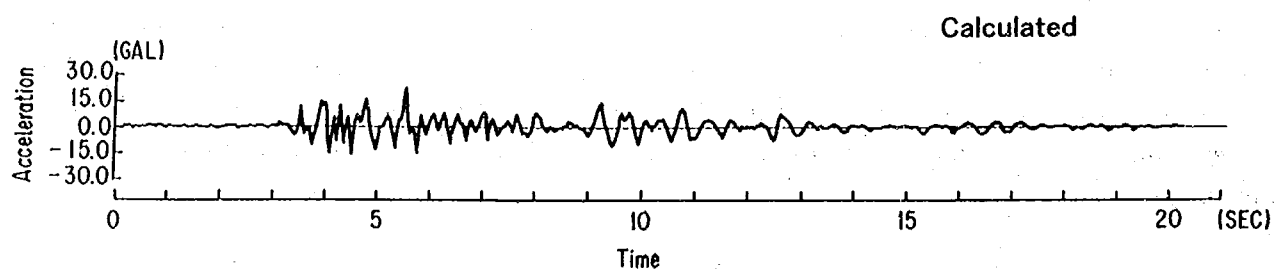
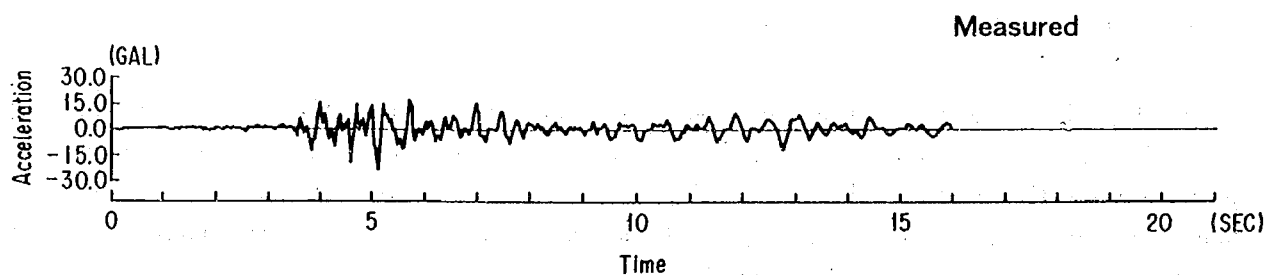


