THE SELECTION OF SEISMIC DESIGN LOADINGS BY THE USE OF RETURN PERIOD GRAPHS

by

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SYNOPSIS

A basis is presented for the selection of suitable levels of structural response for design purposes, taking into account the likelihood of occurence of earthquakes of various magnitudes and the effects of these earthquakes on structures founded in hard and soft soil deposits at various distances from the epicentre. Return periods are found for damaging levels of structural response and suitable design spectra are established from a judgement of what is an appropriate frequency of occurence of structural damage.

1. INTRODUCTION

The work described in this paper arose from the need to specify suitable levels of design earthquake loadings for bridge and viaduct structures along a major expressway in the Island of Luzon in the Philippines.

In general these are low level structures, some of which are of considerable length. Adequate provision against the risk of collapse was provided by arranging for the structures in concept and in detail to be very ductile in major shakings. However along much of the route the ground conditions were poor. It was known that this would lead to more frequent structural shaking due to the magnifying effect of these soils on distant earthquakes.

It was desired to select levels of lateral forces for design, taking this into account, such that the risk of structural damage was at an appropriate level. This paper describes the quantitative method used to achieve this level.

The steps in the process used are:-

(i) Determine the probable frequencies of occurence of earthquakes of various magnitudes in and around the area of interest. (Para 2).

(ii) Obtain acceleration response spectra for earthquakes of various sizes and at various distances from the epicentre on (a) hard ground (Para 3), (b) soft ground (Para 4).

(iii) The envelopes of these spectra for hard and soft ground are then reduced to design levels so chosen that the frequency of damage to individual structures is appropriate. (Paras 5 and 6).

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2. ANALYSIS OF SEISMOLOGICAL RECORDS

Figure 1 shows epicentres of earthquakes recorded in Luzon and reported in references (1), (2) and (3). The records cover the period 1904 to 1972 for magnitudes over 7.7, 1918 to 1972 for magnitudes 7.0 to 7.7, 1953 to 1972 for magnitudes 6.0 to 7.0, and 1965 to 1972 for magnitudes 5.0 to 6.0.

An attempt was made to divide the area into three zones with different levels of seismicity as in Figure 1, zone 3 being the most active and zone 2 the least active. However, as there was insufficient evidence (either from the epicentral data or from geological studies) to support such a zoning arrangement, the whole area was considered as being uniformly active, with zones 2 and 3 as lower and upper bounds respectively of the likely seismicity.

Statistical analysis of these records results in Figure 2, which gives the likely frequencies of occurence of earthquakes of various magnitudes. Also plotted are the seismicities of New Zealand and California, both of which are very similar to that of Luzon. (These are later used in assessing and comparing the design loadings given in this paper and in various world codes).

3. HARD GROUND ANALYSES

The Housner/Jennings series of artificial earthquakes (4) were used as hard ground earthquakes - i.e. for structures on hard deposits. The four types of earthquake in the Housner/Jennings series, designated types A, B, C and D, are intended to simulate the shakings in the epicentral regions of earthquakes of magnitudes approximately 8, 7, 6 and 5 respectively.

Figure 3 shows acceleration response spectra of three type A earthquakes, together with the El Centro spectrum with ordinates factored by 1.5 (since this has for some time been accepted as a maximum by many authorities). The envelope of all these spectra, as shown, is considered to be a conservative basis for a hard ground design spectrum, i.e. the maximum possible elastic response spectrum for a structure on firm ground in the epicentral region of a great earthquake.

Seed and Idriss (5) have published curves describing the decrease in maximum acceleration and the increase in predominant period with distance from the epicentre. These were used to modify the epicentral records to produce accelerograms for sites at 25, 50 and 100 miles from the epicentre for each magnitude. Response spectra were produced for each of these accelerograms, and those for the type B earthquake are shown in Figure 4.

4. SOFT GROUND ANALYSES

A dynamic analysis of the soft soil deposit was carried out by modelling the soil mass as a series of equivalent lumped masses, using a solution technique based on that published by Seed and Idriss (6) and modified by Parton (7). The soil mass is divided into a number of horizontal semi-infinite layers, each of which is assigned a thickness, a weight, a dynamic shear modulus and a damping factor.

