Dynamic Response of Structures Considering Cross-Interaction Subject to Random Incident Waves(ランダム入力波の条件下におけるクロスインタラクションを考慮した構造物の動的応答)

著者	Farhad Behnamfar
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氏　　　　　名	ファルハド・ベナムファル Farhad Behnamfar
授　与　学　位	博士　（工学）
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研究科、専攻野名称	東北大学大学院工学研究科 （博士課程）建築学専攻
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指　導　教　官	東北大学教授　杉村　義広
論文　　審査　委員	東北大学教授　柴田　明徳　東北大学教授　山田　大彦 東北大学助教授　栗田　哲　東北大学助教授　源栄 正人

論 文 内 容 要 旨

CHAPTER 1. Introduction

One of the different aspects of the earthquake engineering is soil-structure interaction (SSI). Out of various problems attributed to SSI, this study is concerned mainly with answering the question how the dynamic response of a structure subject to earthquake excitation varies due to cross-interaction, i.e., when there is another structures near the one under investigation. The effect of spatial variation of ground motion is also taken into account for the definition of the ground motion input to the structure.

Early attempts to deal with the SSI problem from a structural engineering view of point goes back to 1970's when the first analytical solutions were given for the problem of vibration of a circular foundation on the surface of a homogeneous halfspace. Since the finite-element technique was already in a state of maturity at that time, naturally it was used afterwards by many researchers to deal with more difficult problem like irregular footings and sites as well as embedded foundations. The boundary element method came second, to which the experience of researchers with finite element method was a precious resource. This method attracted many because it reduced size of the problem by one order. It was dealing only with the boundaries, hence its name, contrary to the finite element that was a method with which one had to assume elements inside the volume also to analyze the system. Recently attention of researchers working on the soil-structure interaction problem has been mainly concentrated on improved models of ground, more advanced theories for wave propagation in different soils, experimental works, and so on.

While it seems that much more research is needed toward upgrading the theoretical models of soils and foundations, applicablity of the analyses methods to response of real structures is something with equal if not more importance. Considering this fact it is concluded that a more detailed study on the response of structures themselves, resting on flexible soils seems to be necessary. Especially, as the recent studies on adjacent foundations has been revealing, cross-interaction of structures under spatial variation of the earthquake ground motion in a deterministic or random pattern has to be investigated in detail. This has been the motivation behind the research presented in this thesis.

CHAPTER 2: Analysis of Single and Multiple Surface Foundations

Dynamic behavior of foundations resting on the surface of soil was analyzed in this chapter. Many different cases were taken into account including sites consisting of a surface layer with various depths on top of a halfspace, and two surface foundations with their distance variable. The weighted residual technique was used to construct the dynamic stiffness matrix of the foundation, a matrix that is needed in soil-structure interaction analysis. Then two approaches were adopted to analyze the dynamic response of the foundation: the deterministic method and the random method.

With having the first approach, use was made purely of the classical wave propagation theory while in the second approach some devise was used to simulate the real random variation of ground motion in space. A tangible difference between the two approaches is that with the random one, even for vertical propagation of shear waves the amplitude of ground motion varies from point to point on the ground surface. The random approach was extended in this study so that analysis of incidence of surface waves as well as inclined incidence (horizontal propagation) of body waves could be taken into account. Based on the numerical analyses done, it was inferred that cross-interaction effects on the dynamic stiffness coefficients of surface foundations are important as far as the ratio of the distance between foundations to width of them does not exceed a value 3. Also a surface layer can be looked upon as a halfspace when analyzing a surface foundation if ratio of the depth of the layer to the foundation's width is less than 5. It was also observed that in most cases from medium frequencies onward response calculated with random approach was dominant. In this respect, angle of incidence of the body waves was also shown to play an important role in the foundation's response, so that in many cases for incidence angles less than 60 degrees the random response was governing.

