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A NOTE ON CONTRIBUTIONS OF GROUND TORSION TO SEISMIC RESPONSE OF SYMMETRIC MULTISTORIED BUILDINGS

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SUMMARY

Torsional response of structures arising from the torsional component of earthquake ground shaking has been investigated and its relevance in the overall structural response has been examined. Earlier studies had emphasized the significance of torsional excitations without considering the effects of the phase difference between the translational and torsional components on the structural response. Expected values of the largest response peaks have been computed for the fixed-base, symmetric multistoried buildings by idealizing these as simple lumped mass models, and by using a stochastic approach for the analysis. By considering various buildings under the excitation of different earthquakes, dependence of the torsional contributions to total response has been studied for selected scaling parameters.

1. Introduction

Contributions of rotational components of the earthquake ground motion to inertial forces are currently ignored in the design of multistoried buildings. Gupta and Trifunac[3,5] have shown for the rocking component of acceleration that for certain types of ground motions and site conditions, such practice may cause underestimation of the lateral design forces. For the torsional component of ground acceleration also, it is necessary to verify to what extent the buildings are subjected to additional seismic forces. Though many investigations[1,2,6,7,10,11,12] have already been carried out to explore this possibility, most have been only approximate in describing the torsional contributions to the overall response. These attempts have consistently been based on the implicit assumption that the translational and torsional components of ground motion act in phase with each other. This may lead to conservative estimates of the relative torsional contributions because, as Lee and

Trifunac[8] and Trifunac[13] have shown, in case of ideal ground conditions, these components act orthogonal to each other at all the excitation frequencies. Moreover, most previous studies were based on very approximate characterizations of the torsional component(the actual recordings of the torsional component being unavailable) and did not account for the dispersive nature of seismic waves in layered ground. The model[8] used by Gupta and Trifunac[2], though it overcame some of these shortcomings, assumed straight line approximation[8] for the torsional to translational amplitude ratio, and thus may not properly represent some significant peaks in the torsional ground motion[5]. Previous studies have,nevertheless, given useful insight into the nature of torsional contributions, and have demonstrated the significance of building plan dimensions and shear wave velocity in the soil medium.

The purpose of this paper is to obtain a more realistic and improved assessment of the extent to which the overall response of fixed-base multistoried buildings may get modified, due to the inclusion of torsional component in the earthquake ground motion,vis-a-vis various input parameters.This does not include the additional effects of torsional vibrations resulting from the lack of coincidence between the centres of resistance and mass of the

