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論　文　内　容　要　旨

The application of the increased body of knowledge and understanding about the earthquake phenomenon, to the mitigation of the hazard posed by it to mankind, is the single most important benefit that the society can derive from the earthquake research. As the present understanding of earthquake phenomenon is not amenable to accurate forecasting of individual events in terms of place, size, and time, we are primarily concerned with the long term protection against the earthquake hazard. Seismic zonation and microzonation represent the specifications for the long term protection against earthquake hazard in recognition to, respectively, the regional and the local variations in the earthquake damage potential, based on the up-to-date knowledge and understanding of the earthquake phenomenon.

This dissertation is concerned with the investigation of the local variation in the extent of ground shaking considering different levels of regional earthquake hazard, and the representation of the results in the form of seismic microzonation. The primary drive is on aspects related to the existence of ground nonlinearity during severe excitation by large earthquakes, considering the influence of the level of excitation, and the spectral content, particularly long period components, of the incident motion. Following the nature and the sequence of the different aspects of investigation carried out, the dissertation as a whole is organized into two *Parts.* The first *Parts* is concerned with the specific investigations, and second presents a microzonation case study incorporating the results of the first *Part.* Of the seven *Chapters* comprising the dissertation, *Chapter* 1 is concerned with the background and the rationale behind the research, and *Chapter* 7 presents the conclusions. Of the intervening five *Chapters,* the first three and the latter two constitute Parts I and II respectively.

Chapter 1 : Introduction

This *Chapter* deals with the background and the rationale behind the reseaech carried out as part of this dissertation. In this connection, extensive review of the existing literature is also presented. The overall sequence in the different stages of the research that constitute different *Chapters,* and the structural organization of the dissertation, is also discussed.

Chapter 2 : Response to White Noise Type Input Motion

This *Chapter* deals with the effect of the increase in the level of excitation on the amplification of incident motion, ground period elongation, and the response spectra of surface response for different site conditions. For this, the free field nonlinear ground response analysis was carried out for a large number of sites, using the geotechnical database system developed for seismic microzonation study of the central part of Tokyo.

The predominant period of site during the nonlinear response, arrived at from the transfer function analysis, indicate that the natural ground period becomes longer due to nonlinear behavior as the level of excitation increases. At low level of excitation, the predominant period of ground response clearly shows a linear relation with the fundamental ground period T_G, arrived at based on the initial shear modulus considering a discrete dynamic model. The predominant period becomes substantially longer as the level of excitation increases.

Maximum acceleration ratio between surface and base layer is seen to decrease with the increase in the level of excitation, as a result of increased nonlinearity, the effect being dominant in softer sites. The effect of ground softness on the response spectra characteristics is well recognized. The results of this investigation clearly indicate that, additionally, the response spectra at a site also depend on the level of excitation. This in essence brings about the need to consider the excitation dependence of the response spectra in addition to the site dependence. The investigations in this *Chapter* strongly indicate that the level of excitation approaches an *independent variable* in the seismic response of softer sites.

Chapter 3 : Response to a Suite of Scaled Ground Motions

This *Chapter* deals with the nonlinear response to a suite of scaled ground motions with significant variations in the frequency and phase content that can be expected in ground motions, depending on source, fault mechanism and transmission. Noting the need in seismic microzoning to consider different levels of excitation, and the need for mapping stable site effects adequately encompassing the potential severity of future earthquakes, a comparative suitability of selected methods of scaling a suite of ground motions is investigated. Four scaling parameters, with varying degrees and types of energy representation: peak acceleration, peak velocity, rate of energy input, and Housner's spectrum intensity (SI), are selected, and their relative suitability is compared based on the compatibility in the extent of nonlinearity during response history. The parameter *modulus reduction ratio* λ was defined and utilized as the indicator of the extent of nonlinearity.

Of the four parameters selected for relative comparison, the Housner's SI is seen produce most compatible nonlinear response in case of intermediate site conditions (T_G range 0.2 to 0.75 seconds). Housner's SI and peak velocity produce comparable compatibility in case of soft sites, with peak velocity faring slightly better. The compatibility is seen to significantly improve when the spectrum intensity, defined in a period band adequately extented to account for the ground period elongation, was used. Peak acceleration seems to be appropriate for stiff sites with T_G less than about 0.2 seconds, where the extent of nonlinearity is small. The rate of energy input, which is a measure of energy content in the time window of strong shaking, with no regard to energy distribution in different period bands, is noted to be unsuitable as a scaling parameter.