The dynamic shear moduli and damping factors were determined from dynamic tests carried out on soil samples taken from boreholes at several representative sites along the expressway route. The apparatus, developed at the University of Auckland, New Zealand (7), consists of a triaxial cell in which the soil samples were strained in torsion to allow direct evaluation of the shear modulus. The samples were subjected to a consolidation pressure which in each case was equal to the effective overburden pressure in the ground at the sample depth.

For a given base rock accelerogram, the analysis program determined the natural periods and mode shapes for vibration of the soil mass, time histories of acceleration, velocity, displacement, shear stress and shear strain at various levels in the soil throughout the duration of the earthquake, average strains in each layer, and the acceleration, velocity and displacement spectra for structures on the surface of the soil mass.

Since the shear moduli and damping factors are not constant but are strain-dependent, the process becomes an iterative one. Successive approximations are made for these parameters until values are found which are consistent with the average strains in each layer, according to the relationships determined in the dynamic tests described above.

Analyses were made of the response of each soil deposit to the series of earthquakes described in section 3, i.e. types A to D at distances from the epicentre ranging from zero to 100 miles, and also to the El Centro and Koyna earthquakes, which compared well with the results from the artificial records. The acceleration response spectra for the type B earthquakes at one site are reproduced in Figure 5.

The critical responses for determining a soft ground envelope for design purposes are those for the A and D type earthquakes, and these are overplotted on Figure 6. The envelope is clearly quite different in shape from that for hard ground, a fact which is not recognised by many world codes. (See Figure 15).

Since the strains are higher in a large earthquake than in a small one, the shear moduli used will therefore be lower. Thus, it follows that the natural periods of the soil mass will be longer, and this was borne out by the analyses. Figure 7 shows the variation of period with earthquake magnitude and with distance from the epicentre. The first natural period varies from 1.35 to 1.8 seconds, the second from 0.55 to 0.75 seconds and the third from 0.35 to 0.45 seconds. However, although the variation with magnitude is considerable, at any given site the natural periods are always in the same ratios, regardless of the earthquake to which the site is subjected. For example, at the site to which Figure 7 applies, the first six natural periods are always in the ratio

1.000 : 0.417 : 0.250 : 0.177 : 0.144 : 0.117.
These ratios are significantly different at other sites.

A notable feature of the soft ground spectra (e.g. Fig. 5) was the substantial response of the soil, in certain cases, to the second and third natural modes. The first mode is dominant in the epicentral region of a type A earthquake but the second mode becomes important at greater distances from the epicentre and in a type B earthquake. In a type C earthquake the second mode is dominant, and in a type D earthquake (e.g. Koyna) the third mode becomes important and may even dominate. These higher mode responses have a considerable bearing on the shape of the design envelope and in this case were particularly important in view of the fact that the second natural period corresponded to the periods of most of the structures along the Expressway.

If it is assumed that the piles follow the ground movements exactly, then the deflected shapes of the soil mass, produced in the above analysis, become pile deflected shapes also, and as such are useful as an aid to pile design. From these, for example, can be found the position and magnitude of the maximum pile curvature during the earthquake, and hence the potential plastic hinge position.

5. RETURN PERIOD ANALYSIS

The object of the analysis is to calculate the likely return periods of various levels of spectral acceleration, for structures on both hard and soft ground. The results can then be used to estimate the likely return periods of that shaking which will cause damage.

From the response spectra such as Figures 4 and 5 attenuation curves are plotted to describe the variation of structural response with magnitude and with distance from the epicentre. These are plotted for structures of various natural periods and on both hard and soft ground. Figures 8 and 9 show attenuation curves for hard and soft ground respectively, for structures with natural periods in the range 0.5 to 0.8 seconds, which will apply to most of the structures along the expressway. Similar curves can be plotted for structures with other natural periods.

From these curves the areas within which a given earthquake induces structural response greater than a particular level can be determined, assuming these areas of influence to have shapes as shown in Figure 10. These shapes are the loci of points receiving equal amounts of energy from a fault line, along the length of which energy is emitted uniformly in all directions. The fault line lengths are as recommended by Housner (8) - i.e. M8.0 - 200 miles, M7.5 - 80 miles, M7.0 - 27 miles, M6.5 - 9 miles, M6.0 - 5 miles, M5.5 - 3 miles, M5.0 - 2 miles, and the lengths of maximum intensity of shaking are assumed to be 75% of these.