Fig. 5. 2 Sagara site 5, N-S acceleration time histories

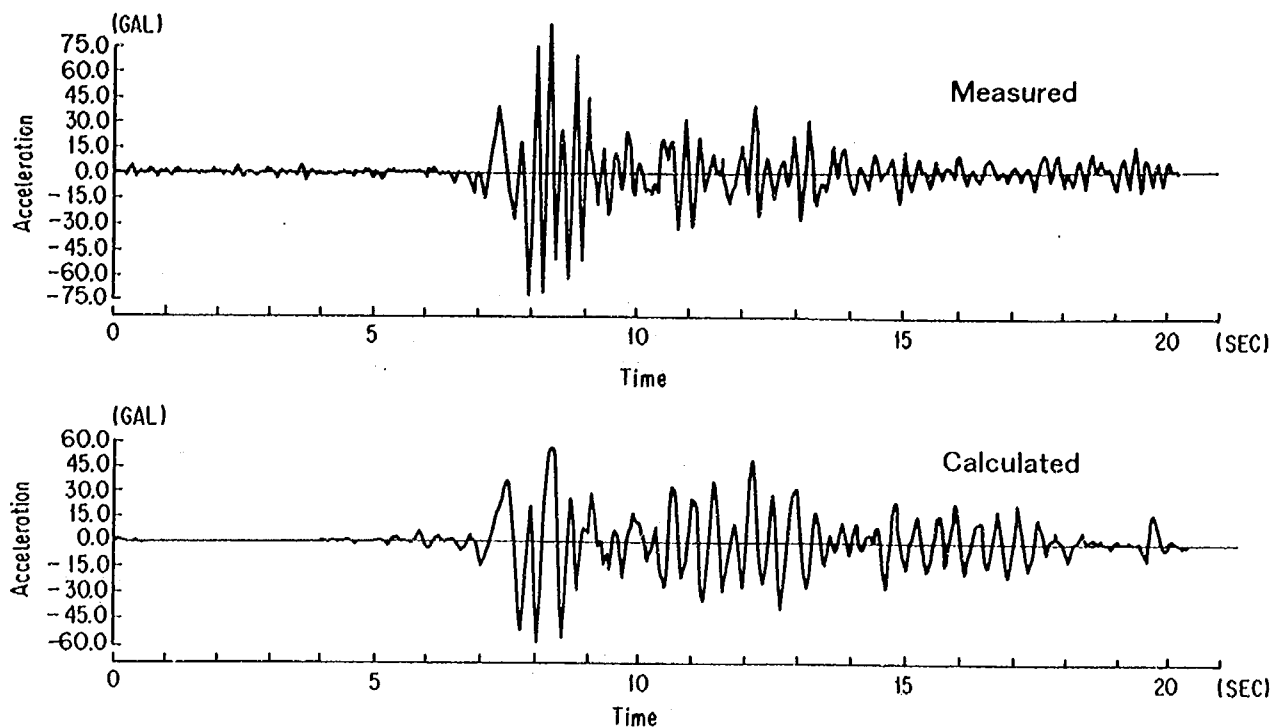


Fig. 5. 3 Numazu site 9, N-S acceleration time histories

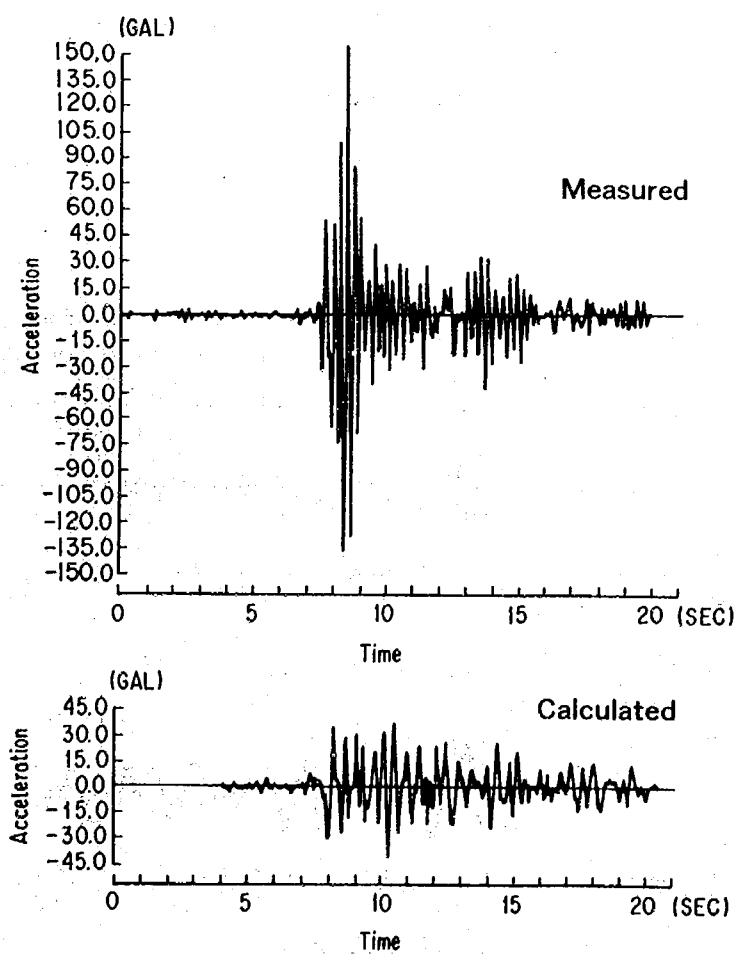


Fig. 5. 4 Numazu site 9, E-W acceleration time histories

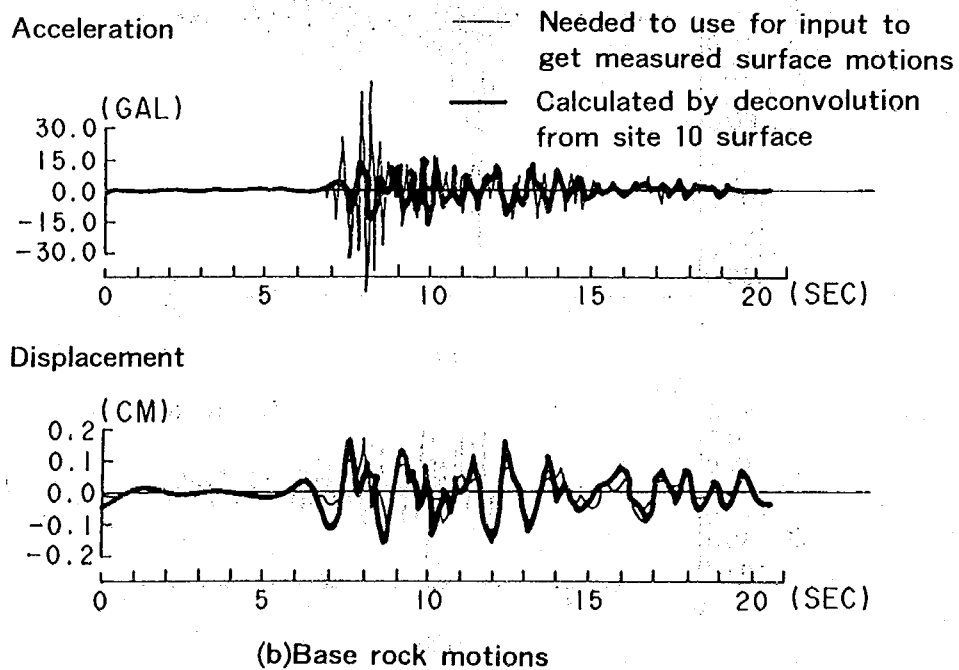
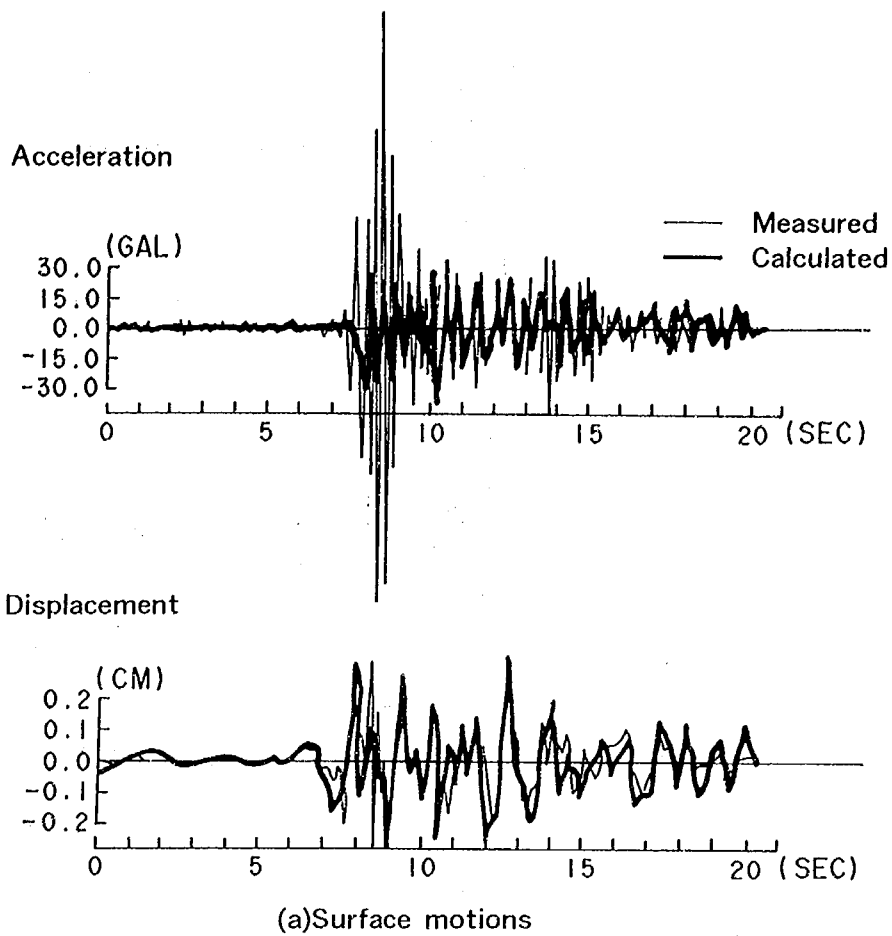