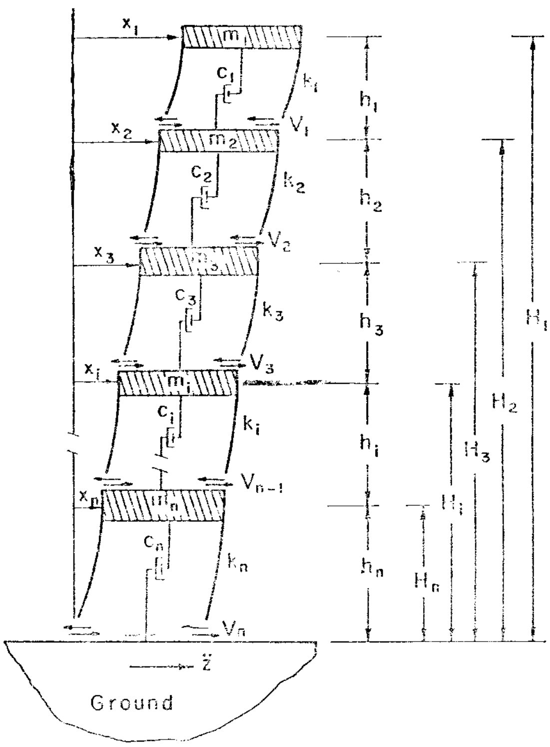

Figure 1 Multi-Degree-of-Freedom System for Translational Vibrations

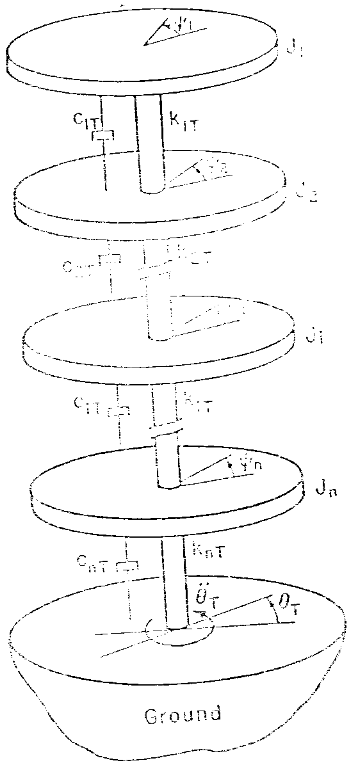

Figure 2 Multi-Degree-of-Freedom System for Torsional Vibrations

structure. Hence, only simple symmetric buildings have been considered in this study. These have been idealized by simple lumped mass models as shown in Figs. 1 and 2, and analyzed using a response spectrum superposition approach[3,4] which can admit the role of phase difference between ground translation and torsion, while assuming it to be independent of frequency (without noticeable loss of accuracy). It uses the similar ideas on representation of the torsional ground acceleration as proposed by Trifunac[13] and Lee and Trifunac[8], and already used by Gupta and Trifunac[2] in their study of the torsional response. However, no simplifying approximation has been made regarding the variation of torsional to translational amplitude ratio with period. Artificial accelerograms and related Fourier spectra are directly used for both rotational and translational components as given by the new SYNACC program[8].

This study has been carried out along the lines of the work proposed by Gupta and Trifunac[5] for the investigation of rocking contributions. By considering the synthetic records at example sites and several buildings with varying periods of vibration, the theoretical formulation[3,4] has been used to estimate the relative increase in the building response due to torsional component for a variety of situations. It has been shown that the torsional component contributes negligibly to the response of symmetric multistoried buildings, contrary to the earlier observations.

2. Example Buildings and Earthquake Sites

Response of 19 multistoried buildings with number of stories varying from 2 to 20 has been studied here. In each building, the floor masses and story stiffness values vary linearly from top to bottom(see Fig. 3)with their relative values so proportioned that the fundamental period of vibration of each building is 0.1 times the number of stories. The critical damping ratio is taken as 0.05 in all the modes (translational and torsional) of vibration. Each building has 25×100m floor dimensions at each story level and four symmetrically arranged columns at the corners. The column stiffnesses in the transverse and longitudinal directions are assumed to be same for same periods of vibrations in the two directions. Furthermore, in the calculation of torsional stiffnesses of various stories, the contributions resulting from the torsional stiffnesses of the columns about their longitudinal axes have been ignored(The torsional frequencies are, thus, approximately 1.73 times the translational frequencies as also observed[6] in the typical high-rise

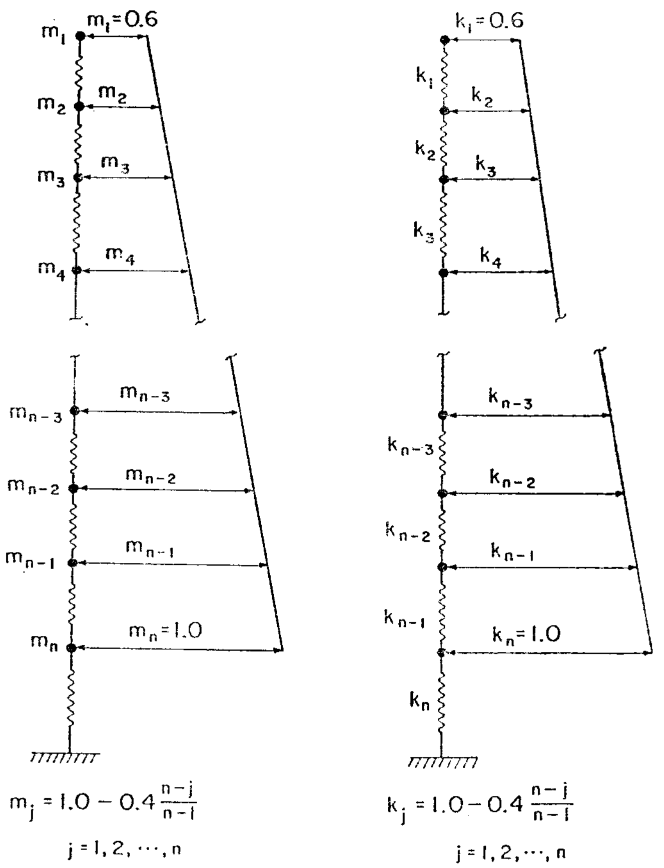

Figure 3 Story Stiffnesses and Floor Masses in a n-Story Building

buildings). Each building has been analyzed first for the translational component of ground motion and then, for the combined action of translational and torsional components. The phase difference between the translational and torsional components has been assumed independent of frequency[3,4], and taken as $\pi/2$ uniformly for all the excitations[8].

