博　士（工　学）　モハメッド　オマール　モハメッド　フセイン

学位論文題名

SEISMIC PERFORMANCE OF STEEL TOWERS OF CABLE-STAYED BRIDGES

（斜張橋鋼製タワーの耐震性能に関する研究）

学位論文内容の要旨

The cable-stayed bridges are the modern and increasingly effective variant on the suspension bridges, in which the cables are anchored in the tower, rather than at the end. The cables may be attached in a radial pattern, extending from several points on the deck to the top of the tower, or in a parallel pattern, in which they are attached to different points on the towers. Of particular interest was the performance of the cable-stayed bridges in the Jan. 17, 1995, Hyogo-ken Nanbu Earthquake, which provided a full-scale test of tower response. The general aim of this study is to investigate the nonlinear response of cable-stayed bridge towers subjected to seismic loading, to show the more realistic modeling of the bridge tower structural behavior for understanding the performance of cable-stayed bridge towers due to seismic excitations, and to follow the predictable behavior of the constructed bridge, hence find present alternative solutions for the expected over structural excitation and enhance the seismic performance by using smart materials and utilize new technology in the future design of bridge towers.

Recently, the construction of lighter, longer, and more slender bridges is enabled due to the developments in design technology, material qualities, and efficient construction techniques in bridge engineering. Numerical parametric study of the steel tower cable-stayed bridge has been conducted to investigate the dynamic behavior considering expected vertical motion at tower base connection. The fundamental period of the steel tower is significantly increased when base plate vertical motion taken into account through base foundation model. The loosening of base plate and concrete due to vertical motion affects the tower dynamic characteristics, this effect becomes more pronounced in case of more loosing of anchor bolts stiffness continuum. The base including the vertical motion provides pronounced reduction in the reaction force and moment responses compared to the original tower response, moreover the presence of vertical motion at both sides of column bases displays more effectiveness in reaction force reduction and moment than its presence at one side. Base plate deformation has a great effect by decreasing of anchor bolts stiffness.

High-seismic structural systems are configured to be capable of withstanding controlled ductile deformations to dissipate energy as they undergo strong ground motions. Controlled rocking approach to seismic resistance allows uplifting of base plates at the foundation while displacement-based steel yielding devices (anchor bolts) are implemented at the uplifting location to control the rocking response. Allowing uplift effectively increases the structure period of vibration, hence the controlled rocking system has an inherent restoring force that allows for base connection self-centering following a seismic event. A discrete proposed base connection modeling representing material and geometrical nonlinear behavior of the base plate is developed in order to enhance rocking effect of bridges by using viscoelastic material. Nonlinear contact of the bridge towers with the base plate and concrete foundation has been demonstrated and its implementation in a finite element nonlinear analysis is presented. The nonlinear finite element dynamic analysis shows the bridge towers rocking influence tower seismic response. The resulting dynamic characteristics of the physical base model including the bridge towers rocking effect are significant different from this of tower structure rocking with its base foundation. The proposed base connections with viscoelastic material is so effective in providing safety rocking for the bridge tower and elongate its natural frequency.

A new challenge to the earthquake engineering community is to develop new technologies that could improve the seismic performance of bridges; these new technologies consist of new construction materials (smart materials) and protective systems. Theoretical, experimental and field evidences confirm the benefits of these cost-effective

technologies and their potential to reduce earthquake losses in highway bridges, these technologies should be further studied experimentally and analytically to enhance their seismic performance. Shape memory alloy material concepts, to improve the bridges seismic performance, are suggested by providing base plate anchor bolts at the tower base. The calculated results prove the effectiveness of using shape memory alloy anchor bolts in reducing structural elements forces and control tower displacement for seismic design. The performance of cable-stayed bridge tower base connections can be improved by introducing ductile damping connecting elements which will enhance the seismic properties over conventional bolted connections. The effectiveness of the proposed SMA anchor connection in the bridge tower is assessed comparing with the ordinary steel anchor connection. The SMA connection effect on the responses of the bridge tower is presented. In addition, the results show the effectiveness of the proposed SMA connection in decreasing the total energy absorbed by the tower structure compared to the ordinary steel connection anchors. The shape memory alloy is more effective in reducing maximum displacement at the tower top and it provides a large elastic deformation range in comparison with ordinary steel anchor bolts. SMA anchor bolts have the ability to return to its original shape after cyclic loadings and therefore their resisting performance remains the same to prevent plastic deformation and damage in the structural columns. SMA anchor bolt effectiveness is mainly affected by its characters rather than its deformation.