Fig. 5. 5 Numazu site 9, E-W motions

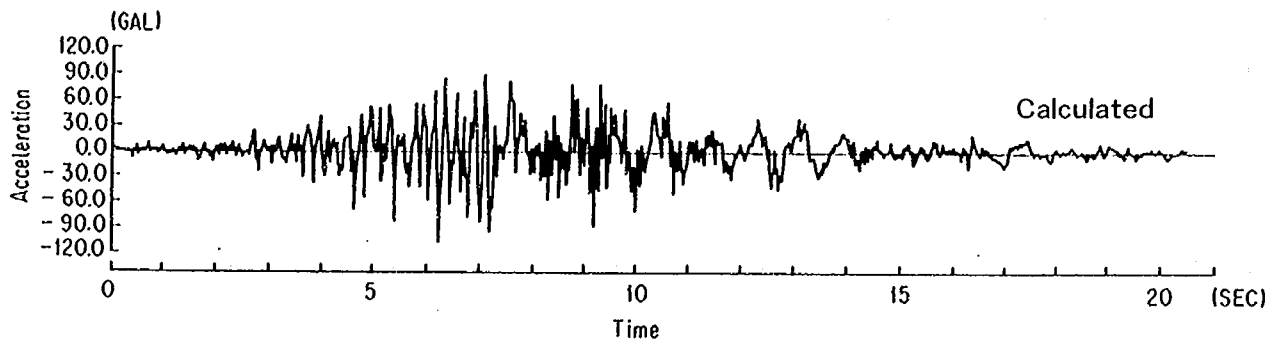
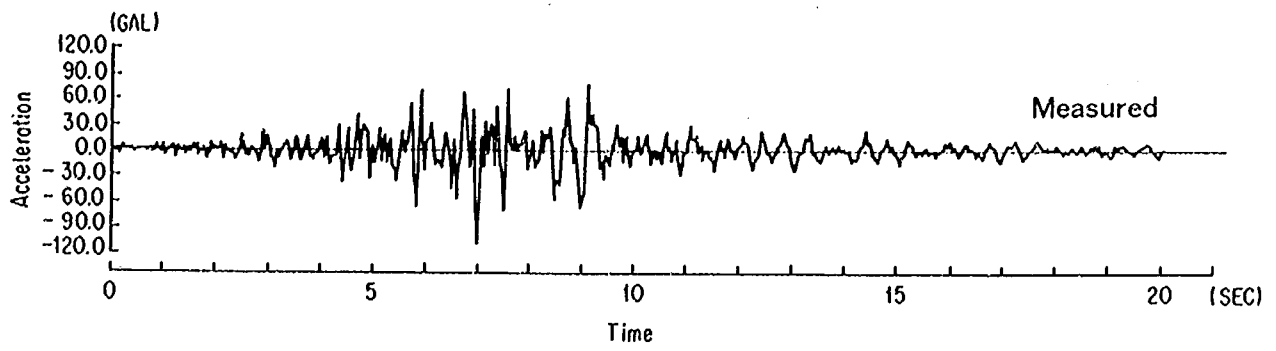


Fig. 5. 6 Matsuzaki site 9, N-S acceleration time history

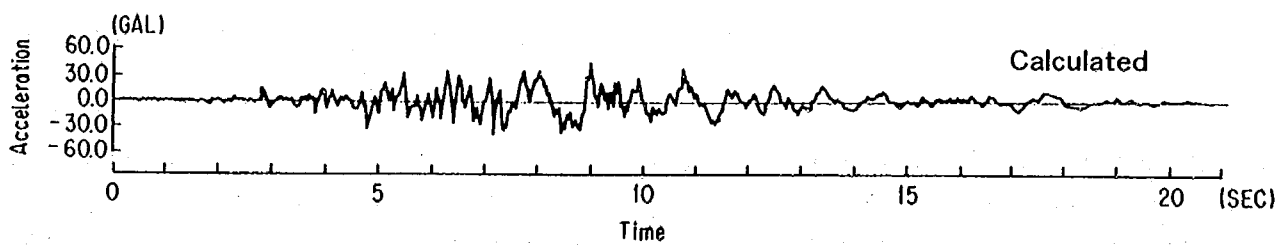
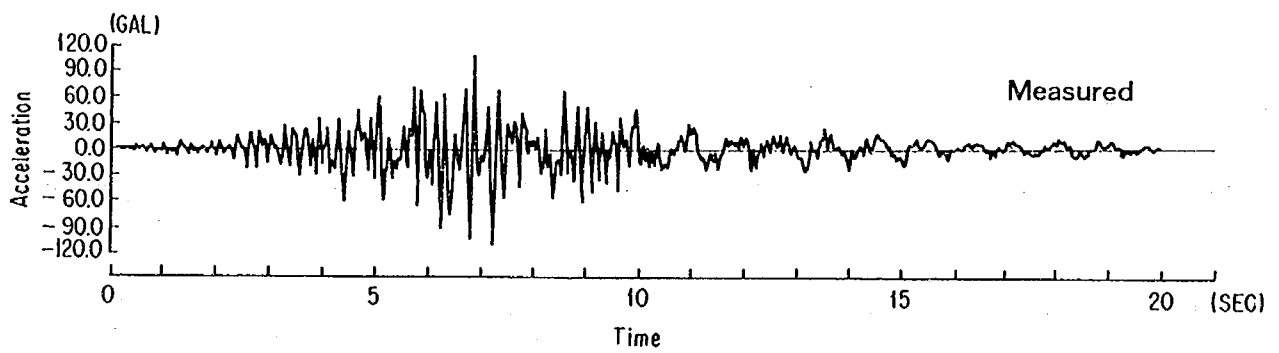


