様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

# 科学研究費助成事業　　研究成果報告書

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研究課題名（和文）衝突と滑りを考慮した斜張橋の地震応答予測モデルの開発とその直下地震への適用

研究課題名（英文）Investigation on Seismic Response of long-span bridges considering connection behavior of collision and stick-slip in nearfield earthquake

研究代表者

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研究成果の概要（和文）：本研究は，部品的構造要素における滑りや衝突に関する3次元を取り入れた三次元非線形構造詳細モデルを斜張橋を対象に開発するものである．大型橋梁のモデル化においては通常，実物大実験を行うことができない．そこで1989年から高密度地震モニタリングを実施している横浜ベイブリッジにおける過去の地震応答データを検証データと考えてモデルの信頼度を高める．なお，横浜ベイブリッジで計測された地震は，大きなものでは2011年3月11日東北地方太平洋沖地震の本震，余震から小さい地震まで含め，50以上の地震記録が得られており，世界でも類のない豊富な地震記録データベースとなっている．

研究成果の概要（英文）：The research is aimed at investigating seismic responses characteristics of long-span cable-supported bridges with focus on the connection between pylon and girder, considering effect of sliding and pounding. The study focuses on Yokohama-Bay bridge where seismic responses from long-term monitoring system data-base from 1989 consisting of more than 50 earthquake records are available. The study was conducted using numerical model, three-dimensional finite element model of the structure and system identification of the seismic responses. The connection behavior in longitudinal direction is modeled as non-linear slip-stick mechanism in Yokohama-Bay bridge In transverse direction, pylon-girder transverse pounding was observed on both bridges during large earthquakes. Pounding mechanism was modeled using structural model by adding pounding induced stiffness and damping.

研究分野：　構造工学・地震工学・維持管理工学

キーワード：　斜張橋の地震応答　　パウンディング　　衝突のモデル化　三次元吊形式橋梁モデル　地震応答

## １．研究開始当初の背景 (Background of the Study)

Past research on the long-span bridges with special structural connection reveals that in longitudinal direction, unexpected sub-performance of link-bearing occurred during moderate earthquakes. Similar unexpected sub-performance was also observed in Higashi-Kobe cable-stayed bridge during 1995 Hyogo-ken earthquake and this caused significant structural damage to the bridge (i.e. end-pier link failure). In lateral direction, lateral pounding between tower and girder have been observed in Higashi-Kobe Bridge during 1995 Hyogo-ken Earthquake, Vincent-Thomas bridge in the US during 1994 Northridge earthquake in addition to the Yokohama-Bay Bridge in 2011 Great East-Japan earthquake.

## ２．研究の目的 (Purpose of the Study)

The main purpose of this study to investigating behavior of tower-girder connection of long-span bridges with regards to longitudinal and transverse motions. In longitudinal direction, the stick-slip behavior of connection was investigated. In transverse direction the pounding of tower and girder was investigated. The investigations utilized structural modeling, finite-element simulation and observation from seismic records obtained from long-term seismic monitoring of two bridges.

## ３．研究の方法 (Research Methodologies)

The research was conducted by simulation using analytical and 3D finite element model to model seismic-induced motion of cable-stayed bridge by incorporating connection behavior and pounding. Data analysis using system identification (time domain, frequency domain and time-frequency domain) and structural modeling.

## 4．研究成果 (Research Results)

(1) Investigation on transverse tower-girder and pier-girder pounding of Yokohama-Bay Bridge observed during 2011 Great East Japan Earthquake was conducted using analytical and finite-element model. The pounding process is studied using model of two-side contact problem between the nodes that correspond to tower and girder at wind shoes locations. Tower-girder connections were modelled as connected springs and the effect of transverse gaps were neglected. Pounding is modelled as two-side contact problem between the nodes that correspond to tower and girder at the connecting points. Equations of motion during non-contact condition and during contact condition are derived and incorporated in the model. The resulted pounding force depends on the stiffness coefficient of contact spring. The resulted formulation is coupled equation of motions and were solved explicitly by piecewise exact method. The values of spring constant that represent the contact stiffness between pier or tower and the girder are determined by adjusting the results of model generated modal parameters to the corresponding modal parameters identified from seismic response. For this purpose, an optimalisation technique was utilized with the objective function to minimize the differences in natural frequency, damping ratio, mode shape, and root-mean-square of accelerations in transverse direction.
It should be noted that transverse pounding between tower and girder was not explicitly considered in design. However, the wind shoes were designed to withstand transverse impact with certain the maximum strength (in case of Yokohama-Bay bridge is 48MN). By employing the model, impact force on the wind shoe is calculated for various scenarios of ground motion. In the case of the main shock of 2011 Great East Japan earthquake, simulated responses show that the maximum impact force on the tower due to the pounding was about 19.9 MN, which is still lower than the capacity. The Japanese seismic design guideline for bridges stipulates two levels of earthquake namely the Level 1 and Level 2. Level 2 earthquake, which is much stronger than Level 1 is the main consideration for important facilities such as Yokohama-Bay Bridge. Simulation using ground motions for Level 2 ground motion give higher pounding force. This gives indication that the effect of transverse pounding between girder and tower on bridge should be treated in

more carefully. Details of the method and analysis are given in journal paper ⑤.The structural model can reasonably simulate the pounding mechanism. The effect of pounding on the structure such as the maximum impact force experienced by tower and wind shoes are also investigated. The model still has some limitations and should be improved in the future especially in anticipation for larger earthquake excitation.

