Engineering Structures 147 (2017) 269–284

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Long-term monitoring of wind field characteristics and dynamic response of a long-span suspension bridge in complex terrain

Aksel Fenerci *, Ole Øiseth, Anders Rønnquist

Department of Structural Engineering, Norwegian University of Science and Technology, Trondheim, Norway

A R T I C L E I N F O

Article history:
Received 18 August 2016
Revised 4 May 2017
Accepted 8 May 2017

Keywords:
Suspension bridge
Bridge monitoring
Field measurement
Wind characteristics
Response surface methodology
Complex terrain
Bridge dynamic response

A B S T R A C T

Long-term monitoring data of wind velocities and accelerations on the Hardanger Bridge are used to investigate the relationship between the wind-loading and response processes. The extensive measurement system consisting of 20 accelerometers and 9 anemometers is described as well as the local topography of the site. The wind and response characteristics are presented using scatter plots and wind rose diagrams. The considerable variability observed in the bridge dynamic response is investigated by utilizing response surface methodology. Simple parameters of the wind field are selected as the predictor variables in the analyses. The variability in response is attributed to the variable wind field, and the effects of the significant parameters on the response are presented in a statistical framework. The agreement of the findings with previous considerations and the implications on the design of long-span suspension bridges are discussed.

1. Introduction

The Norwegian Public Roads Administration (NPRA) is currently seeking solutions to replace several ferry connections along Norway's coastal highway E39 with road transportation. The extraordinary terrain typical of the west coast of Norway, famous for its fjords and tall mountains, requires crossing straits up to 5 km long and 2 km deep, which manifests a challenging task for bridge engineers. The growing demand for longer suspension bridges around the world calls for relatively lighter and slenderer bridge structures, which will be prone to excessive wind excitation. To this day, many bridges exhibited unexpected behavior due to different wind-related phenomena, such as flutter [1], vortex shedding [2] and excessive cable vibrations [1,3], which revealed gaps in the knowledge of loading mechanisms on such structures. To diagnose and minimize these unexpected effects, monitoring of existing structures and analysis of field data are deemed essential [4].

Accurate prediction of wind-induced response of suspension bridges is vitally important for reliable design and assessment of such structures. Predicting the dynamic response, however, accommodates uncertainties due to many sources, including the modeling of gust loading. Following the work of Davenport [5], the dynamic load effects caused by atmospheric turbulence are traditionally described using power spectral densities (PSDs) and coherences of turbulence [6–9]. Consequently, several expressions have been suggested for the spectral densities over the years [6,10,11], which in general depend on basic parameters of the wind field. The results of the recent bridge monitoring efforts [12–16] reveal that the wind field characteristics exhibit variability from site to site. Therefore, the spectral expressions need to be adjusted for the site in question using field measurements [13,17]. The site-specific spectra are generally deduced from single events such as typhoons or averaged over a number of recordings. However, neither approach seems to reflect the actual variability of the wind field present at the particular site, making it difficult to establish design spectra, even for a specific site. Solari and Piccardo [18] presented a collection of wind field statistics taken from field measurement results in the literature. The variability of the results presented by [18], as well as the random and site-dependent nature of wind loading on suspension bridges, encourage a probabilistic description of the wind field [19–21].

The field measurement results of wind statistics and structural responses were reported by several researchers as the outcomes of large measurement campaigns to investigate the effect of wind loading on bridge response and modal properties [4,14,22–24] or to verify numerical simulations [17,25–27]. The studies showed that reasonable predictions of dynamic response can be achieved using the measured turbulence spectra. Other works showed that the spectra can accommodate significant uncertainty and that

* Corresponding author.
E-mail address: aksel.fenerci@ntnu.no (A. Fenerci).

http://dx.doi.org/10.1016/j.engstruct.2017.05.070
0141-0296/

the selection can significantly influence the response estimations [9,28].

In complex terrain, the wind field is expected to be variable and not homogenous. However, modeling the wind field using state-of-the-art methods will not reflect this variability in the dynamic response predictions. Consequently, safety concerns may arise when designing very long suspension bridges. The present study aims to put forth the actual relationship between wind and the response parameters of a long-span suspension bridge located in complex terrain using long-term field data. The thorough analysis of wind field parameters and their effects on the dynamic response will provide insight into the uncertainties involved in wind field modeling and response prediction. For this purpose, field measurement results are presented from an extensive monitoring system installed on the Hardanger Bridge in Norway. The wind and response characteristics for the measurement period are presented. The influence of the wind field on the dynamic response is studied in a statistical framework, using response surface methodology (RSM) with basic wind-related parameters from measurements. The significance of the parameters is assessed using hypothesis testing techniques. Finally, the effects of the significant wind field parameters are presented in the form of two-dimensional surface plots.