Various artificial records have been generated[8,14] for the translational and torsional ground accelerations in case of four example sites: i) Mexico City, Mexico, ii) Westmoreland, Imperial Valley, California, iii) Milikan Library, Pasadena, California, and iv) Hollywood Storage Building, Hollywood, California. Two soil models with different shear wave velocities, 40 and 80 m/sec, in the top layer, and identical otherwise have been considered in case of Mexico City. The shear wave velocities in the top layer for other sites are 1000, 185 and 230 m/sec respectively. Further details of the soil models for these sites may be found in References 3 and 8. The artificial records in case of Mexico City sites are based on the recorded translational(horizontal) motion during the 1985 earthquake, and 10 km "epicentral distance"; this distance is taken much less than the actual value(~400km)because the geological variations over such large distances lead to variations in the dispersion properties of the ground. Group and phase velocity curves computed for the given site conditions are thus applicable for short distances only. In case of Imperial Valley site, a hypothetical earthquake of 6.5 magnitude occuring at 15 km epicentral distance has been considered. The other two sites have been considered each for two types of excitations: i)Borrego Mountain, California earthquake of 1968, and ii) hypothetical earthquakes of magnitudes 5.5, 6.5, 7.5 and 8.5 occuring along San Andreas fault. For the Borrego Mountain Earthquake, respective epicentral distances are taken as 60 and 40 km (actual values are 220 and 240 km) for the same reasons as were applicable to the Mexico City sites; for the hypothetical earthquakes, these are taken as 40 and 50 km, corresponding to the actual distances of these sites from the closest locations on the fault. For hypothetical earthquakes, computed accelerograms have been assumed to have a confidence of not being exceeded equal to 0.5.

3. Results and Discussion

Response calculations have been carried out for each of the 19 example buildings, first for the translational component of ground motion and then, for the combined translational and torsional excitations. Expected values have been computed for the first order peaks of displacement and shear force at each floor of the building being analyzed. It may be noted that the torsional vibrations of symmetric buildings do not lead to any story shear and hence, to compare the translational and torsional contributions to the shear force in a column, story shear for the torsional vibrations is computed by multiplying the longitudinal shear in a column by the total number of columns. The so obtained "fictitious" story shear obviously varies from column to column. In the present study, however, this is not the case since all the columns are equidistant from the axis of rotation. For each of these two response functions(displacement and shear), the magnification factors Γ_i, $i=1,2,\cdots n$(due to the torsional excitation) have been computed by taking the ratio of the peak values for translational plus torsional excitation to those for the translational excitation alone. Since the variation of Γ_i with story level i is small, for each of the example buildings, magnification factors Γ have been obtained for the displacement and shear responses by averaging out the corresponding Γ_i's using the relation $\Gamma=\sum_{i=1}^{n}\Gamma_i/n$. These results have then been represented by the plots showing the variation of magnification factor Γ with the total number of stories n. Since, such plots for the displacement and shear are found to be very similar(as illustrated in Fig. 4 for the Imperial Valley