The products of these areas and the numbers of earthquakes of each magnitude per year per square degree (from Figure 2), with an adjustment to allow for the finite width of the seismic zone, gives the probabilities of occurence of various levels of structural response due to each magnitude. The sums of these contributions from each range of magnitudes then leads to the likely return periods of various levels of structural response. These values have been calculated for structures of various natural periods on both hard and soft ground, and those for periods in the range 0.5 to 0.8 seconds are displayed as typical examples of these in Figures 11 and 12. Figure 12 for instance, shows that for a structure of natural period 0.65 seconds, on soft ground, a structural response of at least 0.3g has a 50% probability of occurrence in any period of 20 years and has a likely return period of 30 years. Such information is extremely valuable in deciding upon a suitable elastic response for design purposes.

It was found that the largest contribution to the risk of a small response is from the moderate earthquakes (i.e. magnitude of about 6.5) as smaller earthquakes, though more frequent, influence only a small area, and larger earthquakes, though influencing a large area, are very rare. However, the risk of a response of 0.7g or greater is due entirely to the large earthquakes (i.e. greater than magnitude 7.0).

Figure 13 shows the general shapes of response spectra having constant return periods for all structural periods. It is noticeable that only for very high return periods are their shapes similar to the shapes of the envelopes in Figures 3 and 6. This suggests that in the reduction of these envelopes to design spectra, the use of a constant reduction factor for all structural periods is not appropriate.

6. DESIGN SPECTRA

The probability of a magnitude 8 earthquake occurring with epicentre at or near a particular site is extremely small. Figure 2 shows that such an event will on the average occur within 35 miles of a given site only once in 1300 years. Thus it is clearly uneconomic to design a structure for the envelopes of spectra in Figures 3 and 6. The value of the return period curves is that they allow a rational method of reducing these envelopes to reasonable design levels. Such a reduction is justified by the fact that it allows for the capacity of concrete members to dissipate energy by plastic rotation when the materials are in the yield range. A structure designed to this philosophy will respond elastically to an earthquake of a moderate magnitude, without incurring damage. However if careful attention is paid to proper type selection and to detailing and ductility the elasto-plastic capacity of the structure will be sufficient to ensure that in a very large earthquake, although sustaining damage, the structure will not collapse and should be able to be repaired economically.

If equal displacement theory is assumed the factor by which the envelopes are reduced will be equal to the ductility factor which the structure will be called upon to provide in a very large earthquake.

Figure 14 shows the recommended elastic design spectra for hard and soft ground. The hard ground spectrum corresponds basically to the envelope of Figure 3 with ordinates reduced by a factor of 8. The soft ground spectrum corresponds basically to the envelope of Figure 6 with a reduction factor of 5. A greater reduction is appropriate on hard ground because of the very rapid attenuation of shaking on hard ground, as can be seen from a comparison of Figures 8 and 9, resulting in considerably higher return periods than on soft ground.

The final design recommendations include a load factor of 1.25 and a capacity reduction factor of 0.75. Therefore the level of shaking at which damage is likely to occur is greater than the design level by a factor of about 1.67. The spectra of damage levels corresponding to the recommended design spectra are also plotted on Figure 14, and in both cases the peaks of the design spectra have been reduced so that the "damage level" spectra each have a constant return period in accordance with Fig. 13. The complete removal of the peak of the soft ground spectrum results from the fact that the analyses have shown that the medium earthquakes (types B and C) do not excite the first natural mode (1.5 seconds) as much as they do the second mode (0.65 seconds). Thus Figure 14 suggests that structures designed by these recommended elastic design spectra should suffer a damaging earthquake on the average every 150 years on hard ground and on the average every 40 years on soft ground.

In Figure 15 the recommended design spectra are compared with design spectra taken from the codes of New Zealand, California and Japan. As can be seen, the recommended spectrum for hard ground is similar to the design spectra of the New Zealand and Californian codes (these are areas of similar seismicity to Luzon - see Figure 2), but neither of these codes recognise the very different nature of the behaviour of structures on soft soil deposits. Furthermore, while the Japanese Railway code recognises this difference, it does not allow for the possibility of high responses to the higher soil modes, as was found to occur in this investigation. (In comparing the Japanese codes with these recommendations, note that Japan has a higher level of seismicity than Luzon).

