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# THE INFLUENCE OF RADIATION DAMPING ON SEISMIC RESPONSE OF SOIL DEPOSITS

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## SYNOPSIS

This paper describes a theoretical investigation of the influence of radiation damping on ground response during earthquake. A method of analysis was developed for seismic response of foundations underlain by deformable bedrock. The method was used to study the influence of "RADIATION DAMPING" on foundation response. It was found that the old fashioned way of treatment of the effect of radiation damping by the introduction of some additional damping in each mode of rigid base solution, where the fundamental period of the overburden is not equal to the predominant period of the bedrock motion, may lead to misleading results. Under these conditions the up-to-date method, which is the developed method, should be used.

## INTRODUCTION

Seismic response of soil deposits resting upon a rock formation depends on the engineering characteristics of the underlying materials. A stiff bedrock interface will reflect a considerable proportion of the seismic energy that would normally be radiated away from the soil deposit, in effect in most cases producing a different response from a soft bedrock. Response study of these deposits is of great importance in seismic designs. Therefore, it is essential to investigate the influence of bedrock characteristics on response of such deposits. Several contributions have throuwn light on the subject. (Refs.1 to 9).

## RADIATION DAMPING RATIO

If a soil deposit rests on the rigid rock the damping, under earthquake loading, is mainly due to viscous and/or hysteresis resistance of the soil to rapid deformation. At the present time the hysteresis concept has commonly been accepted in practice. If a soil deposit rests on the soft rock, the damping has a second component which accounts for loss of energy back into the underlying rock. The intensity of this damping effect is expressed by RADIATION DAMPING RATIO "$\psi$", defined as

$$\psi = \frac{S_s \rho_s \text{ (of soil)}}{S_r \rho_r \text{ (of rock)}} \qquad (1)$$

In equation (1) $S_s$ and $S_r$ are the sheer wave velocities of the overburden and bedrock. $\rho_s$ and $\rho_r$ are the mass densities of the soil and the bedrock. This ratio has no relation to the other soil constants and is obtained from soil and bedrock parameters. Hence the value of "$\psi$" can be computed by means of the above equation.

The amount of energy radiated back into the bedrock at time "t" is related inversely to the velocity with which the base of the deposit moves at time "t" as well as the velocity of input motion.

## FIELD EVIDENCE

Medvedev (1965) has confirmed the importance of Radiatio Damping Ration in the field and has concluded that the smaller the radiation damping ratio, the more severe the expected degree of shaking during an earthquake.

## ANALYTICAL MODEL AND RESULTS

The current research has led to a new design method based on actual earthquake bedrock movements, recorded by strong ground motion instruments, real foundation materials and a new procedure for modelling a transmitting boundary. The original solution of this new theory, together with its accompanying computer programme was used in this study.

The influence of radiation damping ratio on ground response and its comparison with hysteretic damping ratio was studied through analysing a number of idealised layers for the following cases:

CASE 1: Fundamental period of the overburden is equal to the predominant period of the bedrock motion.
CASE 2: Fundamental period of the overburden is different from the predominant period of the bedrock motion.

It is believed that it is only through the following analysis, helped by efficient monitoring, that a better insight into the "Radiation Damping" phenomenon, which would be of interest to practising engineers, could be achieved.

## CASE 1

To show the influence of bedrock characteristics on response of soil deposits to earthquake shocks, for this particular case, analyses were performed on a 45m thick deposit of dense sand underlain by bedrock with shear wave velocities of $\infty$ (completely rigid), 3000, 1500 and 1000 m/sec., subjected at the bedrock level to Parkfield-2 with predominant period of 0.6 second, which corresponds to fundamental period of the deposit 0.6 sec. A hysteretic damping ratio of 0.02 was assigned to all modes of the deposit.

Table 1 shows comparison of maximum acceleration, velocity and displacement developed at the surface of the deposit underlain by above said bedrocks. Based on the results obtained for soil deposits having rock formation with shear wave velocities of 3000, 1500 and 1000 m/sec., maximum surface accelerations vary by 32.6%, 50% and 59.6% respectivily, compared to that of the deposit on infinitely rigid base. Similar conclusions may be drawn concerning the maximum amplitude of ground surface velocities and displacements with variations of 23.81%, 39.44%, 49.72% and 7.56%, 10.03%, 12.24% respectively. The results clearly indicate that amplitude of maximum accelerations are more sensitive to changes in bedrock formation characteristics than the peak velocities and displacements. The influence of bedrock characteristics on frequency characteristics of surface motions were also studies. The results clearly indicate that under CASE 1, frequency characteristics of output motion, are not affected to the extend to be reflected in acceleration response spectrum, whether the shear wave velocity of the underlying bedrock is 3000, 1500, 1000 or $\infty$ m/sec..