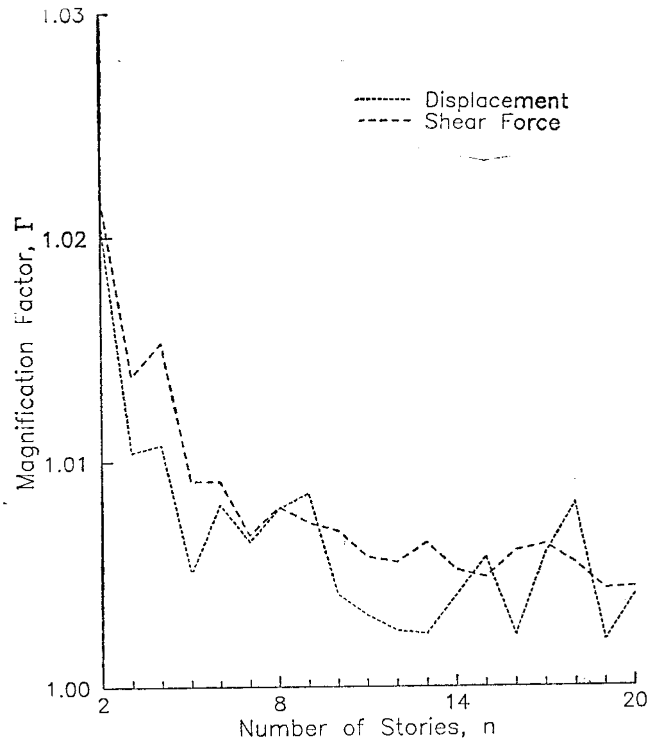

Figure 4 Magnification in Different Response Functions due to Torsional Component at Imperial Valley Site

site),all the subsequent results are presented here considering only displacement as the response function.

Following is the discussion on the effects of various input parameters on the magnification factor Γ. Here, it is important to note that though the torsional motion amplitudes are related to the translational amplitudes nearly in the same way as are the rocking motion amplitudes,[8,9] torsional frequencies usually are higher than translational frequencies for the typical multi-storied buildings[6]. Due to this, the buildings behave as comparatively more stiff in torsional response as compared to the response to rocking. Therefore, the conclusions in case of rocking contributions as presented by Gupta and Trifunac[5] may not prevail here.

i) *Transverse Dimension*:

Torsional contribution to the displacement of a column(in the longitudinal direction)is directly proportional to the transverse distance of column from the center of rotation which, for the example buildings, is one half the transverse floor dimension (equal to 100m as the translational component of ground motion is acting along the longitudinal dimension of 25m). Hence, an increase in the value of transverse dimension should result in greater torsional contributions. This has been illustrated by analyzing the example buildings for the transverse floor dimensions of 25 m and 50 m in addition to the 100 m dimension(the resulting variation in aspect ratio of the building floors will not affect the torsional frequencies here).Fig.5 shows for Mexico

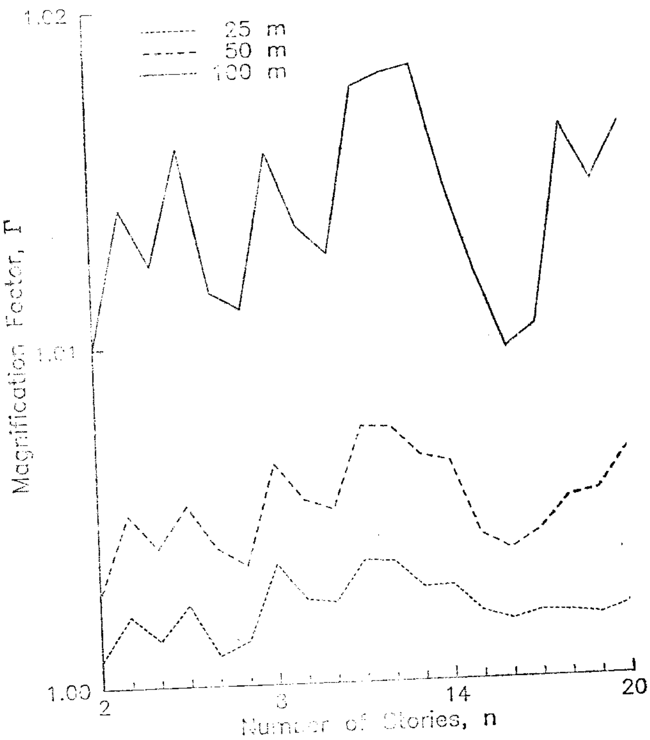

Figure 5 Effect of Transverse Dimension on the Torsional Contributions at Mexico City Site

City site (40 m/sec shear velocity) that an increase in transverse dimension indeed causes higher relative torsional contributions.

ii) *Earthquake Magnitude*:

To see how the earthquake magnitude may affect the torsional contributions, the Hollywood site has been considered for 5.5, 6.5, 7.5 and 8.5 magnitude earthquakes along the San Andreas fault. A comparison of the results for the magnification factor (see Fig. 6) suggests decrease in the relative torsional contributions with the increase in magnitude for most of the buildings; but the results differ so little from each other that it may be worthwhile to ignore the effects of magnitude variation on torsional contributions.

iii) *Concentration of Energy in Long Period Waves*:

Earthquakes associated with the concentration of energy in relatively

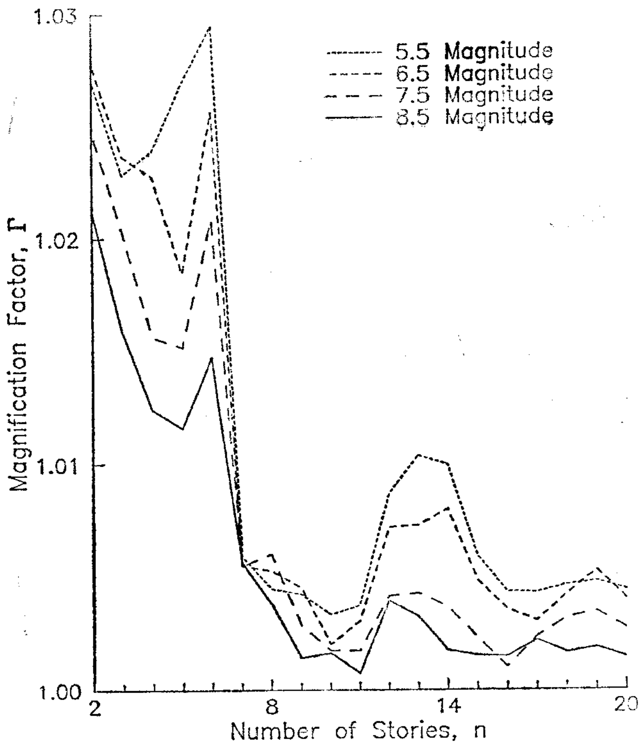

Figure 6 Effect of Magnitude on Torsional Contributions at Hollywood Site

longer periods cause larger contributions of rocking in some multistoried buildings[5]. This happens because the peaks in the rocking motion which usually occur at smaller periods as compared to the translational peaks, excite the typical multistoried buildings at their natural periods. To investigate whether the torsional contributions are also affected by the presence of high energy peaks at long periods in the translational spectra, the sites at Hollywood and Pasadena have been considered. The values of magnification factor Γ for the Borrego Mountain Earthquake have been compared with the magnification factors for the hypothetical, 6.5 magnitude earthquake along San Andreas fault(see Figs. 7 and 8). It is seen that in contrast to the observations for rocking component, Borrego Mountain earthquake does not generate higher torsional contributions. Rather in the case of Pasadena site, it is smaller for all the buildings.

Concentration of energy in the long period waves does not lead here to larger torsional contributions primarily due to the fact that torsional frequencies are not the same as the translational frequencies. Being higher by a factor of 1.73 approximately, they "compensate", to certain extent, the "shift" of the energy peaks to lower periods in the rotational spectra. In this situation, those buildings which respond to the highenergy peaks in the