CHAPTER 3: Analysis of Single and Multiple Embedded Foundations

In this chapter the case of foundations placed in a depth inside a layered halfspace was studied. The dynamic stiffness matrix of single or group foundations was derived using the general principles of elastodynamics, namely, the dynamic reciprocity theorem and the representation theorem. These principles were used in association with the indirect boundary element method to detour the numerical difficulties corresponding to direct boundary element method. It was shown that there were still difficulties when calculating the Green's functions for an embedded foundation when using the conventional equations. A remedy was derived to overcome those difficulties with considering the asymptotic behavior of the functions involved. This way, it became possible to calculate the system both for large wave numbers and frequencies. It was shown that embedding a foundation in the soil has considerable increasing effects on its rocking stiffness coefficients. Also the contact quality of the sidewalls of the foundation with the soil was studied. It was shown that the effects arised in medium and high frequency range were completely different from those in the low frequency range, so it is necessary that the contact condition is investigated with regard to the frequency range of interest to assess an embedded foundation. For the case of double embedded foundations, a distance ratio of 3 was proved to be the upper limit for taking the cross-interaction into account. For smaller distances, in contrast to surface foundations, sharp variations were seen in the values of stiffness coefficients as the two foundations tended to behave like a single one especially for the horizontal degree of freedom. Another topic of study in chapter 3 was the dynamic response of embedded foundations. In the conventional indirect boundary element method it is an inevitable drawback that stiffness matrix and response vector of an embedded foundation are calculated succesively in two separate steps because the geometry of the problem has to be changed from one step to the other. In the first step the fictitious loading surface is offset from the soil-foundation interface but in the second step they are the same. In this study using the concept of boundary integral equation method a new equation was derived that resulted in streamlining the indirect boundary element method when analyzing the dynamic response of embedded group foundations. Using this new equation now it is possible to calculate the stiffness and response vector in one step that is a great reduction in computation time of calculation with the indirect boundary element method. It was shown that the horizontal response of an embedded foundation is larger with deterministic approach but the random rotational motion shows higher values for low frequencies. So, the overall lateral response of foundation taking into account its rocking response can be larger with the random approach. As for effects of sidewall contact on the response, a poor contact proved to be on the unsafe margin only for medium to high frequencies, showing negligible effects for low frequency range. Remarkable increasing effects were seen when evaluating random response of double embedded foundations under vertically propagating shear waves that underlined the importance of cross-interaction between embedded foundations.

CHAPTER 4: Single Structures Subject to deterministic Wave Passage

A single structure resting on the surface of a halfspace through a circular rigid basemat was investigated. Some eccentricity between centers of mass and stiffness in the plan of the building was considered. The main emphasis was to evaluate the respected effects on the lateral motion of the building under various degrees of eccentricity and different types of waves. It was shown that the main part of the torsional response was associated with incidence of SH-waves but SV and R-waves also exhibited considerable contributions in torsional response when there was eccentricity in the plan of the building. It was seen that almost always lateral and torsional motions at the center of building's floor showed their maximum absolute values at the same time or frequency, i.e., were 180 degrees out of phase, resulting in considerable differences between lateral displacements of laterally stiff and soft sides of the building. Torsional effects of P-waves on eccentric buildings shown to be of more importance for lighter structures. Incidence of shear waves with lines of incidence near to horizontal proved to be having more increasing effects on the torsional response of an eccentric building.

CHAPTER 5: Earthquake Wave Passage on Multiple Structures

In this chapter deterministic and random wave passage effects on dynamic response of single or multiple, surface or embedded structures were examined. Four cases of multistory buildings differing in number of stories from 2 to 20 and a case of a massive reactor building were taken into account. For the sites consisting of a halfspace, single structures on the surface and under incidence of Rayleigh waves and vertically propagating shear waves were studied. It was observed that even for stiff soils, incidence of Rayleigh waves was associated with an increase in the lateral response of high-rise buildings due to an extra rotational input compared with vertical incidence of shear waves. The random approach proved to give more reliable results especially with Rayleigh waves when the deterministic theory gave unreasonably high values for the response of the systems. Inclined approach of the body waves also was investigated. It was seen that this could amplify the lateral response of the systems considered by an amount of about 15%. Increasing the value of the spatial coherence parameter proved to have an increasing effect on the response of the structures studied. Also a case of existence of a surface layer on the top of halfspace was examined. It proved to increase the lateral response by about 15% compared to the case of halfspace site. The effects of cross-interaction of buildings were investigated also. The results of the analysis of this section again showed that random approach was a more reasonable theory to calculate the response of buildings to earthquakes. Moreover, it was seen that cross-interaction of buildings regardless of the approach was used, had important effects on the response of the structures. For multistory buildings, the effect was of increasing type for buildings up to a medium height. But for high rise and reactor buildings, cross-interaction tended to decrease response of the system both to vertically propagating shear waves and also surface Rayleigh waves. Embedment of structures in the ground was shown to have remarkable effects on their response. It was seen that the random approach results in response trends consistent with past experimental results. Using the deterministic approach responses of the embedded system surpassed those of the surface system. In the random approach, both for vertically propagating S-waves and horizontally propagating Rayleigh waves there was a decrease in the response. This response was not sensitive to the distance between adjacent foundations under shear waves but showed larger values for closer foundations under Rayleigh waves. Also, compared to single structures, resonance frequency of the system increased for adjacent structures.