(2) From long-term seismic monitoring data of Yokohama-Bay cable-stayed bridge, results for over twenty years of monitoring was investigated in detailed. Structural responses of the bridge from more than one hundred earthquake events between 1990 and 2011 have been recorded, with the largest one being the 2011 Great East-Japan earthquake. Using data monitoring system and by employing relevant methodologies on system identification and structural analysis, various structural aspects such as modal characteristics and their dependency on excitation level, performance of seismic isolation system, response nonlinearity and structural pounding were analyzed. Results of analysis of long-term monitoring of Yokohama-Bay bridge is presented in the conference paper① and journal paper ④.

(3) Investigation on tower-girder connection of long-span suspension bridge during earthquakes were also conducted by case-study of long-term structural monitoring system using seismic responses of Hakucho suspension bridge. The main focus on pylon-girder connection behavior. Monitoring system on the bridge has recorded 213 earthquakes between 1998 and 2006 including intense shaking during the 2003 Tokachi-Oki, the 2004 Kushiro-Oki earthquake, 2005 Miyagi-Oki and 2004 Kushiro earthquake. The results show dependency of natural frequencies and damping ratios of the girder dominant modes on the amplitude of ground motion. This study shows that the increase in damping and decrease in natural frequency as the ground motion amplitude increases. To explain the mechanism, a modal-based inverse analysis model was formulated where the condition of bearings that lead to stick-slip behavior are modeled as additional stiffness and additional damping at the bearings. Influence of additional stiffness and damping due to the friction force at the bearings to this effect was clarified using the results of system identification from long-term seismic monitoring data and their values were quantified for different level of earthquakes. The results suggest a stick-slip behavior at the bearing that is typical of Coulomb friction such that at smaller excitation, bearings remain stuck thus causing higher stiffness; while during larger excitation, the bearings slip and result in lower stiffness and the friction between contacting surfaces increase the damping. Detail model and analysis results were submitted for publication in recent journal paper ①.

(4) Using finite-element model of Yokohama-Bay bridge, the serviceability of the bridge under large earthquake response was investigated under condition of analyzed tower-girder connections mentioned above. In addition to responses of evaluation of seismic response of the bridge, we also study the effect of bridge vibration and their characteristics on the vehicle crossing the bridge. The main focus is on the stability of vehicles when crossing long-span bridge such as Yokohama-Bay bridge during strong earthquake. In this part of study, vehicle stability model was formulated and several critical conditions or criteria for stability were defined. Afterwards, numerical simulations using finite-element model and standard vehicle were conducted assuming real case of a standard truck crossing the Yokohama-Bay bridge during 2011 Great East-Japan earthquake. The results of analysis reveal certain conditions that affect vehicle stability and bridge serviceability during earthquake. Detail model and analysis results were published recently in a journal paper ②.

５．主な発表論文等
（研究代表者、研究分担者及び連携研究者には下線）

〔雑誌論文〕（計５件　全て査読有）

① Dionysius Siringoringo & Yozo Fujino (2018).Seismic Response of a suspension bridge : Insights from Long-term Full-Scale Seismic Monitoring System, Structural Control and Health Monitoring (accepted)
② Dionysius Siringoringo & Yozo Fujino (2018). Lateral Stability of Vehicles Crossing a Bridge during an Earthquake. Journal of Bridge Engineering, 23(4). https://doi.org/10.1061/(ASCE)BE.1943-5592.0001211
③ Dionysius Siringoringo & Yozo Fujino (2017). Wind-induced responses and dynamics characteristics of an asymmetrical base-isolated building observed during typhoons. Journal of Wind Engineering and Industrial Aerodynamics, 167, 183-197.DOI: https://doi.org/10.1016/j.jweia.2017.04.020
④ Yozo Fujino, Dionysius Siringoringo, M. Abe. (2016). Japan's experience on long-span bridges monitoring. Structural Monitoring and Maintenance, 3(3), 233-257. DOI: http://dx.doi.org/10.12989/smm.2016.3.3.233
⑤ Dionysius Siringoringo, G. Takamoto, Y. Fujino.(2015). Analysis of Tower-Girder Transfer Pounding on the Yokohama-Bay Cable-Stayed Bridge during 2011 Great East Japan Earthquake. IABSE Symposium Report. Vol.104(1):1-8. DOI: https://doi.org/10.2749/222137815815776078

〔学会発表〕（計５件 全て査読有）

①Dionysius Siringoringo & Yozo Fujino, (2017), Over Twenty Years Seismic Monitoring Experience of a Cable-Stayed Bridge: Lessons Learned on Structural Assessments, Proc.of the 16th World Conference on Earthquake Engineering, Santiago, Chile.
② Dionysius Siringoringo & Yozo Fujino, (2017), Wind Effects and Dynamics Characteristics of Base-Isolated Building based on Full-scale measurement during Typhoons, X International Conference on Structural Dynamics, EURODYN 2017 Rome, Italy. https://doi.org/10.1016/j.proeng.2017.09.218
③Dionysius Siringoringo, Kenji Narita and Yozo Fujino, Lateral Instability of Vehicle when Crossing a Bridge during Earthquake, The 13th International Workshop on Advanced Smart Materials and Smart Structures Technology (ANCRiSST), July 22-23, 2017, The University of Tokyo, Japan
④ Dionysius Siringoringo & Yozo Fujino, (2016), Seismic Response Analysis of Hakucho Suspension Bridge from Long-term Monitoring System, Proc. of IABSE Conference, Stockholm, Sweden, 1872-1879.
⑤ Dionysius Siringoringo & Yozo Fujino, (2015), Lessons learned from Seismic Monitoring of Yokohama-bay Cable-Stayed Bridge, SHMII-7, Torino, Italy.

〔図書〕（計０件）

〔産業財産権〕

○出願状況（計０件）

名称：-
発明者：-
権利者：-
種類：-
番号：-
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○取得状況（計０件）

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権利者：-
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〔その他〕
ホームページ等

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