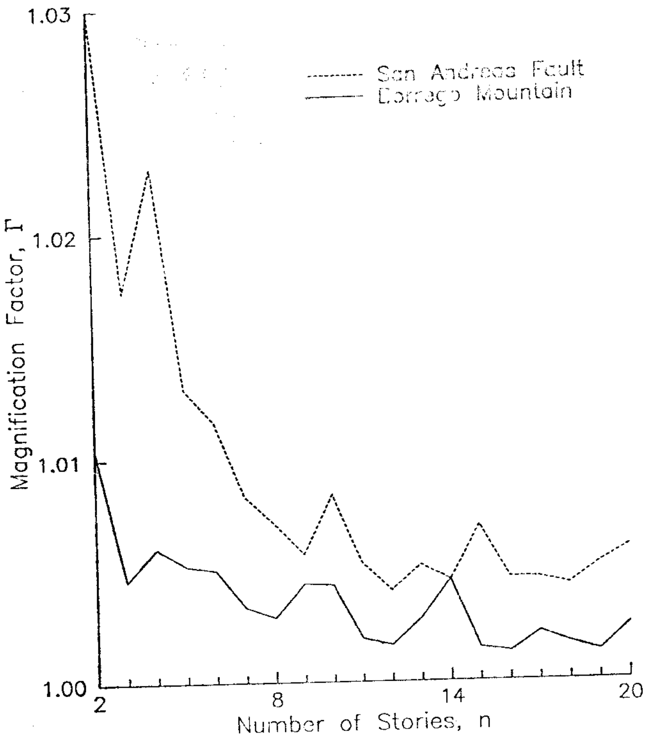

Figure 7 Effect of Concentration of Energy in Long Period Waves on Torsional Contributions at Pasadena Site

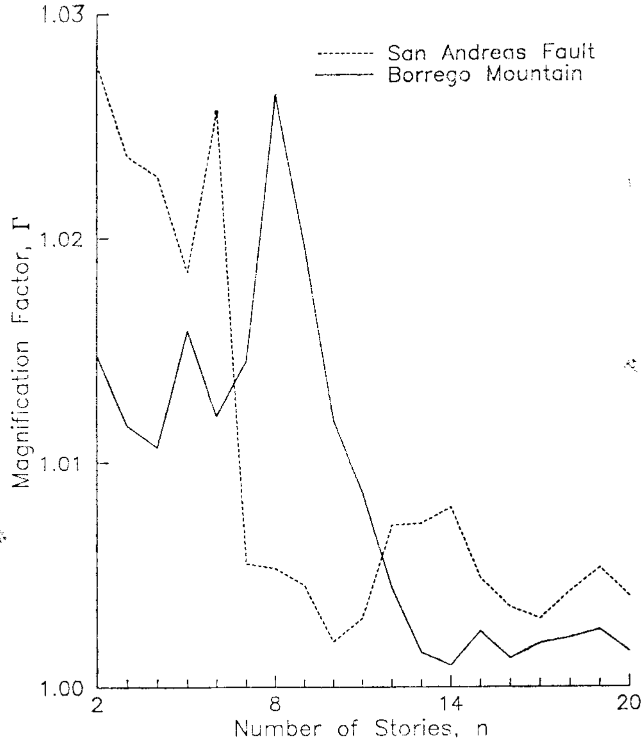

Figure 8 Effect of Concentration of Energy in Long Period Waves on Torsional Contributions at Hollywood Site

torsional spectra, also simultaneously experience the increased translational motion. In case of Pasadena site(Fig. 7), this compensation is nearly total and hence, the torsional contributions(for Borrego Mountain Earthquake)are smaller for all the buildings while for the Hollywood site(Fig.8),some buildings(with 7-11 stories) appear to have slightly higher torsional response. There, the shift of peaks in torsional spectra is comparatively higher and therefore, the compensation is not total. This suggests that in a case of hypothetical buildings where the torsional frequencies are almost the same as the translational frequencies, dominance of long period waves may turn out to have more significant effects on the torsional contributions. To illustrate this, same 19 buildings(as considered before) are taken with the floor dimensions changed to 150 m(longitudinal) × 100 m(transverse), and column stiffness in the transverse direction taken as 0.04 times that in the longitudinal direction, and are analyzed for the same two earthquakes at both the sites. The results are compared in Figs. 9 and 10, from which it is observed

