様　式　C－19、F－19－1、Z－19　(共通)

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令和　４ 年　 ６ 月 １５ 日現在

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研究課題名（和文）スパース推定法を活用した長大橋の地震時局所的損傷の検知法開発と実記録による検証

研究課題名（英文）Development of Seismic Damage Assessment Method for Instrumented Large Civil Structures using Sparse Representation Techniques

研究代表者

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交付決定額（研究期間全体）：（直接経費）　　3,200,000円

研究成果の概要（和文）：長大橋（十勝大橋、新那珂川大橋、勝田橋）を対象に，支承，桁，塔，脚などの損傷を模擬できるモーダルとFEM数値シュミレーションモデルを構築し，様々な損傷パターンを想定し，模擬応答を作成する、振動センサーの応答にスパース推定法（Sparse Representation）という局部変化の同定に強い全く新しい手法を適用し，地震計の最適配置決定法ならびに応答記録からの損傷検知手法を開発し、損傷の位置と程度と分散配置されたセンサーでの波形との関係を明らかにする．膨大な損傷パターンに対してシミュレーションを実施し，教師無しの機械学習法を適用し，観測波形から損傷位置と程度を判定できるシステムを構築する．

研究成果の学術的意義や社会的意義
Using various models of sparse representations, the study shows that structural assessment can be performed using modal & FE based simulation and sparse representation techniques.The methods can be used for structural evaluation after large earthquake to detect damages in bridge bearings.

研究成果の概要（英文）：Structural identification by sparse representation was developed and tested using full-scale seismic monitoring data of three bridges. Modal and FE-based structural identifications were developed according to complexity of structural system. In Tokachi cable-stayed bridge the sparse time-invariant and time-variant recursive subspace identification methods were implemented. Friction damping at the movable bearings was quantified by modal-based inverse analysis and sparse regularization method.In the Katsuta Viaduct, techniques were developed for detecting bearing malfunction from the seismic response using continuous & discrete wavelet transform. Evaluation of bearing condition was conducted by statistical sparse machine-learning technique.In the ShinNakagawa FE-based model was developed and compared with monitoring data. Damages related to isolation bearing were simulated and the results were compared with monitoring from 63 earthquakes in 2017-2020 using sparse model analysis.

研究分野：structural engineering

キーワード：structural assessment　seismic monitoring　sparse representation　seismic isolation　system identification　bridge monitoring　cable-stayed bridge　seismic response

１．研究開始当初の背景

Objectives of the research is to develop structural system identification using Sparse Representation model with the application for structural assessment of long-span bridge. The sub-models are data-driven and can be implemented for structural assessment purpose. Based on these sub-models, pattern recognition and diagnosis on structural condition will be performed. The developed mathematical models will be trained, verified, and validated using numerical model of several bridges. For this purpose, a modal-based and finite-element model of the bridge were developed, and seismic responses of the bridge will be generated using various scenarios of earthquakes. The simulated seismic responses will be used as input to train the model. Several realistic seismic-induced damage scenarios that commonly observed on the suspension bridge will be utilized to generate structure responses and validate model. Information of structural responses will be generated using several sensor arrangements including the current sensor arrangement. Based on these scenarios the efficacy of model in assessing structural condition will be evaluated.

２．研究の目的

Purpose of the research is to develop and implement a structural evaluation system that can assess structural condition after the event of earthquakes using seismic responses of the structure. In this study, special focus is given on the evaluation of bearing conditions of isolated bridges because this structural component was damaged during the 2011 Tohoku earthquake. The system is developed to provide systematic evaluation of bridge bearing condition right after the earthquake using seismic monitoring system.

３．研究の方法

The research was conducted using various models and verification. In the beginning for simulation the structural model, analytical model and data-driven model were developed. Afterwards, for verification, system identification models were developed and implemented.

- For structural modeling the finite-element model of the bridge is developed. In this case the object bridge was Shin-Nakagawa cable-stayed bridge. The FE bridge model was developed using ABAQUS software.
- For simulation, analytical models were investigated using Sparse Representation model.
- The models were tested in simulation using modal analysis and inverse by means of Sparse regularization and clustering analysis using Machine learning technique.
- For verification, seismic monitoring data from Tokachi bridge, Katsuta bridge and Shin-Nakagawa bridge are used.