The computed values for strength of earthquake motion "S" (Refs. 10 & 11) are given in the last column of Table 1. The results illustrate that the energy available for damage to buildings located on the deposit where underlying rock formation has a shear wave velocity of $\infty$ is 7.6 times more that that of 1000 m/sec., 5.4 times more than that having a shear wave velocity of 1500 m/sec. and, finally, 3.2 times more that that having a shear wave velocity of 3000 m/sec..

In order further to consolidate the above conclusions, response of a 75m deposit of loose gravel with bedrock shear wave velocities of 5000, 2500, 1666, 1250 and 1000 m/sec. subjected to Parkfield-2 at the bedrock level at their comparison with the values obtained when underlying rock formation has shear wave velocity of infinity (completely rigid) are shown in Table 2. The results of this set of calculations clearly confirm the observed features reported in the previous set of calculations.

To illustrate the influence of stiffness of the bedrock on acceleration amplification spectra Fig.1 has been included. Fig.1 shows a family of acceleration amplification spectrum for different values of radiation damping ratios. It is observed that the softer the bedrock, the smaller is the amplification, especially at short and intermediate periods. It is also observed that the reduction is amplitudes of amplification spectra at resonance periods are not a linear function of radiation damping ratio.

It is hereby declared that:-

a) The frequency characteristics of surface motions are very slightly influenced by the bedrock characteristics.
b) The amplitude of pulses of surface motions are considerably affected by characteristics of bedrock. In general, a stiffer bedrock develops higher peaks in acceleration, velocity and displacement distribution pattern. The magnitude of the influence on maximum ground surface acceleration is maximized in the case considered i.e. (Case 1).
c) The energy available for damage is highly dependent on the characteristics of bedrock formation.
d) The softer the bedrock the smaller is the acceleration amplification, especially near the natural periods of the overburden.

## CASE 2

In most cases the predominent period of bedrock motion is not equal to the fundamental period of the soil deposit. Table 3 show maximum values of response of six 50m deposit of soft clay with fundamental periods of 1.33 sec. underlain by bedrock having different stiffness characteristics, and their comparison with the case when underlying bedrock is completely rigid, the deposits were subjected to their bedrock level to Parkfield-8 N50E, with a predominent period of 0.15 second and maximum acceleration of 0.28 g. From Table 3 it may be seen that maximum acceleration, velocity and displacement are 31.03%, 15.53% and 14.04% greater for a site having a completely rigid bedrock (S rock=$\infty$) than a soft rock (S rock=750 m/sec., reflecting the major influence of bedrock characteristics on the developed surface motions.

Referring again to Table 3 it is noted that maximum accelerations developed at the surface of the deposit with six different characteristics are less than those reported in Tables 1 and 2, stressing the fact that under the condition that the fundamental period of the overburden is not equal to the predominent period of the bedrock motion, the condition of resonance is violated, thus reducing the effect of bedrock stiffness on computed maximum surface accelerations. It may be noted that the influence of radiation damping ratio on computed maximum surface displacements are considerably more.

To show that frequency characteristics of surface motions are affected by the stiffness of bedrock formation Fig.2 has been included, which represents computed surface acceleration spectrum in normalized form. Considerable differences in frequency patterns of the motions developed on the surface of soils overlying different bedrock formations exists. Great differences in the amptitude of spectral values are also observed.

The damage potential of the sites having different bedrock characteristics are compared in terms of strength "S" (Refs.10 & 11) are given in the last coloan of Table 3. From results, it can be concluded that the deposit underlain by infinitely rigid bedrock ($\psi$ =0.0) is 2.53 times more damaging that that underlain by a soft rock ($\psi$=0.2).

Further comparisons of response of the soft clay subjected at the bedrock level to Parkfield-5 N5W, with predominant period of 0.3 secondare summarized in Table 4. The maximum valves of developed accelerations, velocities and displacements and their comparison with the case when the underlying bedrock is completely rigid (S rock=$\infty$) and the amount of energy available for damage at the surface.

It may be noted that the sites subjected to Parkfield-5 N5W have developed greater response values, although the peak value of acceleration time history of Parfield-5 N5W is 0.02g. less than Parkfield-8 N50E. This is because the predominent period of Parkfield-5 0.3 sec. is much closer to the fundamental periods of the deposits than that of Parfield-8 0.15 sec. The influence of radiation damping ratio on maximum surface acceleration for both cases is given in columns three of tables 3 and 4. The results clearly illustrate that radiation damping ratio has more influence on suppressing the response for the latter case than the former, indicating that radiation damping ratio is less effective in the first few higher modes of vibrations which contribute more to the developed response in the former case. Fig.2 show computed surface normalized acceleration spectrum for the latter case. From the results, it is readily apparent that at periods close to the periods of first and second modes of vibration, i.e. 1.33 sec. and 0.44 sec., frequency characteristics of the motions vary at the six sites. Differences in amplitudes of spectral values are observed, which are considerably great near the resonant periods of the deposit, emphasising the importance of radiation damping ratio on the developed response near the resonant periods of the overburden.