Fig. 5. 7 Matsuzaki site 11, N-S acceleration time history

6. ACCELERATION RESPONSE SPECTRA

6. 1 Sagara

The calculated and measured acceleration response spectra for locations 3 and 5 are shown in Figs. 6. 1 and 6. 2, respectively. It can be seen that for location 3, the agreement between calculated and measured values is reasonably good for periods above 0.25 sec but not very good for periods below this level. At 0.15 sec the measured motions are a factor of more than 6 greater than the calculated motions. Even at 0.7 sec where at first glance the agreement appears to be fairly good, there is nearly a factor of two difference between calculated and measured values.

For location 5 (Fig. 6. 2), the calculated values are a little greater than those measured at low periods, are lower than those measured at intermediate periods and about the same at high periods.

The displacement time histories for both of these motions (Figs. 3. 1 and 3. 2) show reasonably good agreement between measured and calculated values whereas the acceleration time histories (Figs. 4. 1 and 4. 2) show good agreement for location 5 and poor agreement for location 3.

It appears that any lack of agreement in acceleration or displacement time histories gets exaggerated in the acceleration response spectra at certain periods. The measured and calculated acceleration response spectra can easily differ by 60 to 600%, even if the displacement time histories appear to be in reasonably good agreement.

6. 2 Numazu

Similar conclusions can be obtained from the acceleration response spectra at Numazu (Figs. 6. 3 and 6. 4).

For the location 9 N-S component (Fig. 6. 3), at the low periods the measured values are much greater than the calculated, at the intermediate periods the calculated are greater than the measured, and at the high periods the values are about the same. It should be noted for this component, both the displacement time histories and the acceleration time histories showed reasonably good agreement between measured and calculated values. However, it can be seen that very substantial differences existed between the measured and calculated acceleration response spectra.

For the location 9 E-W component, even greater differences existed (Fig. 6. 4). A factor of seven difference was found at a period of 0.25 sec. At lower periods the difference was a factor of four. At higher periods good agreement was found. For this component, the agreement between measured and calculated acceleration and displacement time histories was not particularly good.

6. 3 Matsuzaki

At Matsuzaki location 9 (Fig. 6. 5), the acceleration response spectrum shows poor agreement between calculated and measured values at low periods. But unlike the other acceleration response spectra already described, for this location the calculated were higher than the measured values.

At location 11 (Fig. 6. 6), the response spectrum was much like the others which had the measured values greater than those calculated at low periods.