４．研究成果

Structural system identification by sparse system representation was developed and carried out using real data from full-scale seismic monitoring of the Tokachi cable-stayed bridge, Katsuta viaduct and Shin-Nakagawa cable-stayed bridge. The research employs both modal-based and FE-based structural system identifications according to the availability and complexity of the structural system.

In the Tokachi Bridge both the sparse time-invariant and time-variant recursive subspace identification methods were implemented for structural identification of cable-stayed bridge that is equipped with moveable spherical frictional plate (SFP). Supplementary damping caused by friction force at the movable SFP bearings was identified as the main source of the large damping, and it was quantified by a modal-based inverse analysis using the sparse regularization method. Results of the analyses confirm the influence of moveable SFP bearings performance with its

Coulomb-friction type stick-slip behavior on the dynamic characteristics of the bridge. Detailed outcome of this study has been published in reference [1].

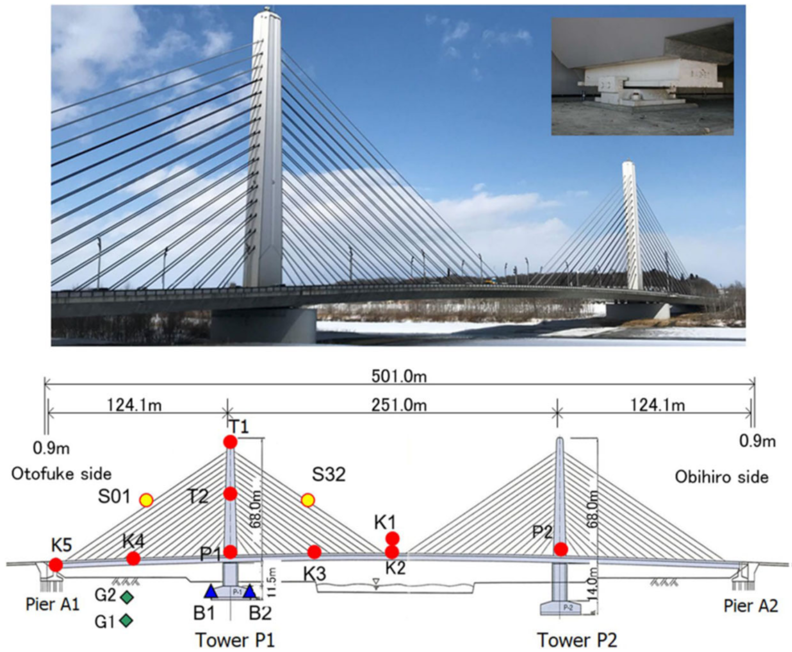

Fig. 1 Tokachi cable-stayed bridge (42.93 N, 143.203E), dimension, and sensors layout. (Inset: moveable spherical frictional plate (SFP) bearings used at both ends of the girder)

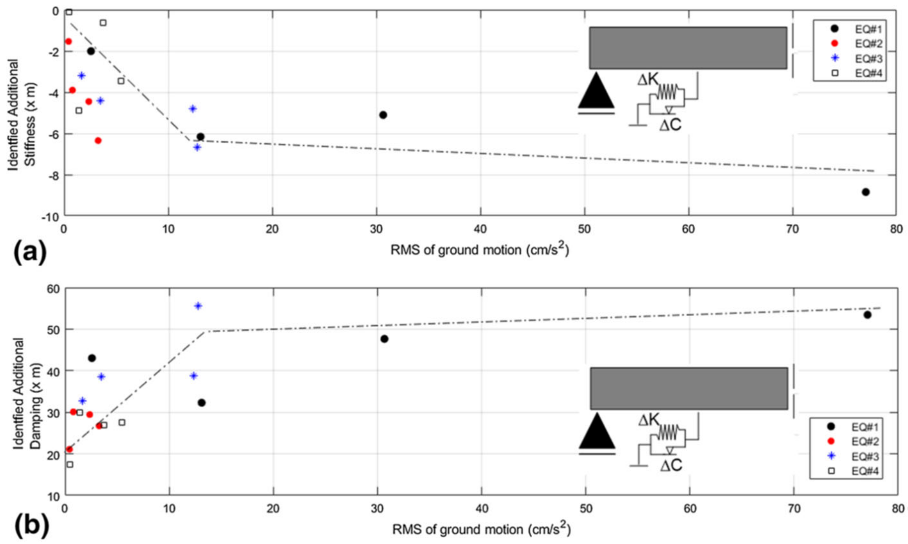

Fig. 2. Inverse analysis and sparse regularization results of: **a** identified supplementary stiffness and **b** identified supplementary damping caused by friction forces of the movable SFP bearings at the girder ends.