It is hereby declared that:-

a) The computed surface time histories of a soil deposit, in amplitude and frequency content, is influenced by radiation damping ratio. The extent of influence is considerably more on response amplitudes.
b) Strength of an earthquake motion at a given site, in terms of total energy which would be supplied to structures located on the site, is considerably dependent on the stiffness characteristics of bedrock motion.
c) The shapes of the computed surface response spectra curves are directly tied in with the deformability of bedrock formation.

## CONCLUSIONS

The results illustrate clearly that the deformability of the bedrock formation has an important effect on the seismic response characteristics of the soil deposits. Consequently, the usual assumption that the overburden rests on an infinitelty rigid bedrock formation should be discarded. The influence of bedrock formation on response was studies in terms of radiation damping ratio. It was shown that the radiation damping ratio in most cases influences frequency characteristics and amplitudes of motions. A higher radiation damping ratio was found, in general, to develop a smaller response with completely different frequency characteristics. The frequency characteristics of the motions was found to be unaffected only under the special condition that the fundamental period of the deposit is equal to the predominant period of the bedrock motion. Under this condition, the influence of bedrock formation characteristics on computed response is maximized and amplitudes of motions are affected considerably. It was only under this special condition that equivalence between the radiation and hysteretic damping ratios could be established.

The results also emphasise the need to determine the stiffness characteristics of bedrock formation in planning investigation programmes of soil and rock conditions. In defining the location of bedrock interface errors associated with this parameter should be accounted for in the response calculations. Choice of method of analysis should be based on every situation. If the soil conditions are clear and simple, for instance, if the site for a structure is located above a continuous layer of soft clay with well defined upper and lower boundaries underlain by a very deep formation of shale, errors due to using a one-dimensional model rather than a three-dimensional model in response analysis can hardly exceed twenty percent.

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TABLE 1 Data on the Influence of Bedrock Characteristics on Reponse of Soil Deposits.

| RADIATION DAMPING RATIO | MAX. SUR. ABS. ACC. (g) | $1 - \frac{ACC_{RAD}}{ACC_{0.0}} \times 100\%$ | MAX. SUR. ABS. VEL. (cm/sec) | $1 - \frac{VEL_{RAD}}{VEL_{0.0}} \times 100\%$ | MAX. SUR. ABS. DIS. (cm) | $1 - \frac{DIS_{RAD}}{DIS_{0.0}} \times 100\%$ | STRENGTH $(cm/sec)^2$ |
|---|---|---|---|---|---|---|---|
| 0.0 | 2.30 | 0.00 | 254.01 | 0.00 | 41.68 | 0.00 | 28172 |
| 0.1 | 1.55 | 32.6 | 193.51 | 23.81 | 38.53 | 7.56 | 8613 |
| 0.2 | 1.15 | 50.0 | 153.83 | 39.44 | 37.50 | 10.03 | 5134 |
| 0.3 | 0.93 | 59.6 | 127.72 | 49.72 | 36.58 | 12.24 | 3697 |

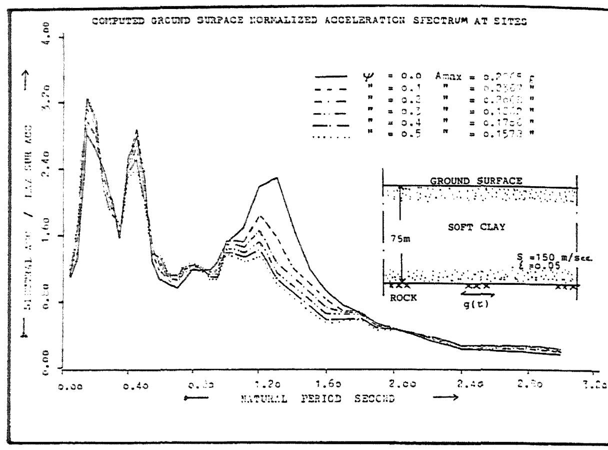


FIG. 1 Influence of Radiation Damping Ratio on Ground Surface Response

TABLE 2 Data on the Influence of Bedrock Characteristics on Reponse of Soil Deposits.