A noticeable feature of Figure 14 is the discrepancy between the return periods for structural damage of 40 and 160 years for soft and hard ground respectively. Ideally, all structures along the route should have a similar damage risk. Thus the spectra of Figure 14 could be further adjusted if desired by increasing the soft ground spectrum and reducing the hard ground spectrum, taking into account the return periods of damage, the cost of the structure, and any special features of the structure.

7. CONCLUSION

A rational choice of seismic design loading must take into account the likelihoodof occurence of earthquakes of various magnitudes, the rate of attenuation of these earthquakes with distance from the epicentre, and the response to those earthquakes of structures founded on both hard and soft soil deposits. The method presented in this paper embodies these three factors and therefore allows the selection of design spectra to be a matter of judgement of acceptable return periods for damaging earthquakes for the particular structure being considered.

8. REFERENCES

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9. ACKNOWLEDGEMENT

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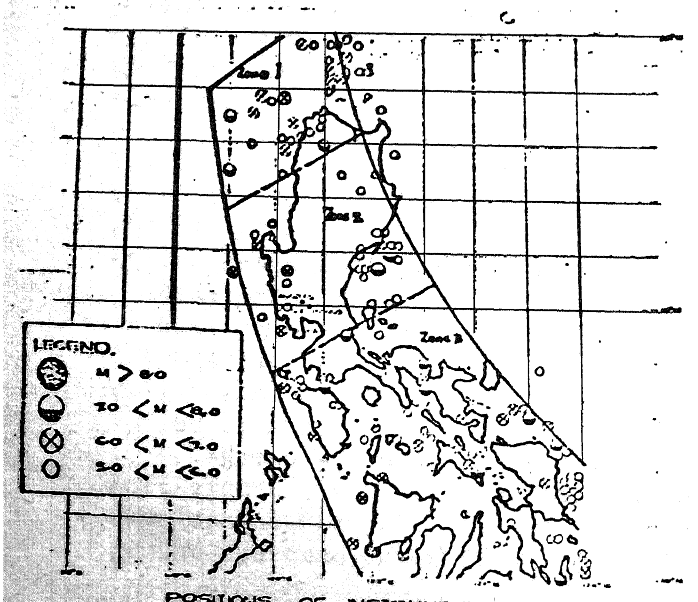

