Proceedings of Ninth World Conference on Earthquake Engineering
August 2-9, 1988, Tokyo-Kyoto, JAPAN (Vol.II)

3-4-9

IMPORTANCE OF SURFACE WAVE ENERGY IN SITE RESPONSE

Per B. SELNES, Bjørn ROGNLIEN and Farrokh NADIM

Norwegian Geotechnical Institute, Oslo, Norway

SUMMARY

Recorded values from a site in a deep sedimentary basin are compared with computed values from analytical and empirical procedures. The analyses show that both equivalent linear and non-linear site response analyses give reasonable agreement with recorded values when surface wave energy is removed from the earthquake record. The empirical relations give better agreement with the complete record.

INTRODUCTION

The ground shaking at a soil site is the result of the superposition of different types of waves. The relative importance of the different wave forms depends on factors such as source mechanism, distance, direction to the source, topography and sediment geometry. Analytical procedures which assume the horizontal components of the shaking to be caused by vertically travelling shear waves are commonly used. Comparisons between values computed with such procedures and recorded values seem, however, to indicate that the computed values may underpredict the response in higher periods (1).

One reason for this discrepancy may be the energy in surface waves. Many of the available strong motion records in the world data bases are obtained from sedimentary basin and bowl structures. Significant amounts of energy in surface waves in such structures have been found both in recorded values (e.g. 2,3,4,5) and in analyses (e.g. 4,6). Surface wave energy is most important for higher periods since low period energy is more rapidly attenuated. Records and empirical relations from basin and bowl structures may, therefore, give considerably higher response in the high period range than would be expected for horizontally layered structures.

In the present study, the importance of energy in surface waves for the site response is illustrated through a detailed study of a site in a deep sedimentary basin. Surface wave energy is removed from recorded values and comparisons are made with computed values using various analytical and empirical procedures.

SITE AND EARTHQUAKE

The Orion site (Holiday Inn, 8244 Orion Blvd) in the middle of the San Fernando Valley, a 20 by 40 km sedimentary basin north of Los Angeles, was selected for the study. The soil foundation at the site consists of 244 m sand and gravel (7), overlying some 4 - 5 km of sedimentary rock (5). Soil properties are shown in Table 1.

Table 1 Soil Parameters for 8244 Orion Blvd. Estimated from Ref. 7

Depth, m	Unit Weight, t/m³	Type
0 - 6	1.85	Sand K_2 = 1.0 (GWL at 30 m)
6 - 22	1.9	
22 - 75	1.95	
75 - 140	2.05	Gravelly Sand K_2 = 1.5
140 - 242	2.1	
242 -	2.2	Rock V = 1200 m/s

The average stiffness - strain (8) and damping - strain (9) relations for sand on Fig. 1 were used in the computations. Due to the large sediment depth, the influence of confining stress on the damping parameter was taken into account in the analyses (9).

Strong motion accelerograms were obtained in the San Fernando Valley during a M = 6.4 earthquake in 1971. The distances from the Orion site to the fault break and the epicentre were approximately 8 km and 13 km, respectively. The recording instruments were located in the first floor of an eight story building; this may have suppressed the energy for periods at and below the fundamental period of the building. A rule of thumb is that the fundamental period is equal to the number of stories divided by ten; the horizontal records should therefore be relatively little affected for periods above 1 s. Velocity spectra for the motions are shown in Fig. 2 (all spectra are shown for 5% of critical damping).

The records used as input (control motion) to the analytical procedures were from a hard rock site, the Griffith Park Observatory (GP) at a distance of some 20 km from the fault break. The records were scaled by a factor of 1.7 to account for difference in distance (10). The E-W component of the GP record were also scaled with a frequency variable factor to fit the average recorded rock spectrum for M = 6.5 earthquakes (11).

The rock spectra are shown in Fig. 2. The GP spectra do not have the relatively flat shape usually found in free field, flat ground rock spectra and the peak around 1. s may be due to topographical effects. The records were still used in the analyses since no good rock records from closer sites were available and since the GP site had similar direction (azimuth) to the fault break as the soil site.