Spectrum intensity amplification (*SIA*) is proposed as an adequate indicator of whether there will be a concentrated damage potential to a certain range of structures at a site, and is considered a suitable parameter for microzonation. The concept of limited band spectrum intensity (LBSI) is suggested for this purpose. When the input ground motions are scaled by spectrum intensity, the predominant period of ground during the nonlinear response show fairly low coefficient of variation, again indicating compatibility in the extent of nonlinear response. In addition, the average spectrum intensity of surface response is comparable to the spectrum intensity of surface response due to the target ground motion. This is an indication that the intensity of surface response to the target input motion is, on the average, comparable to the mean intensity of surface motions due to scaled input motions. In addition, the average spectrum intensity of surface response is comparable to the spectrum intensity of surface response due to target ground motion. This is an indication that the intensity of surface response to the target input motion is, on the average, comparable to the mean intensity of surface motions due to scaled input motions.

Chapter 4 : **Influence of Long Period Components**

This *Chapter* is devoted to the investigation of the influence of long period components in the incident motion on the nonlinear ground response. Although uncertainties abound in the correct assessment of the period band in which the seismic energy of a potentially destructive future earthquake would be concentrated, the proportion of the energy in long period range is believed to increase with the size of the earthquake. Considering observations in the preceding *Chapters* that the soft sites undergo large elongation in ground period at increased level of excitation, the presence of long period components in the incident motion can be a destructive consequence. The results of the investigation indicate ample evidence of the increasingly dominant role of the long period components in nonlinear ground response.

For stiff site conditions, where the effect of soil nonlinearity is small, only *primary* effect marked by the appearance of long period spectral ordinates at the ground surface response waves, corresponding to the respective incident waves, can be noted, with very insignificant effect on the maximum surface acceleration. For soft site conditions, the so called *secondary* effects develop as a result of the increased extent of nonlinear excitation, with consequent substantial elongation in ground period, as the long period components increase in the incident motion. Thus the soft sites tend to amplify further the already large long period components in the incident motion. There is clear evidence that the presence or absence of the long period components can be detrimental to the extent of nonlinear excitation the soft sites receive.

The maximum surface response acceleration at soft sites increase with the increase in the long period components in the incident excitation, as a result of the increased nonlinear response and consequent amplification of long period components. In contrast, the maximum surface response acceleration at stiff sites remain practically unaffected.

The spectral characteristics of the surface motion at stiff sites are affected little by the presence of long period components, except for the *primary* effect. In contrast, the response spectra of surface motion at soft sites indicate substantial *secondary* effects. The *secondary* effects are marked by larger spectral ordinates at longer periods, as the long period contents in the incident motion increase. In addition, there is larger spectral response at short period corresponding to the higher maximum acceleration noted above.

The deficiency of short period components in the incident motion has little influence on the nonlinear ground response. The deficiency in the long period components, however, results in reduction in the extent of nonlinear excitation, as well as in the maximum surface response acceleration, in case of soft sites. This is a clear indication that the long period components in the incident earthquake motion can influence the surface acceleration observed at soft site condition, causing larger peak surface acceleration in spite of the larger extent of nonlinearity.

Chapter 5 : Incident Motion Response Spectra

This *Chapter* is the first of the two chapters in *Part* II and is concerned with the detailed investigation for the characterization on the three levels of incident motion, defined as *frequent, medium,* and *extreme* levels, applicable to seismic microzonation case study of Sendai. Attempt has made to compile diverse pieces of information in the subject areas of seismology, geotechnical engineering, and earthquake engineering, to develop a *methodology* for the characterization of incident motions in terms of response spectra. One of the primary concerns in this process has been the adequate representation of long period components. For this, the empirical Green's function method is utilized for the prediction of large earthquakes from the records of small earthquakes.

The three response spectra representing the *frequent, medium,* and *extreme* levels of earthquake occurrence expectancy in Sendai are utilized to generate response spectra compatible incident motions. The two stage iterative scheme, first in frequency domain and then in time domain, is utilized for the generation of the response spectra compatible incident motions. Whereas the *methodology* developed and utilized in this *Chapter* has specific purpose of microzonation case study, it is nevertheless amenable to most general applications, constrained with the availability of suitable database.

Chapter 6 : Response Analysis and Seismic Microzonation

This *Chapter* presents a case study on seismic microzonation considering soil nonlinearity and the level of excitation. Sendai is taken up as the case study urban area, and the *frequent, medium* and *extreme* levels of incident motions developed in *Chapter* 5 are utilized for this purpose. Two sources of geotechnical informations, one comprising of the collection of past borehole records, and the other from the recording stations of the Sendai dense array system, have been utilized. The three levels of the incident motions are considered to represent the corresponding levels of seismic hazard, and the nature of ground shaking hazard at different site conditions are discussed.