CHAPTER 6: Conclusions

In this study an investigation on some problems associated with dynamic soil-structure interaction phenomenon was presented. The main emphasis was on applying theory of spatially random wave propagation on dynamic analysis of soil-structure systems and variation of dynamic response of structures when they are adjacent to each other, the so-called "cross-interaction" problem. It was shown that assuming a certain level of incoherency in the ground motion is needed to have realistic response values of the adjacent structures especially under incidence of surface waves. Also, cross-interaction of structures can increase or decrease their response dependent on their distance. This is a very important factor when analysing adjacent structures for earhquake ground motion.

審査結果の要旨

地震時における構造物の応答は隣接する他の構造物の応答の影響、いわゆるクロスインタラクションの影響を受ける。また、それらの位置が異なれば、入力地震動の確定的な位相差による空間変動ばかりでなく確率的な空間変動（ランダム入力）を考慮する必要がある。しかし、建物の耐震設計ではこれらの要因は考慮されていないのが現状であり、今後、設計の精度を高めるためにはこれらの要因を解明し、適切に導入することが望まれる。本論文は、このような観点からランダム入力波の条件下におけるクロスインタラクションを考慮した構造物の動的応答の解明の糸口を見出そうとしたもので、全編6章からなっている。

第1章は序論であり、関連する既往の研究を概括した後、論文の研究目的について述べている。

第2章では、均質半無限弾性体上に表層とその上に基礎が存在する場合を想定し、動的剛性をグリーン関数に基づいて可能な限り厳密な構成則を適用して求めている。その際、表層の深さ、入力波の型、構造物の隣接距離など、新しいパラメータを導入して検討している。その結果、隣接距離が基礎幅の3倍以内であると隣接構造物の影響を極端に受けること、また、斜め入射波であったり、ランダム入力波である場合には基礎の応答は大きくなることを見出している。

第3章では、第2章の基礎が表層内に埋め込まれた条件にある場合を扱っている。ここでは、基礎の深さと基礎側面の土との接触の有無を新たなパラメータとして導入している。その際、実体波のみでなく表面波も対象として新しい構成式の組立て方を提案し、数値解析の速度向上を図っている。主要な解析結果としては、第2章と同様に隣接距離が基礎幅の3倍以内であると動的剛性に急な変化が生じ、クロスインタラクションによる大きな影響を受けることを示唆している。

第4章では、隣接距離が十分大きければそれぞれが単独構造物である場合と等価になることを考慮し、まず、埋込みのない基礎が単独に存在する場合の応答解析を行っている。特徴的な点としては、質量と剛性に偏心がある場合を解析しており、偏心による捩れ応答が大きくなること、とくにP波に対する捩れ応答が軽い構造物では重要な問題となることを指摘している。

第5章では、クロスインタラクションの有無（埋込みのある場合とない場合の単独構造物と2棟構造物）と入力波の確率的空間変動の有無の条件を組み合わせたケースに対し、実体波とレイリー波が入力した場合のパラメトリック解析を行っている。その主要な結果として、確定的な実体波入力の場合は、隣接構造物の振動が主としてレイリー波の伝搬によって影響を及ぼすため、隣接構造物の距離がその固有周期に対応するレイリー波の波長の倍数に一致するときに対象構造物の応答に大きく影響するという周期性をみせながら、距離の減少とともに増大するクロスインタラクション特有の性状を見出している。また、確定的なレイリー波入力の場合は、距離の減少とともにロッキング振動が卓越する隣接構造物の影響が周期性をみせながら現れるものの、逆に、単独構造物の場合より応答が減少することを指摘している。ただし、確率的な空間変動の条件を考慮すると、レイリー波の場合、周期性をみせながら距離の減少とともに応答は増大する傾向へ変わり、実体波の場合の応答特性と同様の傾向を示すという従来にない指摘を行っている。

第6章は結論である。

以上要するに、本論文は従来余り検討されることのなかった構造物の地震応答に対するクロスインタラクションと入力波の空間変動の影響について論じたもので、地震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。