ENERGY IN SURFACE WAVES

The Orion site is located in a sedimentary basin at a distance of 7 - 8 km from the nearest rock shore. Surface waves may be generated by the basin shape (2-D modes) and by the energy fed in from nearby rock shores. Measurements of microseisms in the San Fernando basin gave maximum values for periods in the range 3 - 5 s relatively independent of location and sediment depths. This has been attributed to basin effects (5).

Separation of surface and body waves in ground motions may be obtained from dense observation networks, while separation from a single observation site cannot be accurately performed. Reference 12 has, however, proposed a simplified separation technique for single site observations based on the dispersive character of the surface wave energy which may be identified from the evolutionary power spectra of the accelerograms.

The evolutionary power spectra from the E-W component of the Orion records on Fig. 3 show early arrival of non-dispersive energy (body waves) in the first 15 s of shaking in periods up to 1.0 - 1.5 s. Dispersive energy arrives later and mostly after 15 s of shaking. The time to the onset of the surface waves may approximately correspond to the difference between the time it takes body and surface waves to propagate to the site.

Rayleigh waves have furthermore a characteristic elliptical motion which may sometimes be recognizable from the recordings. As seen on Fig. 4, the Orion motion contains a clearly recognizable trace of Rayleigh waves after about 16 - 18 s of shaking.

Most surface wave energy seems to arrive after the body waves have subsided, i.e. after about 16 s of shaking. The difference between the first 16 s of shaking and the full record (40 s) should therefore be due to surface wave energy. The ground shaking during the first 16 s is therefore what might be expected if the Orion site had been located on horizontally layered sediment structure and not in a sedimentary basin during the San Fernando earthquake.

Figure 5 shows the average velocity spectrum for the two horizontal components of the ground motion at the Orion site for a duration of 16 s and 40 s. The spectral values in the period range 2 - 5 s are up to 40% lower for the 16 s record than for the spectrum from the complete records. Spectra for different time windows for the hard rock GP records show no maxima after 16 s and most maxima are within the first 12 s.

ANALYSES

One-dimensional analyses were carried out with equivalent linear and non-linear formulations of the soil behaviour. A modification of the 1-D wave propagation program SHAKE (13,14) was used for the equivalent linear analyses. A mixed lumped/consistent mass finite difference program (15) was used for the non-linear analyses with a piece-wise linear stress-strain relationship (Iwan model) matched to give the same stiffness-strain relation as in the equivalent linear procedure. Rayleigh damping was used in addition to the hysteretic damping in the non-linear analyses to give the same damping values for low strain levels in the two procedures.

The site response was computed for the two sets of rock motions described previously and results are shown in Fig. 6. The computed values for periods above 1 - 1.5 s. are generally within 30% of the values from the 16 s record. Figure 7 shows the results when the spectra computed for the two sets of rock motions are averaged. The equivalent linear analysis give significantly higher values for low periods than the non-linear analyses, but the two methods are in good agreement for higher periods.

The computed values are significantly higher than the recorded ones for periods below 1.5 s probably due to the effect of the dynamic response of the building on the recorded values, and the spurious peak in the GP records around 1 s.

The computed values underestimate the values in the range 2. - 5. s considerably compared to the full recorded motion. As expected, standard one-dimensional analytical procedures are not able to simulate cases with significant energy in surface waves.

EMPIRICAL RELATIONS

The response for the Orion site has also been evaluated from empirical relations developed for the western USA. The maximum acceleration for deep cohesionless soils for a M = 6.5 earthquake at a distance of 8 km from the fault break is 0.35 g according to Ref. 10. The response spectrum for deep cohesionless soil sites for M = 6.4 earthquakes proposed in Ref. 11 and extended to higher periods and slightly modified by Ref. 16, was scaled to 0.35 g to give a spectrum for the Orion site.