The site dependent, and the level of excitation dependent, response spectra of surface response motion are developed, and their characteristics discussed. The site dependent response spectra are compared with the response spectra of incident motion at the exposed base layer, from which it is illustrated that there is remarkable shift in the influential period band towards long period range as the extent of nonlinear response increases. Spatial distribution of the ground types, where the respective site dependent response spectra are applicable, is also presented in the form of color coded map.

The site dependent nature of the spectrum intensity amplification (SIA), proposed in *Chapter* 3 as a potentially suitable parameter for seismic microzonation, is presented. Some cases of the spatial variations of SIA are plotted on the map, and a case study on the suitability of SIA, in adequately representing the ground shaking hazard, is illustrated by comparison with observed damage patterns. Considering that the ground shaking aspects of seismic hazard tends to dominate most of the earthquake damage patterns worldwide, the proposed method of suitably representing it in the form of seismic microzonation is significant.

The trend in the extent of the ground nonlinearity at different site conditions is investigated in terms of the modulus reduction ratio, another parameter proposed in *Chapter* 3 for this purpose. Some case studies on the spatial variation of the site dependent nonlinear site effects are also presented. Overall, *Chapter* 6 illustrates the suitability and credibility of the results of investigations made in *Part* I. In addition, a naw direction in the method of accounting for the site dependent nature of the ground nonlinearity, in the assessment of ground shaking hazard, has been initiated.

Chapter 7 : Conclusions

This *Chapter* presents the summary of findings of the investigations carried out in this research, outlining the concrete results chapter-wise, together with their implications to seismic microzonation. Considering the broad and interdisciplinary nature of the aspects involved in seismic microzonation, and the potential relationship of these aspects with the nonlinearity and level of excitation in ground response, the possibilities for the extension and continuation of the research initiated as part of this dissertation are virtually limitless. Attempt is made in this *Chapter* to point out some of the immediate continuation possibilities. A short note on the future directions in the seismic microzonation is also presented.

審 査 結 果 の 要 旨

地震動は地盤の影響により場所によって異なる特製を示し，生じる地震被害もそれに左右されることが知られている。このために個々の地盤の性質を踏まえて将来の地震動の性質を表現しようとする地震マイクロゾーネーションは，都市地域の地震災害およびその対策を検討する場合に必要となる。特に，軟弱な地盤を中心として入力地震動のレベル設定とそれにともなう非線形応答性状の評価が重要になるが，これについて未だ系統的研究はなされていない。本論文は，地盤の非線形応答性状に及ぼす要因を非線形応答解析手法を用いて明らかにし，これを都市地域の地震マイクロゾーネーションに反映させる方法を開発したもので，全編7章よりなる。

第1章は序論であり，本研究の背景，目的について述べ，あわせて関連する既往の研究を整理したうえで本研究の意義を明らかにしている。

第2章では，入力地震動レベルの増大に伴う地盤の非線形応答性状の特徴を，東京都心部の地盤データを用いて白色性人工地震波に対する非線形応答解析により検討し，特に軟弱地盤では非線形性により応答特性に顕著な変化が現れることから，応答評価にあたって入力レベルを独立変数として考慮すべきことを示している。

第3章では，前章を受けて，非線形応答を扱う際の入力レベルの指標について検討し，様々な特性を持つ多数の入力波を同等な非線形応答を生じさせるようにスケーリングするために，スペクトル強度（SI）が適することを示している。また新たにSI増幅率および帯域制限SIの考え方を提案し，これが軟弱地盤における強い非線形効果の考慮や，特定の周期を持つ構造物群の被害推定に有用であることを示している。

第4章では，入力地震動の周期特性，特に長周期成分が非線形地盤応答に及ぼす影響について検討し，軟弱地盤で長周期成分の影響が著しいことをを示している。

第5章では，第2～4章に基づき，マイクロゾーネーションを行うにあたっての入力スペクトル設定方法について検討し，仙台地域におけるケーススタディを行っている。

第6章では，前章までの成果を基にして，地盤の非線形特性と入力のレベルを考慮した地震マイクロゾーネーション手法をまとめ，仙台における評価例を通じてその妥当性を示している。

第7章は結論である。

以上要するに本論文は，非線形地盤応答に及ぼす入力のレベル及び周波数特性の影響を，多くに実在地盤データと非線形応答解析手法を用いて詳細かつ系統的に検討し，特に軟弱地盤の非線形性状を適切に評価する各種方法を明示したうえで，その結果を用いて都市地域における地震マイクロゾーネーションを行う手法をまとめ，仙台におけるケーススタディを通じてその有効性を示すとともに耐震防災上有用な種々の示唆を与えたもので，建築構造学，耐震工学ならびに都市防災工学の発展に寄与するところが少なくない。

よって，本論文は博士（工学）の学位論文として合格と認める。