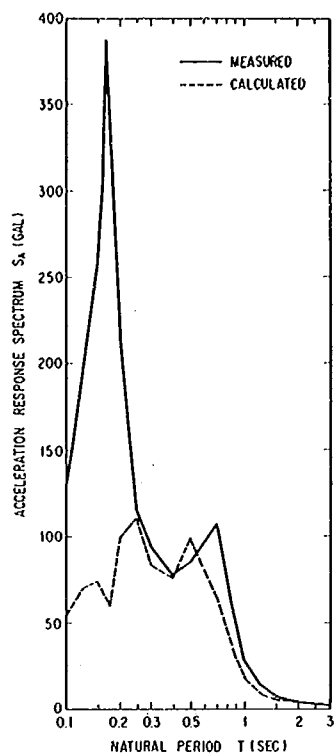


Fig. 6. 1 Sagara site 3, E-W
acceleration response spectra

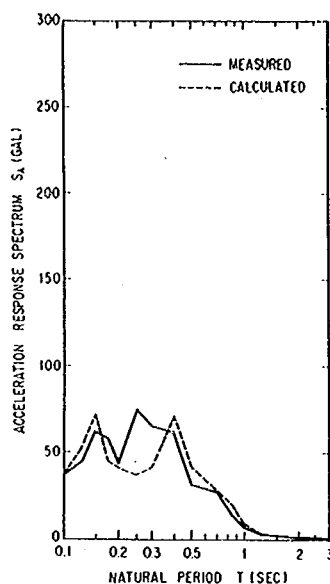


Fig. 6. 2 Sagara site 5, N-S
acceleration response spectra

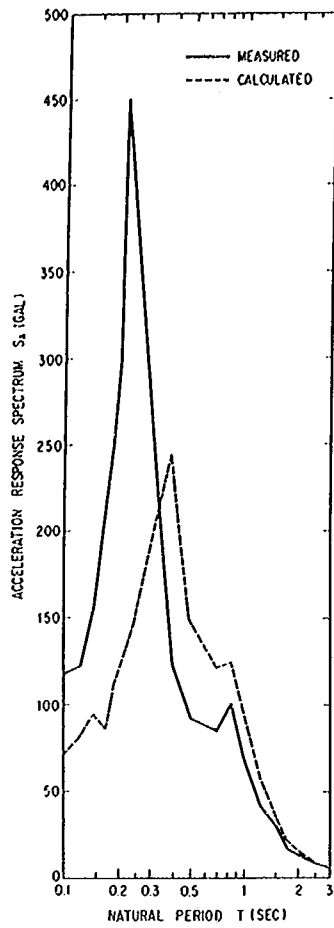


Fig. 6. 3 Numazu site 9, N-S
acceleration response spectra

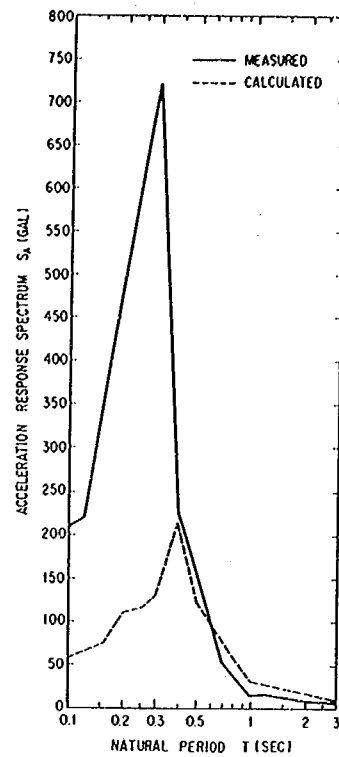


Fig. 6. 4 Numazu site 9, E-W
acceleration response spectra

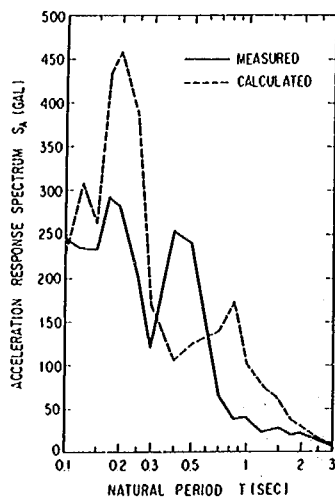


Fig. 6. 5 Matsuzaki site 9, N-S
acceleration response spectra

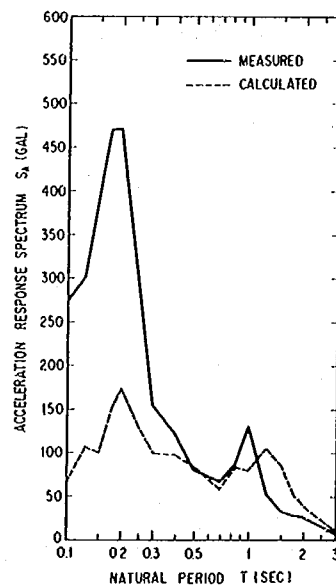


Fig. 6. 6 Matsuzaki site 11, N-S
acceleration response spectra

7. INFLUENCE OF SOIL PROPERTIES

The effects of varying the equivalent linear properties of soil stiffness and damping were investigated by changing the input parameters between high and low values of stiffness and high and low values of damping.

The equivalent linear stiffness curves used for the analyses are shown in Fig. 7. 1. The high modulus curve used in the analyses corresponds to the curve given by Zen and Higuchi (5) for a plasticity index of 70, and the low modulus curves corresponds to a non-plastic material curve. High and low damping curves were selected from the curves presented by Sun et al. (6) as shown in Fig. 7. 2.

It should be noted that at low strains (eg. 0.01%) the difference in stiffness between the low and high modulus curves is small - only about 20%. Whereas at high strain levels (eg. 1.0%) the difference is extremely large - about a factor of ten.

The opposite is true for the damping values. At low strains (eg. 0.01%) the difference between the low and high curves is large - about a factor of five. Whereas at high strains (eg. 1%) the difference is only a factor of two.

Thus it might be expected that a change in the damping curve would have a greater influence than a change in the stiffness curve at small strains. At large strains it might be expected that a change in the stiffness curve would have a greater effect than a change in the damping curve.

The Sagara site 4 which was mostly clay was used for the study of the influence of soil properties. The input motions consisted of the same as those studied earlier for the earthquake of March 16, 1983. This ground motion produced maximum strains in the range of 0.1 to 0.2% which might be considered to be an intermediate range of strain.

Four combinations of soil properties corresponding to the curves shown in Figs. 7. 1 and 7. 2 were considered:

1. Low modulus curve - low damping curve
2. High modulus curve - low damping curve
3. Low modulus curve - high damping curve
4. High modulus curve - high damping curve

The calculated displacement time histories for the four combinations are shown in Fig. 7. 3. It can be seen that the maximum peak displacement is obtained for the low modulus - low damping combination, and the minimum peak displacement is obtained for the high modulus - high damping combination. It can also be seen that the frequency content and shapes of the time histories remain nearly the same no matter what combination is used.

Similar observations can be made for the acceleration time histories shown in Fig. 7. 4. The magnitudes are greatest for the low modulus - low damping case and smallest for the high

modulus - high damping case. Also the frequency and shapes remain about the same.

A comparison between the curves generated by Iwasaki's equations and the curves by Zen and Higuchi (5) is shown in Fig. 7. 5. Iwasaki's (2) equations indicate that normalized stiffness is dependent on effective stress and thus a range of curves were used for the clay site (Sagara location 4). This range of curves falls within the range given by Zen and Higuchi, especially for the strain range experienced (0.1 to 0.2%). It was found overall that Iwasaki's curves gave very reasonable representations of the soil properties for all of the sites studied.