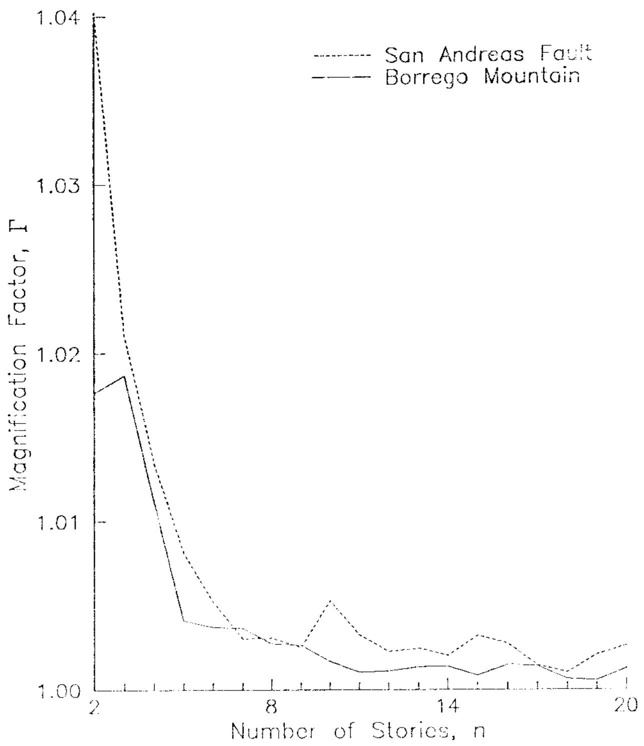

Figure 9 Effect of Concentration of Energy in Long Period Waves on Torsional Contributions at Pasadena Site(Fictiticus Case)

that the difference between the two curves now is much smaller in case of Pasadena site while in case of Hollywood site, torsional contributions due to Borrego Mountain earthquake are slightly larger.

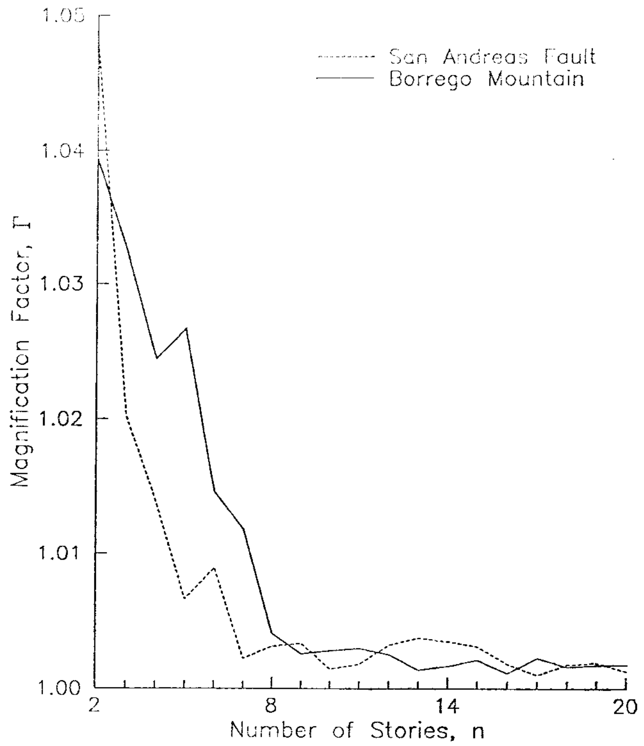

Figure 10　Effect of Concentration of Energy in Long Period Waves on Torsional Contributions at Hollywood Site(Fictitious Case)

iv) *Minimum Shear Wave Velocity*:

The torsional to translational amplitude ratio is inversely proportional to the phase velocity of waves at a given period[8]. For significant periods of interest, this in turn depends on the minimum shear wave velocity, β_{min} in the soil stratum(usually in the top layer)for various modes. Lower is β_{min}, greater will be the torsional amplitudes in the ground motion. To illustrate the effects of variation in β_{min} on the torsional contributions to the overall response, both Mexico City sites have been considered. Magnification factors Γ have been computed and compared for these two cases as shown in Fig.11. It is observed from the figure that the increased value of β_{min} does not necessarily result in decreased torsional contributions for all the buildings as was the case with rocking contributions. Relatively higher amplitudes in the torsional spectrum(for softer ground conditions)here do not cause greater torsional contributions for all the buildings because the ratio of torsional amplitudes to the translational amplitudes is smaller (one half of that for rocking amplitudes) and also, the compensation for the shifting of peaks is different in the two cases.