2. The Hardanger Bridge and its surroundings

The Hardanger Bridge (Fig. 1) crosses the Hardangerfjord in Hordaland county of Norway, connecting the small towns of Bu and Vallavik (Fig. 2). Since its completion in 2013, it remains the longest suspension bridge in Norway with its slender main span of 1310 m. The bridge deck has a well-streamlined box shape and guide vanes were installed underneath the deck to mitigate vortex-induced vibrations. The bridge girder is 18.5 meters wide and 3.2 meters high, supporting two traffic lanes and a bicycle lane, making the bridge exceptionally slender compared to existing structures with similar scales. The bridge direction deviates approximately 25° from the north-south direction, towards the west, perpendicular to the fjord. The bridge is surrounded by steep mountains (1000–1500 m high) to the north and the south. The view of the surrounding fjords and mountains is shown Fig. 3.

The dynamic characteristics of the Hardanger Bridge, namely its natural frequencies and mode shapes are extracted from a finite element (FE) model of the bridge through eigenvalue analysis. The FE model was provided by NPRA. According to the analysis, the first lateral symmetric mode occurs at 0.05 Hz, followed by an antisymmetric lateral mode at 0.098 Hz. The first vertical asymmetric and symmetric frequencies of the structure were calculated as 0.11 Hz and 0.14 Hz, respectively. The first torsional vibration frequency was 0.36 Hz. The fundamental frequencies of the structure under 16 m/s wind were also identified by [29], using Operational Modal Analysis (OMA). The results were similar to the FE analysis.

3. The measurement system

The Hardanger Bridge was instrumented with an extensive monitoring system after its completion to measure the wind veloc-

Fig. 1. The Hardanger Bridge.

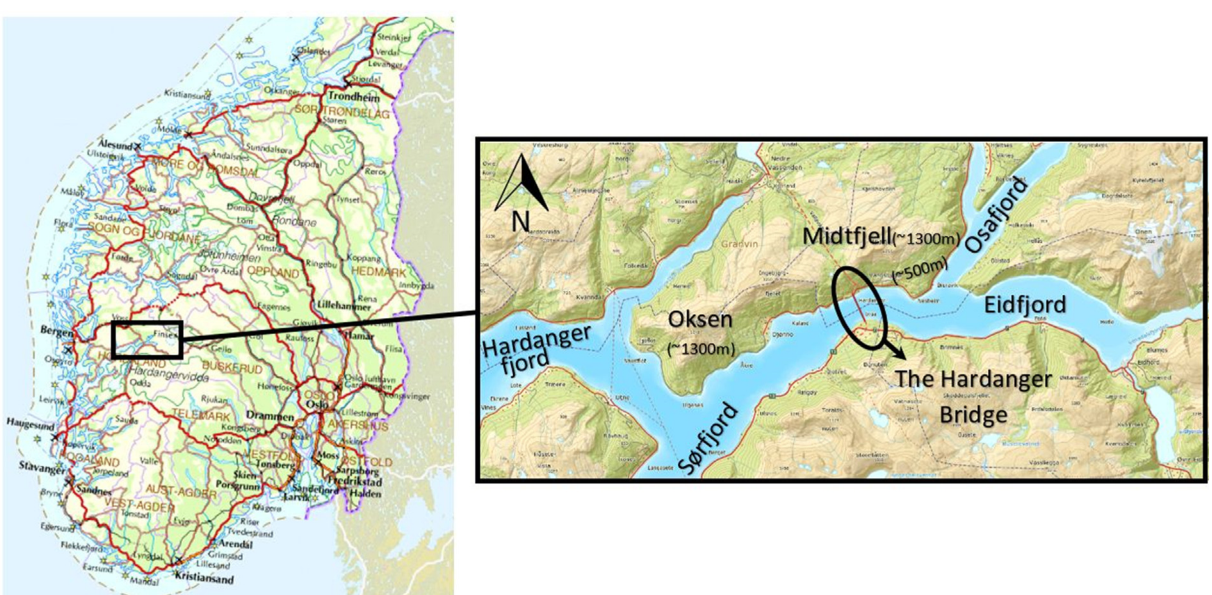

Fig. 2. Location and local topography (map images from Kartverket©).