| RADIATION DAMPING RATIO | MAX. SUR. ABS. ACC. (Kg) | $1 - \frac{ACC._{RAD}}{ACC._{0.0}} \times 100\%$ | MAX. SUR. ABS. VEL. (cm/sec) | $1 - \frac{VEL._{RAD}}{VEL._{0.0}} \times 100\%$ | MAX. SUR. ABS. DIS. (cm) | $1 - \frac{DIS._{RAD}}{DIS._{0.0}} \times 100\%$ |
|---|---|---|---|---|---|---|
| 0.0 | 1.063 | 00.00% | 137.758 | 00.00% | 37.155 | 00.00% |
| 0.1 | 0.857 | 19.48% | 117.568 | 14.36% | 36.446 | 1.90% |
| 0.2 | 0.714 | 32.83% | 104.702 | 23.99% | 35.720 | 3.86% |
| 0.3 | 0.611 | 42.52% | 94.663 | 31.28% | 35.055 | 5.65% |
| 0.4 | 0.535 | 49.67% | 87.656 | 36.37% | 34.425 | 7.35% |
| 0.5 | 0.478 | 55.03% | 82.014 | 40.46% | 33.815 | 8.98% |

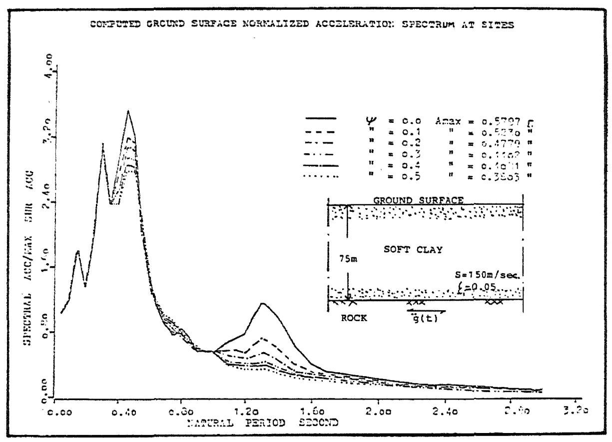


FIG. 2 Influence of Radiation Damping Ratio on Ground Surface Response

TABLE 3 Data on the Influence of Bedrock Characteristics on Reponse of Soil Deposits.

| RADIATION DAMPING RATIO | MAX. SUR. ABS. ACC. | $1 - \frac{ACC._{RAD}}{ACC._{0.0}} \times 100\%$ | MAX. SUR. ABS. VEL. (cm/sec) | $1 - \frac{VEL._{RAD}}{VEL._{0.0}} \times 100\%$ | MAX. SUR. ABS. DIS. | $1 - \frac{DIS._{RAD}}{DIS._{0.0}} \times 100\%$ | STRENGTH $(cm/sec)^2$ |
|---|---|---|---|---|---|---|---|
| 0.0 | 0.29 | 00.00 | 23.82 | 0.00 | 18.16 | 0.00 | 965 |
| 0.1 | 0.24 | 17.24 | 21.76 | 8.65 | 16.60 | 8.59 | 542 |
| 0.2 | 0.20 | 31.03 | 20.12 | 15.53 | 15.61 | 14.04 | 381 |
| 0.3 | 0.19 | 34.48 | 18.78 | 21.16 | 14.95 | 17.67 | 299 |
| 0.4 | 0.17 | 41.38 | 17.66 | 25.86 | 14.48 | 20.26 | 250 |
| 0.5 | 0.16 | 44.83 | 16.73 | 29.76 | 14.13 | 22.19 | 218 |

TABLE 4 Data on the Influence of Bedrock Characteristics on Reponse of Soil Deposits.

| RADIATION DAMPING RATIO | MAX. SUR. ABS. ACC. (g) | $1 - \frac{ACC_{RAD}}{ACC_{0.0}} \times 100\%$ | MAX. SUR. ABS. VEL. (cm/sec) | $1 - \frac{VEL_{RAD}}{VEL_{0.0}} \times 100\%$ | MAX. SUR. ABS. DIS. (cm) | $1 - \frac{DIS_{RAD}}{DIS_{0.0}} \times 100\%$ | STRENGTH $(cm/sec)^2$ |
|---|---|---|---|---|---|---|---|
| 0.0 | 0.58 | 0.00 | 49.95 | 0.00 | 11.44 | 0.00 | 953 |
| 0.1 | 0.52 | 10.34 | 44.22 | 11.47 | 10.01 | 12.5 | 542 |
| 0.2 | 0.48 | 17.24 | 39.66 | 20.60 | 9.38 | 18.00 | 401 |
| 0.3 | 0.44 | 24.13 | 35.96 | 28.00 | 9.03 | 21.06 | 325 |
| 0.4 | 0.40 | 31.03 | 32.92 | 34.09 | 8.78 | 23.25 | 277.44 |
| 0.5 | 0.38 | 34.48 | 30.45 | 39.03 | 8.58 | 25.0 | 245.35 |