Figure 9 shows the empirically estimated spectrum together with the recorded spectra. The empirical spectrum gives excellent fit to the spectrum for the full recorded motion for periods above 1 s, but overestimate the response for periods in the range 2. - 5. s by 50 - 70% for the recorded motion when surface wave energy has been removed.

The empirical relations used here are, however, to a large extent based on records from the San Fernando earthquake and may give a too flattering picture of the ability of empirical relations to predict site response.

CONCLUSIONS

A strong motion record from a site located in a deep sedimentary basin is shown to contain significant energy in surface waves. Comparison between computed and recorded values when surface wave energy has been removed from the recorded values show that:

- both equivalent linear and non-linear procedures give reasonable values for the site response in the higher period range.
- empirical relations developed for the western U.S.A. overestimate the response for higher periods by 40 - 70%.

Records from sedimentary basins may have considerably longer duration and higher response in the high period range than would be expected for records from horizontally layered structures. One-dimensional procedures based on vertically propagating energy may be adequate for analyses of horizontally layered sediment structures, but may seriously underestimate the response in higher periods for sites located in sedimentary basins.

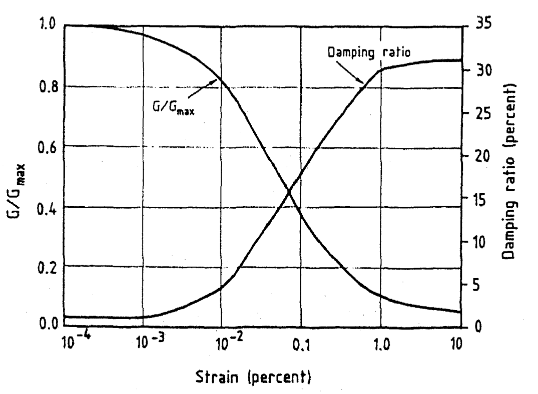

Fig. 1 Strain dependent shear moduli (8) and damping values (9) for sand used in the analyses.

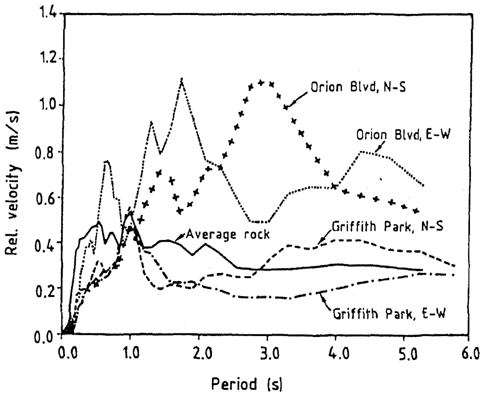

Fig. 2 Velocity spectra for soil and rock records.

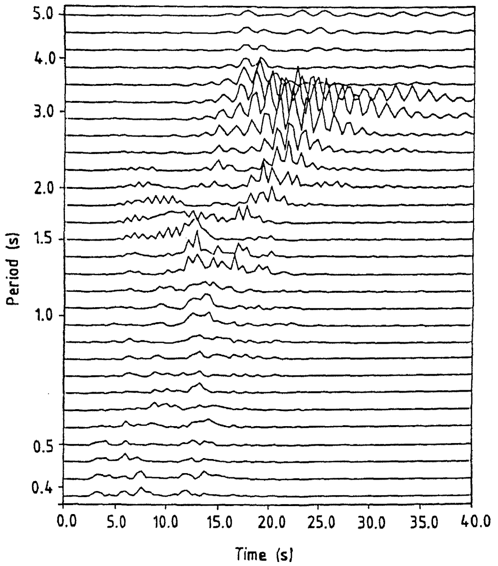

Fig. 3 Evolutionary power spectra for the E-W component of the Orion records.