FIG. 1 POSITIONS OF INSTRUMENTALLY RECORDED EPICENTRES FOR LUZON

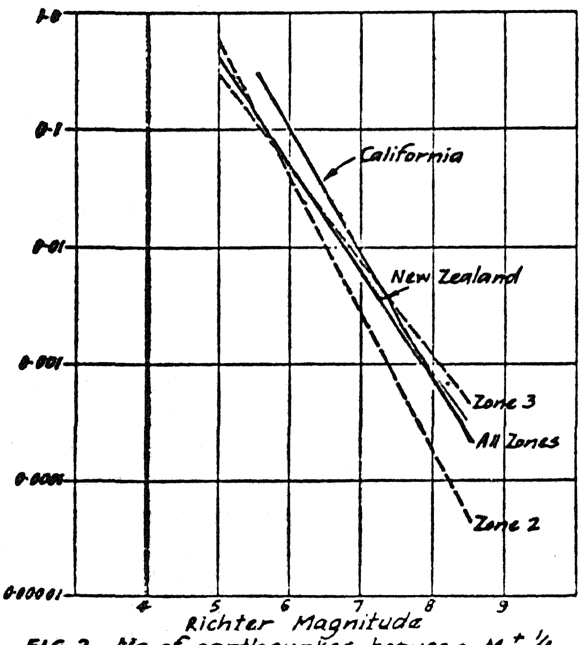

FIG. 2 No. of earthquakes between M ± 1/4 per year per square degree

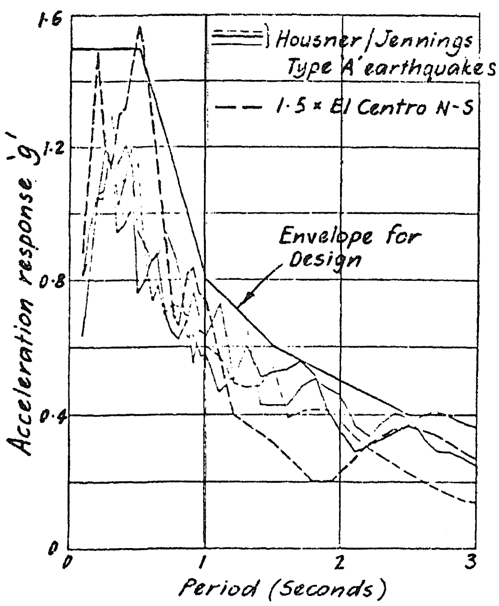

FIG. 3 Hard ground response spectra

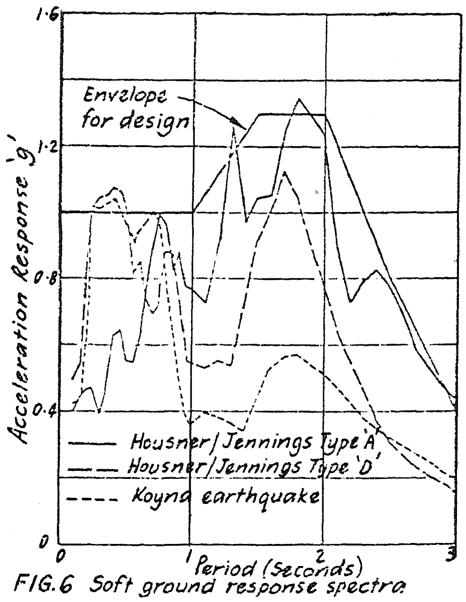

FIG. 6 Soft ground response spectra

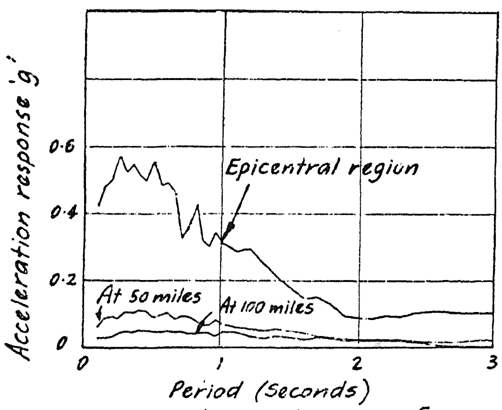

FIG. 4 Hard ground spectra for Type 'B' earthquake (5% damping)

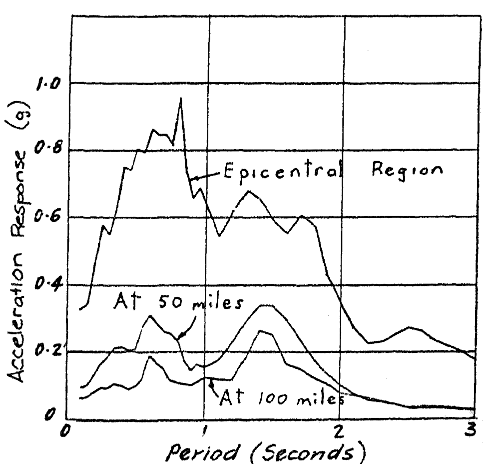

FIG. 5 Soft ground spectra for Type 'B' earthquake (5% damping)