The preceding results show that in the example earthquakes taken for

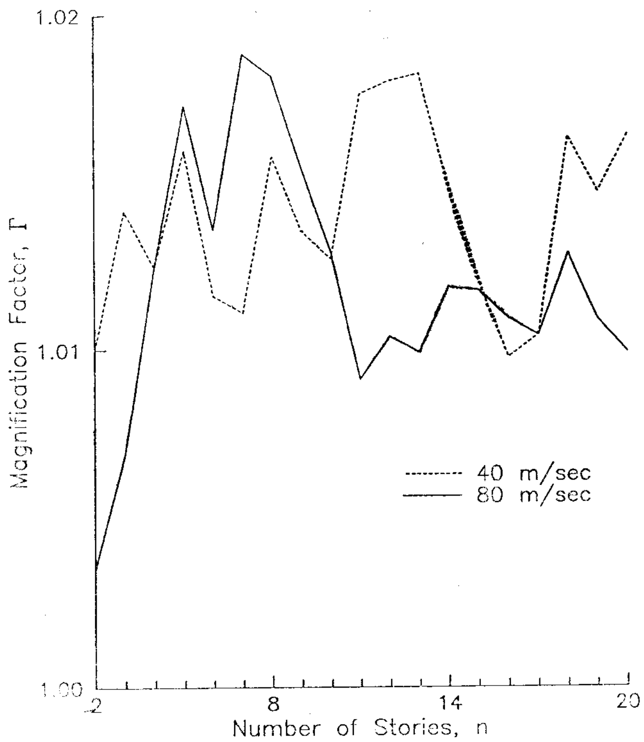

Figure 11 Effect of Minimum Shear Wave Velocity on Torsional Contributions

the study here, torsional component contributes little to the overall response of the typical multistoried buildings. This is contrary to the observations of Gupta and Trifunac[2] based on a similar analysis approach. For a simple three story building(fundamental translational and torsional frequencies being 14.5 rad/sec and 21.6 rad/sec respectively) with floor aspect ratio = 5, and β_{min} = 350 m/sec in the ground, they observed approximately 11% increase in the maximum displacement response due to torsional motion. A parallel case in the present analysis shows, however, less than 1% increase. The approach of Gupta and Trifunac[2] consists of linear combination of the individual responses of translational and torsional components which corresponds to zero phase difference between these components, and is, thus, based on the assumption that the maxima for these components occur at the same time. Present results are, however, based on $\pi/2$ phase difference, for which the vectorial addition in case of 11% increase, should correspond to just 0.6% increase which is of the same order as observed in this study. The estimates of Gupta and Trifunac[2] on relative torsional contributions thus appear to be on the conservative side.

4. Conclusions

This study has shown that the torsional component of ground motion contributes little to the overall response of the typical multistoried buildings. Earlier studies emphasized greater significance of this component as they apparently combined the individual responses of translational and torsional components in a conservative manner, to obtain the building response to the combined excitation of these components.

For the range of buildings and types of earthquakes studied here, following conclusions are made:

1) Contribution of the torsional component rises with the increase in lateral dimensions of the buildings.

2) Earthquake magnitude has negligible effect on the extent of relative torsional contribution to response.

3) For a particular earthquake, it is important to know how much the high energy peaks of the translational motion are shifted in the torsional spectrum. This, along with the ratio of torsional to translational frequencies, has been observed to be an important criterion in determining the extent of relative contribution of the torsional component. If the amount of shift is closer to the ratio of frequencies, smaller contributions are likely. This applies to the typical earthquakes having energy well-distributed amongst various frequencies. For the earthquakes with two or more "pockets" of energy, further investigations are necessary. The parameters governing the amount of shift of the peaks also need to be identified.

4) The buildings situated on softer grounds may not necessarily receive larger contributions from the torsional component like rocking component and as pointed in the earlier studies, because for certain buildings, the effects of greater amplification associated with softer grounds (which are less compared to rocking[8,9]) may be compensated by the effects of relative shift in the high energy peaks for the two cases.

Above conclusions are based on the assumption that the buildings are supported on the rigid foundation. In case of flexible foundations, soil-structure interaction may amplify the relative torsional contributions[10]. Then, natural periods of the system are reduced and the foundation rotates in the vertical plane due to rotational yielding of the supporting soil medium. Further, the ratio of torsional to translational natural frequencies may also change. It is necessary to examine the conclusions of this study in separate efforts for such interaction effects.

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地面扭转对多层对称建筑地震反应的影响

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提　　要

研究了地震动扭转分量引起的结构扭转反应并分析了其与整个结构反应的关联性。早先的研究曾经强调扭转激扰的重要性，但并未考虑结构反应的平移与扭转分量之间的相位差的效应。将固定基底的多层对称建筑理想化为简单的集中质量模型并采用随机的分析方法计算了最大反应峰值的期望值。通过考察在不同地震激扰下的各种建筑物，针对选定的一些标定参数研究了扭转作用对整体反应的相关性。