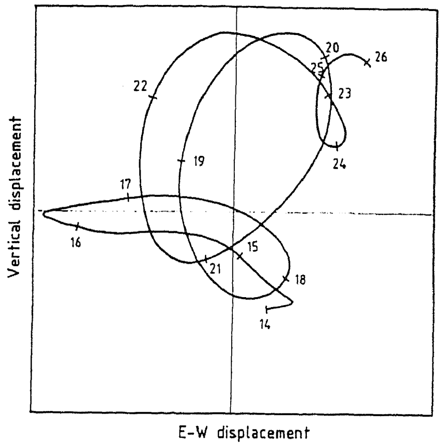

Fig. 4 Ground displacements for the Orion site projected on a vertical E-W plane. Numbers on the curve are duration in seconds.

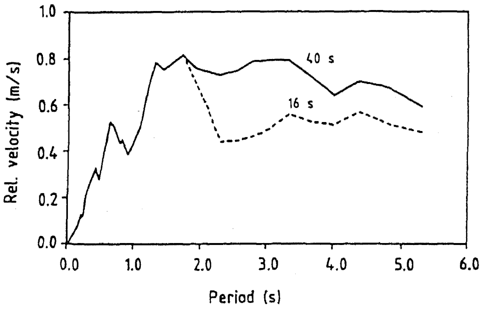

Fig. 5 Average velocity spectra for 16 and 40 s duration of shaking for the horizontal components of shaking at the Orion site.

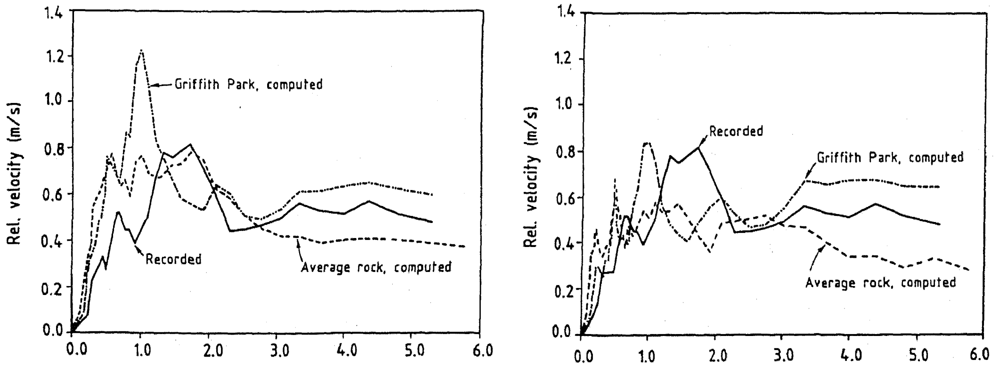

Fig. 6 Comparison between recorded values and values computed with equivalent linear (left) and non-linear (right) procedures. The recorded spectrum is from the first 16 s of the Orion records. The two horizontal components have been averaged in the figure for both the recorded and computed spectra.

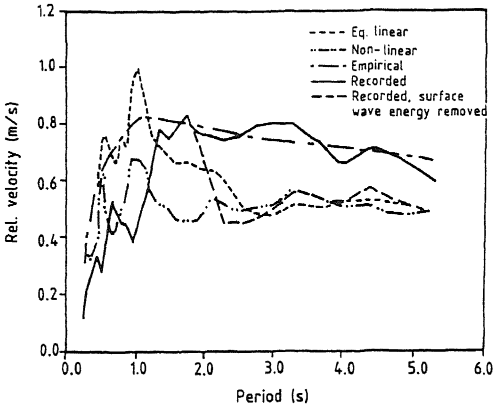

Fig. 7 Comparison between recorded spectra and spectra computed with different analytical and empirical procedures for the Orion site. The spectra from the horizontal components are averaged in the figure, the spectra from the analyses are, furthermore, averaged from computations with two sets of control motions.

ACKNOWLEDGEMENT

The work described in this paper was partly supported by the Royal Norwegian Council for Scientific and Industiral Research (NTNF), Statoil a.s, Norsk Hydro a.s, A/S Norske Shell and Esso Norge a.s. Their support is gratefully acknowledged.