In the Katsuta Viaduct, techniques for detecting bearing malfunction directly from the seismic response of the bridge using wavelet transform time-varying identification. The techniques consist of 1) continuous wavelet transform to identify instantaneous frequency based on which stiffness changes associated with isolation bearing condition can be traced, and 2) details component of discrete wavelet transform based on which discontinuity of acceleration response associated with isolation state can be identified. To facilitate direct detection based on both CWT and DWT results, classification of bearing condition was performed using k-means sparse cluster classification method. The method was tested in FE numerical simulation before implemented on the bridge. Results of simulation using three-dimensional finite element model of continuous multi-span isolated bridge have shown the effectiveness and accuracy of the proposed technique to characterize behavior of isolation bearing and detect any changes related to bearing malfunction such as locking phenomenon directly from seismic record of the bridge without the need of structural model or reference state. Detailed outcome of this study has been published in reference [2].

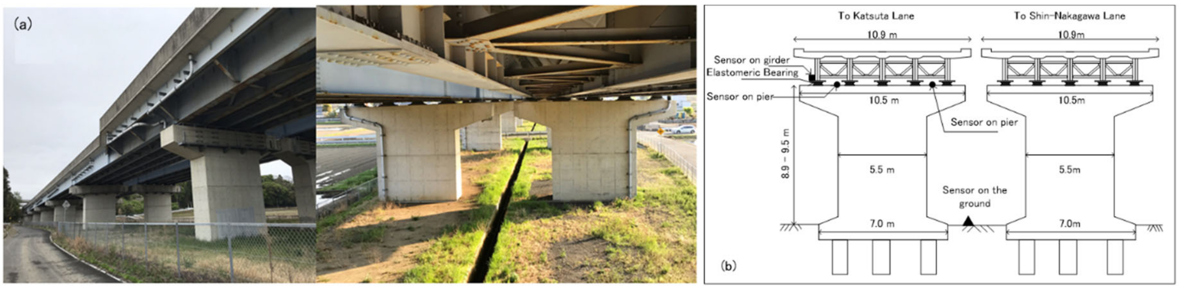

Fig. 3. Katsuta Highway multi-span viaduct (a) Photos (b) Dimension.

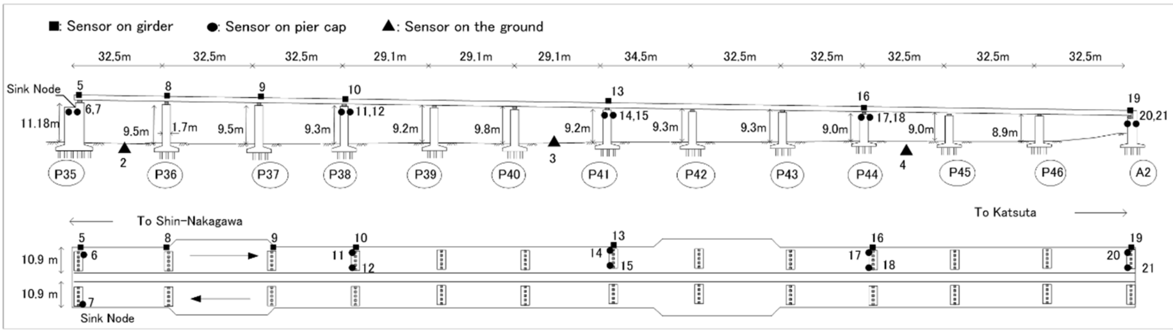

Fig. 4. Katsuta Highway multi-span viaduct wireless monitoring system.

Normalized Distance

	EQ1	EQ2	EQ3	EQ4	EQ5	EQ6	EQ7	EQ8	EQ9	EQ10	EQ11	EQ12	EQ13	EQ14	EQ15
ND-P35	N.A	0.705	0.844	0.786	0.645	0.715	0.697	0.654	0.679	0.942	0.739	0.09	0.567	0.065	0.157
ND-P38	0.999	0.981	0.863	0.941	0.762	0.899	0.948	0.95	0.971	0.96	0.874	0.579	0.107	0.047	0.15
ND-P41	0.938	0.93	0.876	0.802	0.733	0.876	0.806	0.889	0.936	0.925	0.825	0.677	0.114	0.056	0.157
ND-P44	0.785	0.848	0.722	0.708	0.6	0.802	0.7	0.761	0.602	0.811	0.74	0.101	0.111	0.274	0.152
ND-AB2	0.863	0.894	0.893	0.754	0.746	0.873	0.958	0.872	0.984	0.558	0.952	0.426	0.093	0.138	0.156