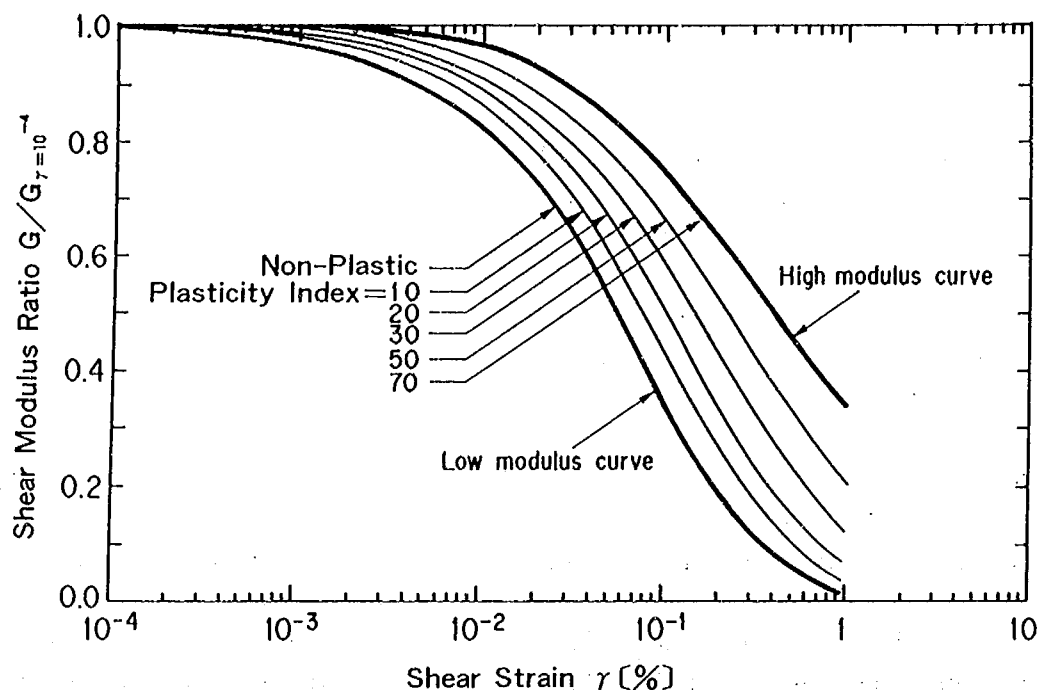


Fig. 7. 1 Normalized modulus reduction relationship for laboratory prepared clay samples with different plasticity indices (after Zen and Higuchi, 1984)

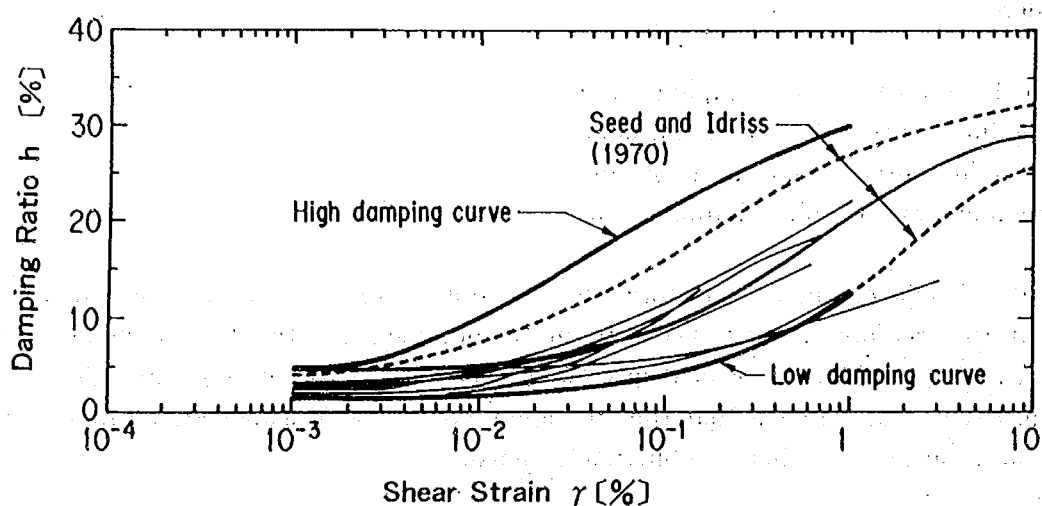


Fig. 7. 2 Strain dependent damping ratios for clays (Sun, Golesorkhi and Seed, 1988).