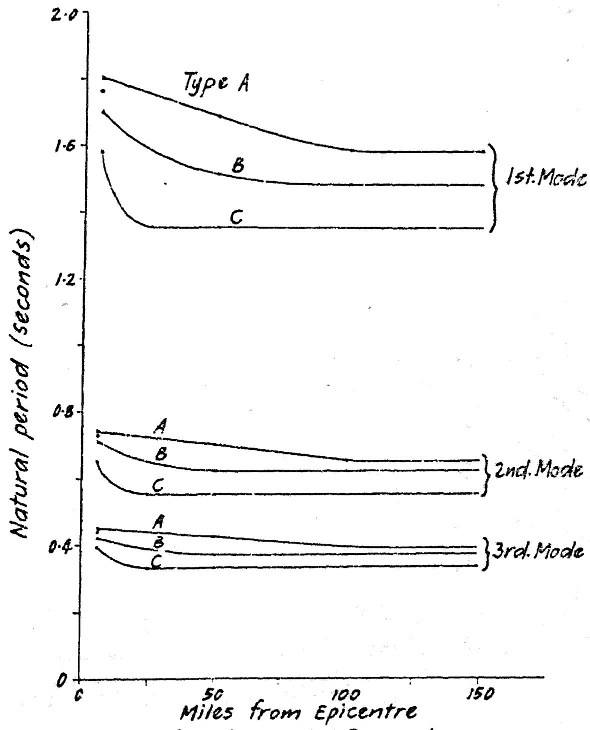

FIG. 7 Natural periods of soil deposit

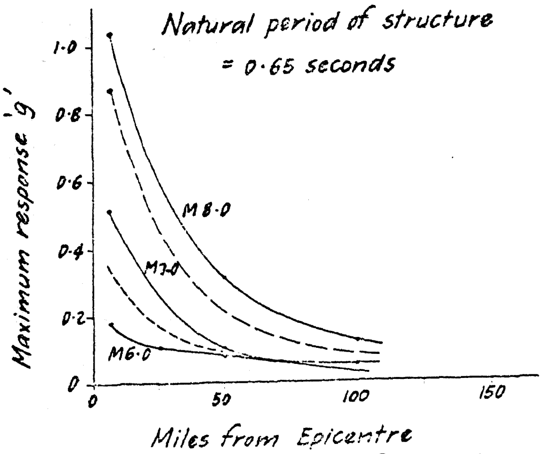

FIG. 8 Attenuation curves for hard ground

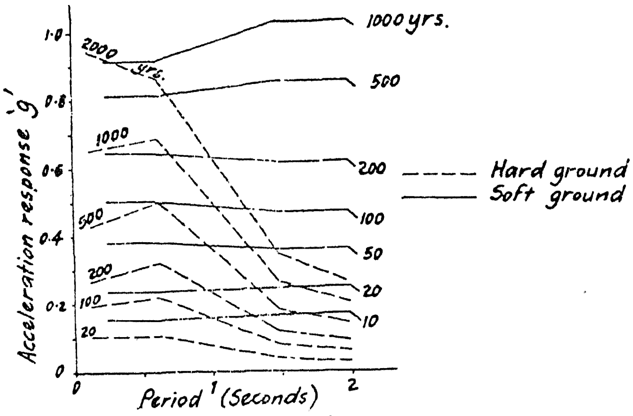

FIG. 13 Response spectra for constant return periods

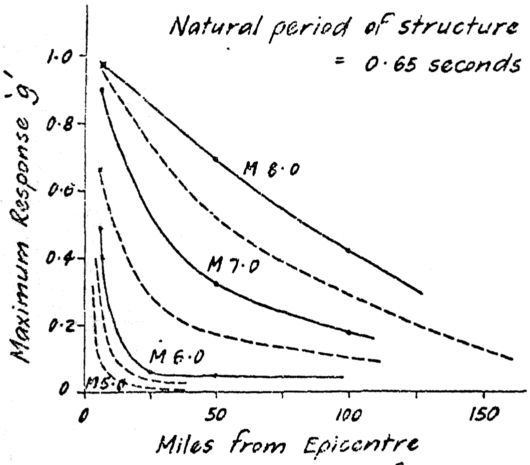

FIG. 9 Attenuation curves for soft ground

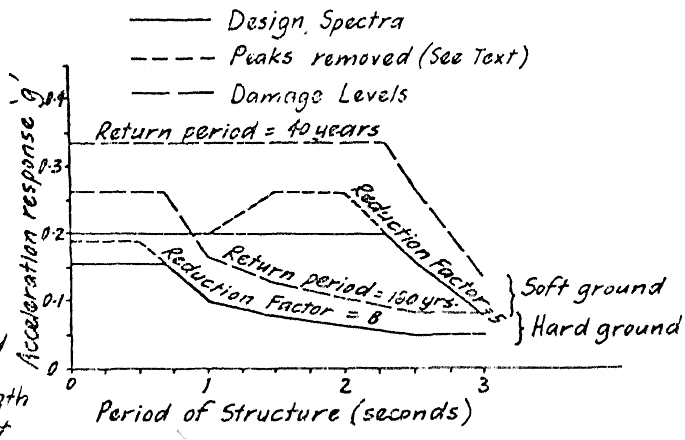

FIG. 14 Recommended Design Spectra