Earthquakes

Fig. 4. Example of classification of bearing condition on Katsuta Highway multi-span viaduct based on *k-means* sparse clustering method of the instantaneous frequencies obtained from CWT of accelerations (ND values closer to one means moveable bearing, closer to zero means locked bearing). [2]

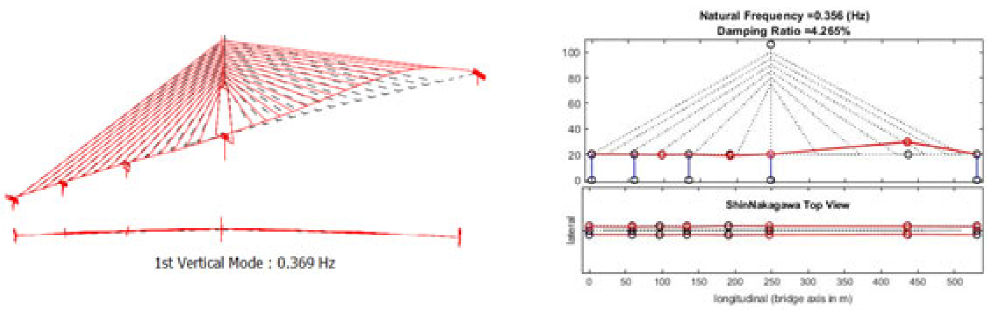

Fig. 5. Finite Element model and identified modes of Shin-Nakagawa bridge from seismic response

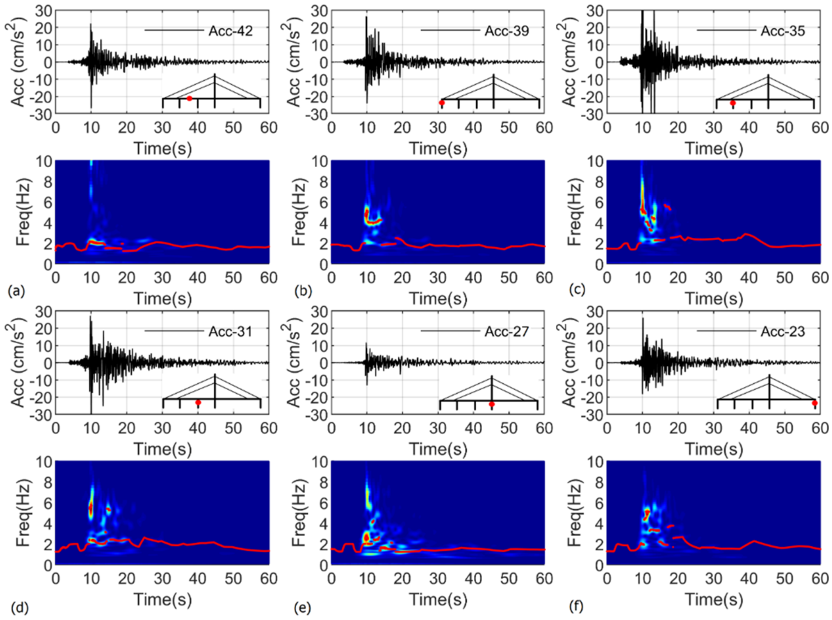

Fig. 6. Example of the use of identification for bearing condition assessment of Shin-Nakagawa bridge from seismic response

In the Shin-Nakagawa Bridge an-FE model was also developed in Abaqus for comparison with monitoring results. Damages related to isolation bearing implementation were simulated and the results were compared with monitoring from 63 seismic events in 45 months (2017-2020) using the CWT-DWT and Sparse model analysis. Girder and the piers/pylon recorded accelerations are utilized to identify instantaneous frequency associated with isolation bearing condition. Results of analysis indicate that the seismic isolation bearing has effectively decoupled the superstructure from the substructure, and this can be detected from the method developed in this study. The high-frequency filtering effect can be clearly observed from the seismic records of the girder during the large earthquakes. Detailed outcome of this study has been published in reference [3].