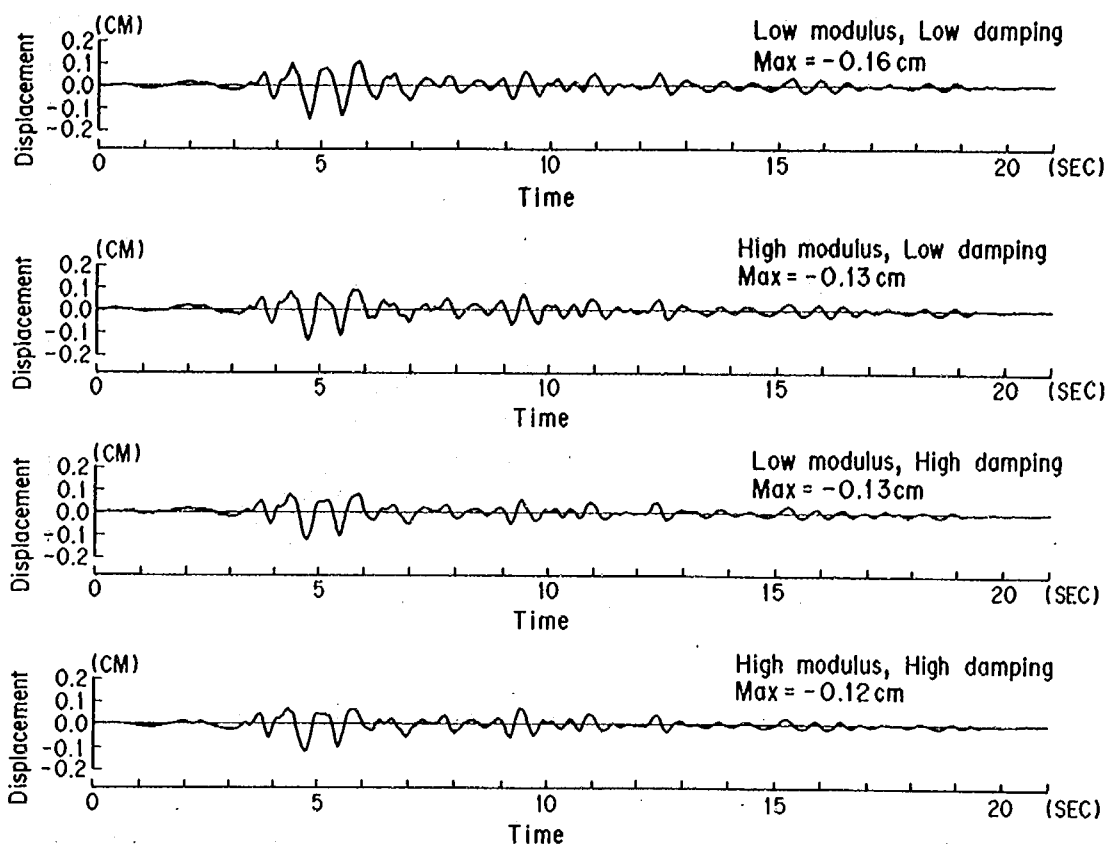


Fig. 7. 3 Effects of stiffness and damping, displacement time histories, Sagara site 4

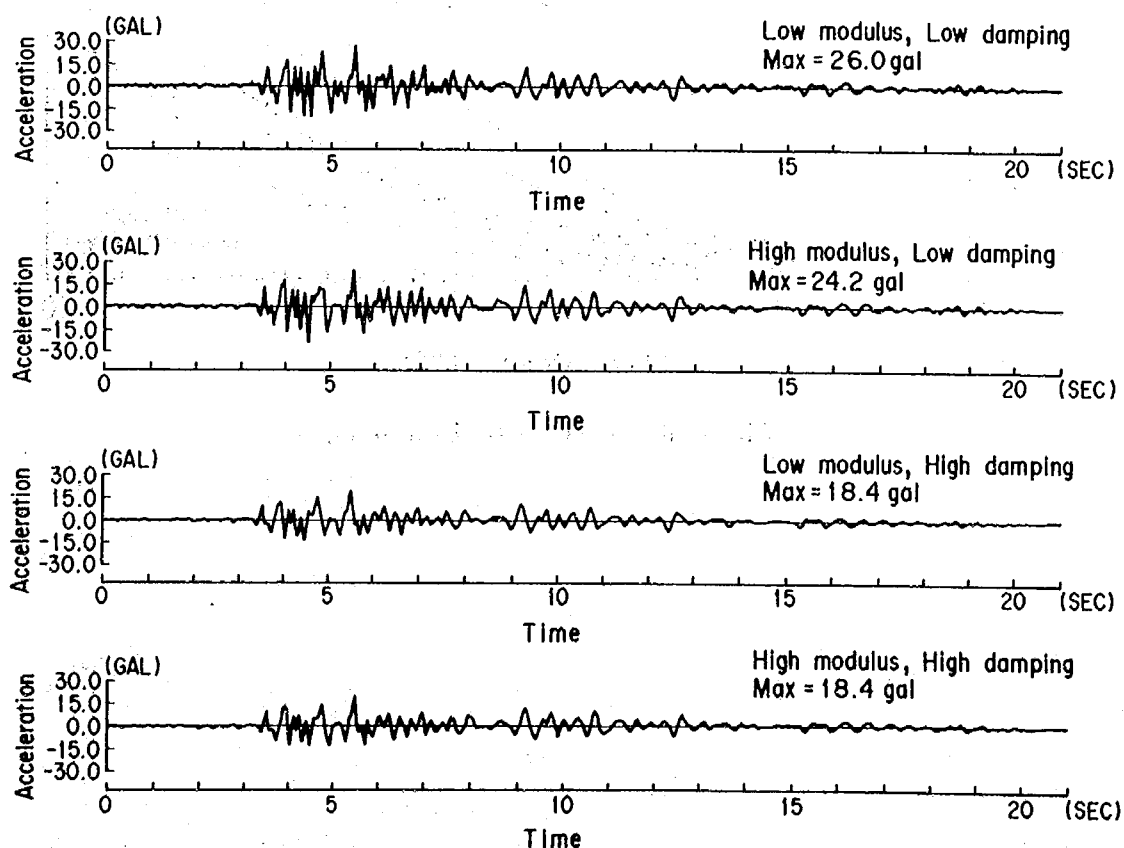


Fig. 7. 4 Effects of stiffness and damping, acceleration time histories, Sagara site 4