REFERENCES

1. Sadigh, K. (1984). Characteristics of strong motion records and their implications for earthquake-resistant design. Presented at Earthquake Engineering Research Institute. Seminar 12. Stanford, California. 45 p.
2. Tucker, B.E. and J.L. King (1984). Dependence of sediment-filled valley response on input amplitude and valley properties. Bulletin of Seismological Society of America, Vol. 74, pp. 153-165.
3. Toriumi, I.S., S. Ohta and N. Murai (1984). Earthquake motion characteristics of Osaka plain. World Conference on Earthquake Engineering, 8. San Francisco, Proceedings, Vol. 2, pp. 761-768.
4. Ohta, T., S. Hiehata, K. Takahashi, E. Kitamura, M. Motosaka, M. Katama and M. Miyamura (1986). Research on the strong ground motion in Mexico City during the earthquake of September 19, 1985, Michoacan-Guerrero, Mexico. Kajima Institute of Construction Technology, Report, No. 68.
5. Kagami H., S. Okada, K. Shiono, M. Oner, M. Dravinski and A. K. Mal (1986). Observation of 1- to 5-second microtremors and their application to earthquake engineering. Part III. A two-dimensional study of site effects in the San Fernando valley. Bulletin of the Seismological Society of America, Vol. 76, No. 6 pp. 1801-1812, December.
6. Bard, P-Y. and J-C. Gariel (1986). The seismic response of two-dimensional sedimentary deposits with large vertical velocity gradients. Bulletin of the Seismological Society of America, Vol.76, No. 2, pp. 343-346, April.
7. Martin, P.P. and H.B. Seed (1982). One-dimensional dynamic ground response analyses. American Society of Civil Engineers. Proceedings, Vol. 108, No GT7, pp. 935-952.
8. Seed, H.B. and I.M. Idriss (1970). Soil moduli and damping factors for dynamic response analyses. University of California, Berkeley. College of Engineering. Earthquake Engineering Research Center. Report, EERC 70-10. 18 p.
9. Selnes, P.B. (1985). Foundation engineering criteria for gravity platforms. Damping in soils: a litterature study. Norwegian Geotechnical Institute, Report, 40013-28.
10. Seed, H.B., R. Murarka, J. Lysmer and I.M. Idriss (1975). Relationships between maximum acceleration, maximum velocity, distance from source and local site conditions for moderately strong earthquakes. University of California, Berkeley. College of Engineering. Earthquake Engineering Research Center. Report, EERC 75-17, 15 p.
11. Seed, H.B., C. Ugas and J. Lysmer (1974). Site-dependent spectra for earthquake resistant design. University of California, Berkeley. College of Engineering. Earthquake Engineering Research Center. Report, EERC 74-12, 15 p.
12. Sugito, M., H. Goto and F. Aikawa (1984). Simplified separation technique of body and surface waves in strong motion accelerograms. Proceedings of JSCE, Structural/Earthquake Eng. Vol. 1, No. 2, October, pp 71-76.
13. Schnabel, P.B., J. Lysmer and H.B. Seed (1972). SHAKE: a computer program for earthquake response analysis of horizontally layered sites. University of California, Berkeley. College of Engineering. Earthquake Engineering Research Center. Report, EERC 72-12. 88 p.
14. Selnes, P.B. (1987). SHAKE(N): Computer program for one-dimensional wave propagation studies. Norwegian Geotechnical Institute, Internal Report, 51508-23.
15. Nadim, F. (1987). AMPLE - a computer program for analysis of amplification earthquakes. Norwegian Geotechnical Institute, Internal Report, 51508-20.
16. Idriss I.M. (1985). Evaluating seismic risk in engineering practice. International Conference on Soil Mechanics and Foundation Engineering, 11. San Fransisco, Proceedings, Vol. 1, pp. 255-320.