The effect of the soil?structure interaction is noticeable especially for stiff and massive structures resting on the relatively soft ground. When foundation soil is subjected to seismic ground motion its response is dictated by the soil characteristic properties, the soil conditions and the characteristics of the earthquake. Two important things that may distinguish the soil?structure interaction system from the general structural dynamic system are the unbounded nature and the non-linear characteristics of the soil medium. Far-field ground motions are characterized by low peak ground acceleration and high frequency, whereas near-fault ground motions have a high peak ground velocity and long period pulse. Soil structure interaction effects could vary significantly according to the characteristics of the near-fault earthquakes record, the scaling criterion and the seismic performance indicator representing the soil structure interaction. The difficulties that typically arise in the analysis of soil?structure interaction are often related to the soil rather than the superstructure. The soil component in the interaction problem is often modeled as an elastic continuum, a spring system, or by a finite element model of the soil half-space. Finite element approaches, on the other hand, can produce reasonably accurate solutions for a wide range of problems. Spring based solutions are often preferred as a compromise between accuracy and computational simplicity. Soil?structure systems associated with small elastic deformations of the foundations can often be solved with acceptable accuracy using elastic-interaction-springs. Earthquake ground motion may significantly differ among the support points, especially for long bridges, in terms of amplitude, frequency content and arrival time, thus inducing under certain circumstances significant forces and deformations. An analytical approach to estimate the seismic response characteristics and to predict the earthquake response of cable-stayed bridge towers accounting for soil non-linearities has been developed. The supporting soil is decomposed to some concave bounded media, with non-linear properties, and the unbounded medium representing the far-field soil zone. The finite element is used to evaluate the unbounded soil?s reaction on the soil structure interface and to model the bounded media. The results show the efficiency of the proposed approach in seismic analyses of the complex soil structure interaction systems. The soil response is affected through the depth of the soil profile where it significantly decreases at the excavated zone adjacent to the structure and slight decreases for the rigid soil in far field.

学位論文審査の要旨

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学 位 論 文 題 名

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1995 年 1 月 17 日に発生した兵庫県南部地震では、高速道路、国道、市町村道や鉄道などの橋梁構造物が甚大な被害を受けた。その後、道路橋耐震設計の再検討がなされ、道路橋示方書・耐震設計編の改訂が行われた。また、中小規模の支間長を有する高架橋を中心として耐震設計の再考がなされ、免震設計や制震設計の研究が盛んに行われている。しかし、吊橋や斜張橋のような長大支間長を有する橋梁主塔の耐震性能に関する研究は数少なく、その耐震設計手法も確立されていないのが現状である。

本論文は、斜張橋鋼製タワーを対象として 3 次元立体骨組構造にモデル化を行い、材料および幾何学的非線形性を考慮した弾塑性有限変位動的応答解析プログラムを開発し、大規模地震動を受ける斜張橋タワーの非線形応答性状を明らかにし、耐震性能設計に資する新たな知見を得たものである。

本論文は全 7 章から構成されており、各章の内容は以下のようである。

第 1 章では、研究の背景および既往の研究成果をまとめ、本研究の目的を明確に示し、各章の構成について記述している。

第 2 章では、有限変位問題を支配する仮想仕事方程式に基づき、有限要素法の手法により接線剛性マトリックスを定式化している。材料の非線形性はひずみ硬化を考慮したバイリニア型の応力—ひずみ関係で表現されている。構造物の幾何学的非線形性と材料非線形性を含む時刻歴応答解析では修正ニュートンラフソン法とニューマーク β 法を併用した数値計算により実施する方法を開発している。斜張橋鋼製タワーはファイバー要素を用いた 3 次元骨組構造にモデル化され、上部構造-基礎-地盤との動的相互作用はギャップ要素を用いた Winkler モデルを採用している。また、入力地震波は兵庫県南部地震で記録された加速度波形を採用し、橋軸方向に N-S 成分、橋軸直角方向に E-W 成分および鉛直方向に U-D 成分を同時入力する手法を提示し、開発した弾塑性有限変位動的応答解析プログラムの適用性を拡大している。

第 3 章では、斜張橋鋼製タワーに作用する地震力を軽減する対策の一つとして、塔基部鋼板の

アップリフトを認めることを提案し、有益な知見を得ている。塔基部に設置されるアンカーボルトの限定された損傷を認めることにより、塔頂部の残留変位が減少し、塔基部に発生する面内曲げモーメントおよびせん断力が低減されることを明らかにしている。また、損傷部材の履歴エネルギー吸収効果により、耐震性能が向上することを提示している。

第 4 章では、斜張橋鋼製タワーのロッキング振動にともなう地震応答性状を明らかにし、塔基部下面に弾塑性エネルギー吸収材料の挿入を提案することにより、その効果を検討している。弾塑性エネルギー吸収材料を使用した場合、斜張橋鋼製タワーの長周期化が図られ、主塔基部に発生する断面力がかなり軽減さることを論述している。

第 5 章では、アンカーボルト頭部を形状記憶合金で置換することを提案し、その耐震性能を検討している。エネルギー吸収機能を有する形状記憶合金を用いることにより、主塔頭頂部の面内応答変位および残留変位が減じることを確認している。また、塔基部に発生する負反力も低減されることから、形状記憶合金を適用することの有用性を明示している。

第 6 章では、斜張橋鋼製タワーの大地震時動的応答性状における地盤やフーチング基礎との動的相互作用の影響について明らかにしている。地盤やフーチング基礎との動的相互作用を考慮することにより、動的応答性状がやや長周期化することを確認している。また、フーチング基礎の応答鉛直変位は地震動の鉛直成分よりもフーチング基礎のロッキング振動による影響が大きいことを明らかにしている。さらに、フーチング基礎の浮き上がりは斜張橋鋼製タワーの動的応答変位に与える影響は小さいものの、塔基部の断面力をかなり軽減させることを提示している。

第 7 章では、各章で明らかとなった内容を要約し、本論文を総括している。

これを要するに、著者は斜張橋鋼製タワーの 3 次元非線形地震応答を把握するために不可欠な弾塑性有限変位動的応答解析手法を開発するとともに、大規模地震動による非線形動的応答性状を明らかにし、耐震性能向上に資する新たな知見を得たものであり、橋梁工学、鋼構造学、地震工学に貢献するところ大なるものがある。よって著者は、北海道大学博士 (工学) の学位を授与される資格あるものと認める。