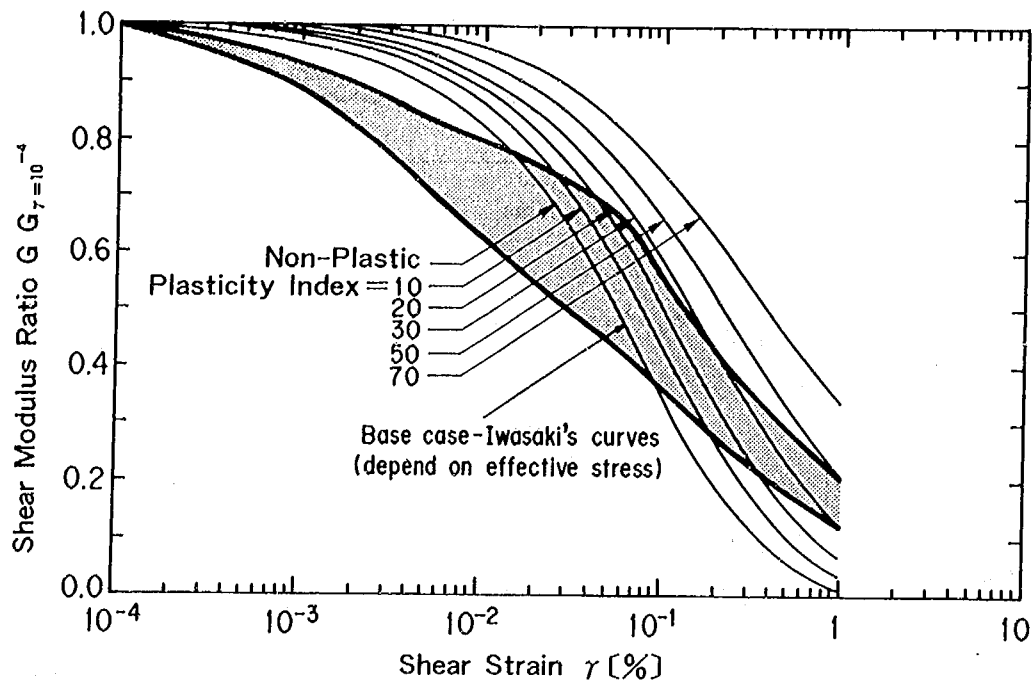


Fig. 7. 5 Sagara site 4 modulus ratio - mud

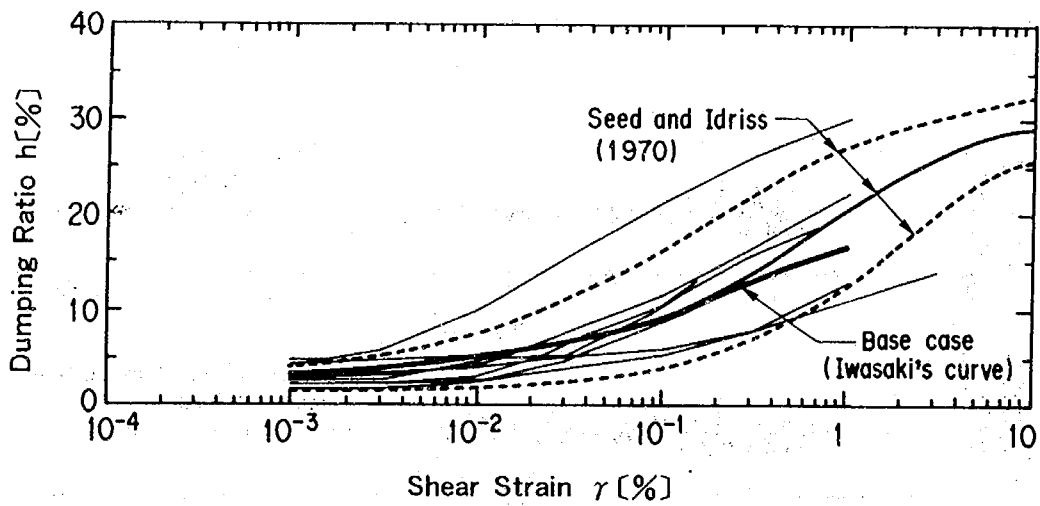


Fig. 7. 6 Sagara site 4 damping

8. CONCLUSIONS

The following conclusions can be drawn from this study with the restriction that they pertain to the moderate level of ground motion experienced in the recordings being caused by earthquakes of magnitude between 5.7 and 6.5 at distances between 41 and 96 km:

1. The displacement time histories give evidence that vertically propagating shear waves are the dominant source of ground motion at the beginning of the record, and that the soil properties have been reasonably represented by the equivalent linear representation using Iwasaki's method of developing the properties.
2. At later times in the ground motion, the agreement between measured and calculated displacement became worse than it was at the beginning. Differences in both magnitude and phase occurred while the frequency content was reasonably well represented by the calculations. This appears to indicate that vertically propagating shear waves are not the only source of the ground motion and that these differences become more important at later stages in the record, or that the soil properties are not well represented by equivalent linear properties after several cycles of motion.
3. The measured and calculated displacement time histories showed a greater amount of disagreement at later times for the Matsuzaki site which had significant topography, than for the other sites which had little topography. This result hints that even small amounts of topography may cause the ground motions to differ from that caused by vertically propagating shear waves, and that the source of the disagreement for the displacement time histories at the flat sites was due to the assumption of vertically propagating shear waves and not due to the assumption of equivalent linear soil properties.
4. The good agreement between calculated and measured displacement time histories at Numazu location 9 N-S indicates that the soil properties for the location were well represented by the equivalent linear soil properties obtained by Iwasaki's method, and that vertically propagating shear waves were the dominant source of motion at least at the beginning of the record. However, the displacement time history in the E-W direction lacked three significant pulses. The source of these pulses is not known as there is no downhole instrument at this location. These pulses are the source of large accelerations as for 13 of 16 recorded earthquakes location 9 E-W had the greatest acceleration at Numazu. It seems likely that these pulses were in the base rock motions at least to partial extent, as they represent the significant difference between the base rock motions calculated by deconvolution from the surface motions at other locations and at location 9. Reasons for this may be a focusing of the motions due to rock and travel path characteristics.
5. The Sagara and Matsuzaki acceleration time histories indicate that sometimes it is possible to calculate reasonable representations of the acceleration time histories by one-dimensional equivalent linear methods and sometimes it is not possible. Reasons for this are unclear. In general though, the methods did not work well in predicting the peak acceleration at any of the Sagara, Numazu or Matsuzaki sites.

6. Significant differences between measured and calculated acceleration response spectra existed for all of the locations studied. At some period in the response spectra the differences were at least 50%. They were as much as a factor of seven. In most cases the calculations underpredicted the measured ground motions at low periods, however in one case the calculations significantly overpredicted the low period portion of the acceleration response spectra.

7. Changes in the equivalent linear soil properties within a reasonable range produced only small changes in the calculated ground motions. The frequency content and shape of the time histories were not significantly modified by varying the soil properties. The greatest effect was on magnitudes.

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