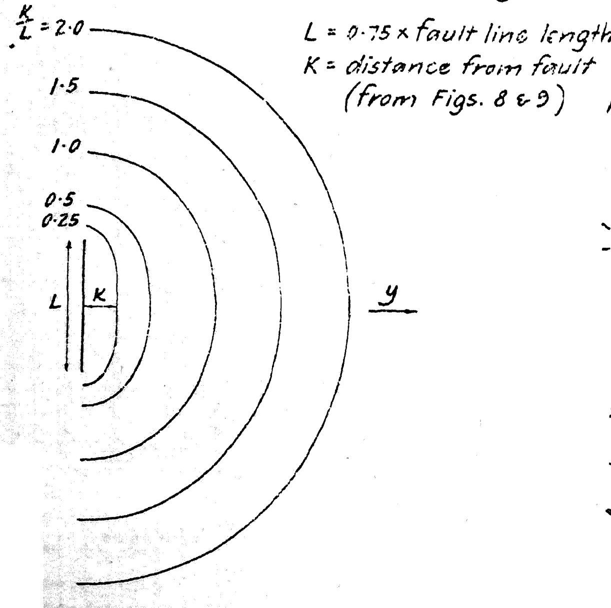

FIG. 10 Lines of equal effect due to energy emission along a fault line.
Lines conform to :

$$\frac{L}{y}\left[\tan^{-1}\left(\frac{L-2x}{2y}\right)+\tan^{-1}\left(\frac{L+2x}{2y}\right)\right]=\frac{2}{K}\tan^{-1}\left(\frac{L}{2K}\right)$$

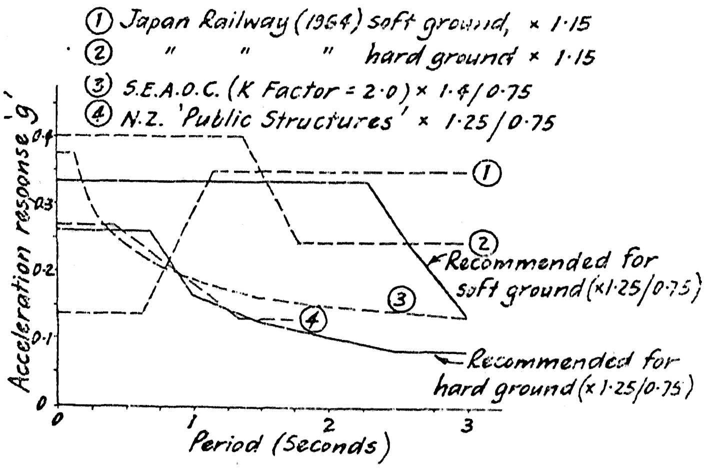

FIG. 15 Comparison of recommended design curves with world codes. (All curves are factored to incipient damage level.)