Main publications from this research:

[1]. Siringoringo, D.M., Fujino, Y. (2021). Influence of movable bearings performance on the dynamic characteristics of a cable-stayed bridge : insights from seismic monitoring records. Bull Earthquake Eng (2021). https://doi.org/10.1007/s10518-021-01282-y

[2]. Siringoringo, D. M., & Fujino, Y. (2021). Wavelet-based analysis for detection of isolation bearing malfunction in a continuous multi-span Girder Bridge. Journal of Earthquake Engineering, 1-31.https://doi.org/10.1080/13632469.2020.1868363

[3].Siringoringo, D. M., Fujino, Y., Suzuki, M.(2022). Implementation of Wireless Sensor Network for Continuous Seismic Monitoring of Isolated Cable-Stayed Bridge. Journal of Bridge Engineering, 27(4), 04022011.https://doi.org/10.1061/(ASCE)BE.1943-5592.0001813

５．主な発表論文等

〔雑誌論文〕　計13件（うち査読付論文　12件／うち国際共著　12件／うちオープンアクセス　1件）

１．著者名	４．巻
Dionysius M Siringoringo, Yozo Fujino, Makoto Suzuki	27(4)
２．論文標題	５．発行年
Implementation of Wireless Sensor Network for Continuous Seismic Monitoring of Isolated Cable-Stayed Bridge	2022年
３．雑誌名	６．最初と最後の頁
Journal of Bridge Engineering ASCE	04022011-1-15
掲載論文のDOI（デジタルオブジェクト識別子）	査読の有無
10.1061/(ASCE)BE.1943-5592.0001813	有
オープンアクセス	国際共著
オープンアクセスではない、又はオープンアクセスが困難	該当する

１．著者名	４．巻
Dionysius M Siringoringo, Yozo Fujino	NA
２．論文標題	５．発行年
Influence of movable bearings performance on the dynamic characteristics of a cable-stayed bridge : insights from seismic monitoring records	2021年
３．雑誌名	６．最初と最後の頁
Bulletin of Earthquake Engineering	1-33
掲載論文のDOI（デジタルオブジェクト識別子）	査読の有無
10.1007/s10518-021-01282-y	有
オープンアクセス	国際共著
オープンアクセスではない、又はオープンアクセスが困難	該当する

１．著者名	４．巻
Dionysius M Siringoringo, Yozo Fujino	NA
２．論文標題	５．発行年
Wavelet-Based Analysis for Detection of Isolation Bearing Malfunction in a Continuous Multi-Span Girder Bridge	2021年
３．雑誌名	６．最初と最後の頁
Journal of Earthquake Engineering	1-31
掲載論文のDOI（デジタルオブジェクト識別子）	査読の有無
10.1080/13632469.2020.1868363	有
オープンアクセス	国際共著
オープンアクセスではない、又はオープンアクセスが困難	該当する

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Modal analysis and tension estimation of stay cables using noncontact vision-based motion magnification method	2022年
３．雑誌名	６．最初と最後の頁
Structural Control Health Monitoring	1-25
掲載論文のDOI（デジタルオブジェクト識別子）	査読の有無
10.1002/stc.2957	有
オープンアクセス	国際共著
オープンアクセスではない、又はオープンアクセスが困難	該当する

１．著者名 Dionysius M Siringoringo, Samten Wangchuk, Yozo Fujino	４．巻 244
２．論文標題 Noncontact operational modal analysis of light poles by vision-based motion-magnification method	５．発行年 2021年
３．雑誌名 Engineering Structures	６．最初と最後の頁 112728-1-14
掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.engstruct.2021.112728	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 Zhen Sun, Dionysius M. Siringoringo, Yozo Fujino	４．巻 229
２．論文標題 Load-carrying capacity evaluation of girder bridge using moving vehicle	５．発行年 2021年
３．雑誌名 Engineering Structures	６．最初と最後の頁 111645-1-14
掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.engstruct.2020.111645	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 Jothi Thiyagarajan, Dionysius M. Siringoringo, Samten Wangchuk, Yozo Fujino	４．巻 27(2)
２．論文標題 Implementation of video motion magnification technique for non-contact operational modal analysis of light poles	５．発行年 2021年
３．雑誌名 Smart Structures and Systems	６．最初と最後の頁 227-239
掲載論文のDOI（デジタルオブジェクト識別子） 10.12989/sss.2021.27.2.227	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 Dionysius M. Siringoringo, Yozo Fujino, Masaaki Yabe	４．巻 17(5)
２．論文標題 Investigation on vehicle lateral instability when crossing a curved highway bridge during an earthquake	５．発行年 2021年
３．雑誌名 Structure and Infrastructure Engineering	６．最初と最後の頁 720-740
掲載論文のDOI（デジタルオブジェクト識別子） 10.1080/15732479.2020.1766515	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 Dionysius M Siringoringo, Yozo Fujino, Ayami Nagasaki, Takuro Matsubara	４．巻 17(5)
２．論文標題 Seismic performance evaluation of existing light poles on elevated highway bridges	５．発行年 2021年
３．雑誌名 Structure and Infrastructure Engineering	６．最初と最後の頁 649-663
掲載論文のDOI（デジタルオブジェクト識別子） 10.1080/15732479.2020.1760894	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 Yozo Fujino, Dionysius M Siringoringo, Yoshiki Ikeda, Tomonori Nagayama, and Tsukasa Mizutani	４．巻 5(6)
２．論文標題 Research and Implementations of Structural Monitoring for Bridges and Buildings in Japan	５．発行年 2019年
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掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.eng.2019.09.006	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