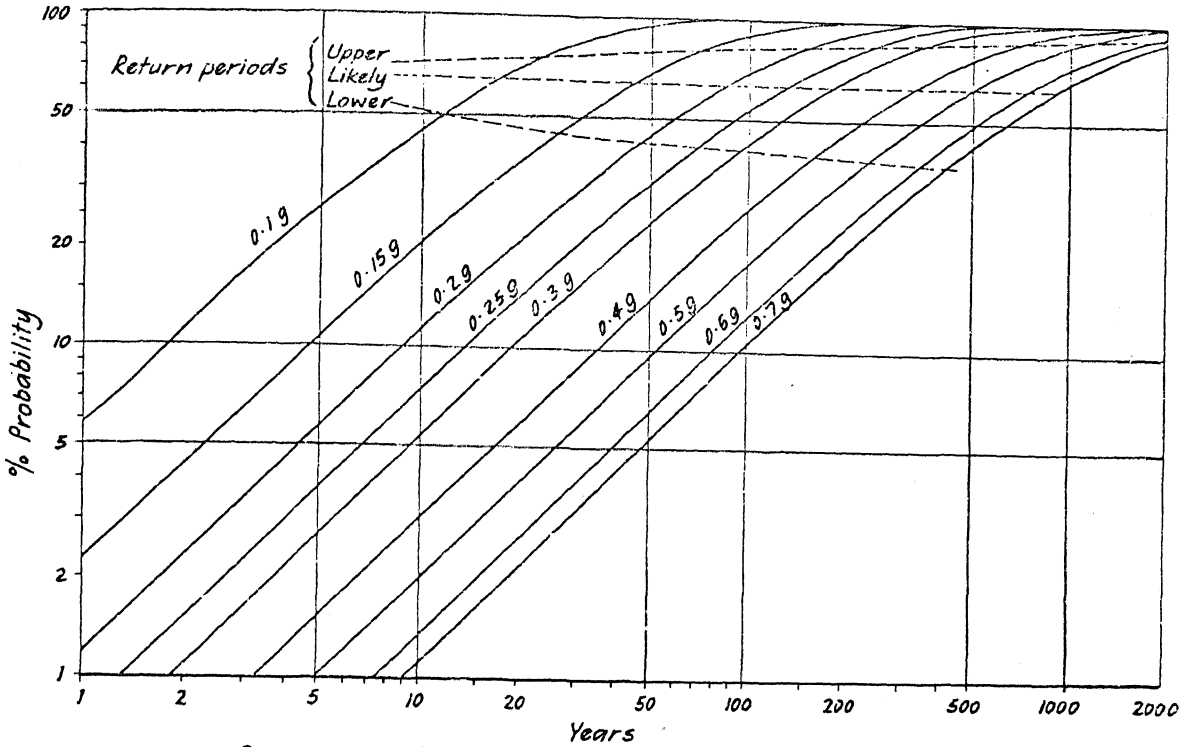

FIG. 11 Probability of occurrence of a given structural acceleration response within a given period of time on hard ground. (Period of structure = 0·65 secs.)

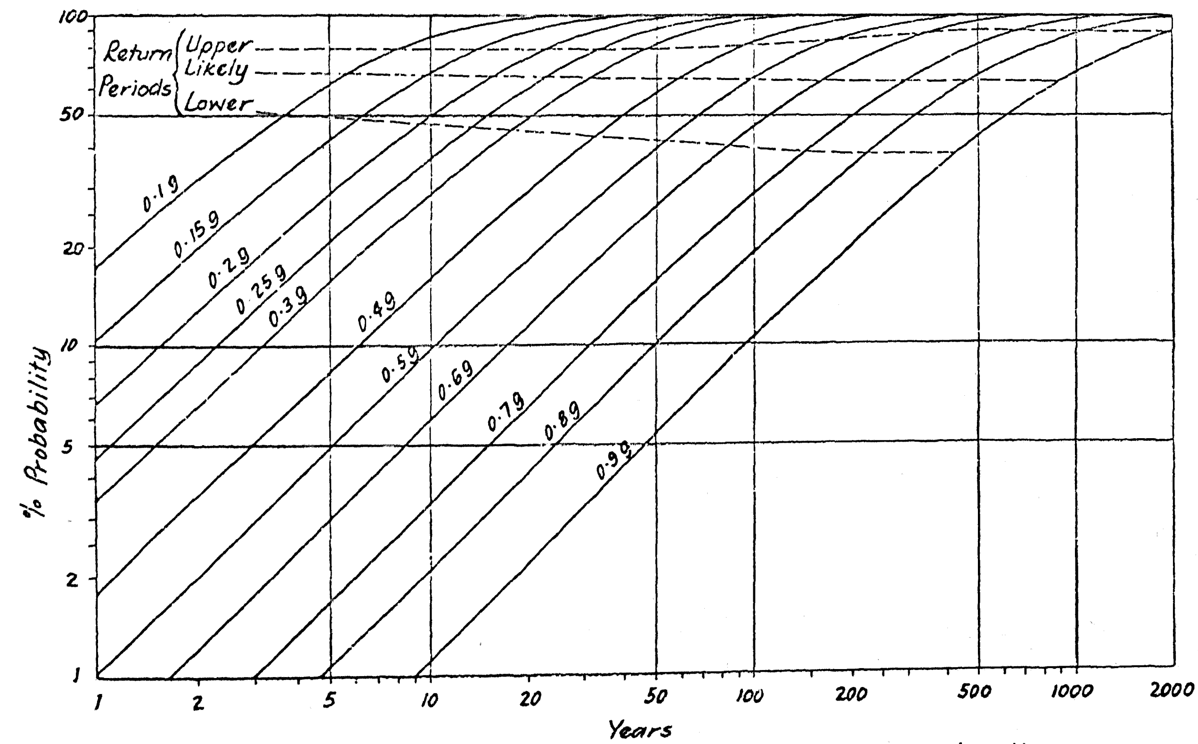

FIG. 12 Probability of occurrence of a given structural acceleration response within a given period of time on soft ground (Period of structure = 0·65 secs.)