１．著者名 Yozo Fujino & Dionysius M. Siringoringo	４．巻 16
２．論文標題 Recent research and development programs for infrastructures maintenance, renovation and management in Japan	５．発行年 2020年
３．雑誌名 Structure & Infrastructure Engineering	６．最初と最後の頁 3-25
掲載論文のDOI（デジタルオブジェクト識別子） 10.1080/15732479.2019.1650077	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 Dionysius M Siringoringo, Yozo Fujino, Ayami Nagasaki, Takuro Matsubara	４．巻 NA
２．論文標題 Seismic performance evaluation of existing light poles on elevated highway bridges	５．発行年 2020年
３．雑誌名 Structure & Infrastructure Engineering	６．最初と最後の頁 NA
掲載論文のDOI（デジタルオブジェクト識別子） 10.1080/15732479.2020.1760894	査読の有無 無
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 －

１．著者名 Dionysius M Siringoringo, Yozo Fujino	４．巻 25(11)
２．論文標題 Seismic response of a suspension bridge: Insights from long‐term full‐scale seismic monitoring system	５．発行年 2018年
３．雑誌名 Structural Control and Health Monitoring	６．最初と最後の頁 e2252-2276
掲載論文のDOI（デジタルオブジェクト識別子） 10.1002/stc.2252	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

〔学会発表〕　計5件（うち招待講演　0件／うち国際学会　5件）

１．発表者名 Dionysius M. Siringoringo
２．発表標題 Continuous Seismic Monitoring of Seismically-Isolated Cable-Stayed Bridge by Wireless Sensor Network
３．学会等名 17 World Conference on Earthquake Engineering (WCEE)（国際学会）
４．発表年 2021年

１．発表者名 Dionysius M. Siringoringo
２．発表標題 Seismic Monitoring of Cable-Stayed Bridge using Wireless Sensor Networks
３．学会等名 IABMAS Conference 2021（国際学会）
４．発表年 2021年

１．発表者名 Dionysius M. Siringoringo
２．発表標題 Vision-based vibration measurement of Stay-cables by Video Motion Magnification and Dynamic Mode Decomposition
３．学会等名 EVACES 2021（国際学会）
４．発表年 2021年

１．発表者名 Dionysius M. Siringoringo, Yozo Fujino, Makoto Suzuki, Vaibhav Mehta
２．発表標題 Seismic Monitoring of Cable-stayed Bridge Using Wireless Sensor Network
３．学会等名 International Workshop of Structural Health Monitoring. September 10-12, 2019, Stanford, California, USA（国際学会）
４．発表年 2019年

１．発表者名 Dionysius M. Siringoringo
２．発表標題 Long-term Seismic Monitoring of a Long-span Suspension Bridge
３．学会等名 The 7th World Conference on Structural Control and Monitoring (7WCSCM)（国際学会）
４．発表年 2018年

〔図書〕　計1件

１．著者名 Yozo Fujino, Dionysius M. Siringoringo, Masaru Kikuchi, Kazuhiko Kasai, and Toshihide Kashima	４．発行年 2019年
２．出版社 Springer	５．総ページ数 440-447
３．書名 Seismic Monitoring of Seismically Isolated Bridges and Buildings in Japan - Case Studies and Lessons Learned in Seismic Structural Health Monitoring: From Theory to Successful Applications	

〔産業財産権〕

〔その他〕

－

６．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関