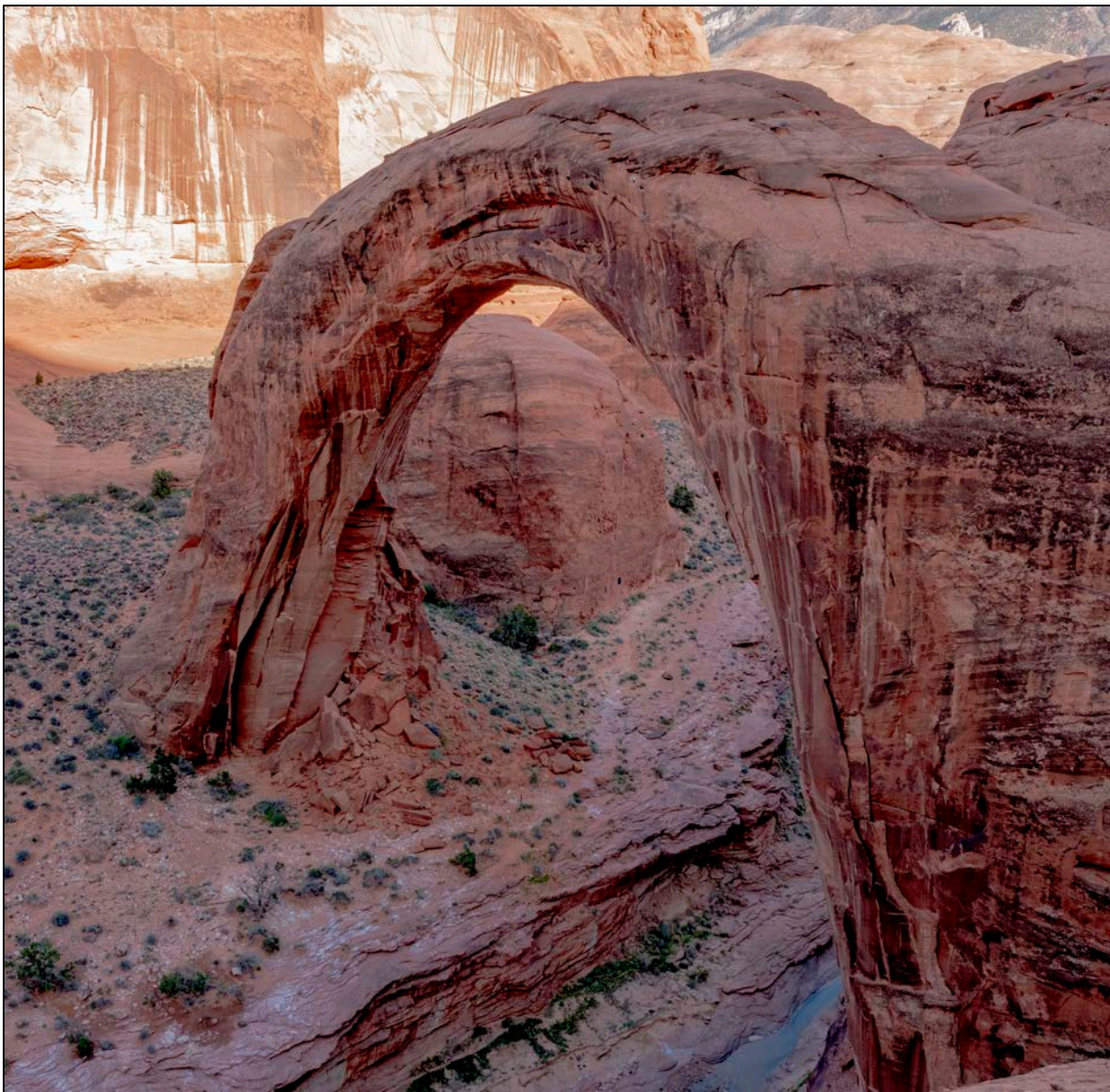




Rainbow Bridge Vibration Risk Assessment

Ambient Vibration Testing and Computer Modeling results for Rainbow Bridge

Natural Resource Report NPS/RABR/NRR—2018/1617



ON THE COVER

Image of Rainbow Bridge from the approach to the south buttress.
(NPS/JOHN WOOD)

Rainbow Bridge Vibration Risk Assessment

Ambient Vibration Testing and Computer Modeling results for Rainbow Bridge

Natural Resource Report NPS/RABR/NRR—2018/1617

Jeffrey R. Moore

The University of Utah
Department of Geology and Geophysics
115 South 1460 East, Rm 383
Salt Lake City, Utah 84112
jeff.moore@utah.edu

April 2018

U.S. Department of the Interior
National Park Service
Natural Resource Stewardship and Science
Fort Collins, Colorado

The National Park Service, Natural Resource Stewardship and Science office in Fort Collins, Colorado, publishes a range of reports that address natural resource topics. These reports are of interest and applicability to a broad audience in the National Park Service and others in natural resource management, including scientists, conservation and environmental constituencies, and the public.

The Natural Resource Report Series is used to disseminate comprehensive information and analysis about natural resources and related topics concerning lands managed by the National Park Service. The series supports the advancement of science, informed decision-making, and the achievement of the National Park Service mission. The series also provides a forum for presenting more lengthy results that may not be accepted by publications with page limitations.

All manuscripts in the series receive the appropriate level of peer review to ensure that the information is scientifically credible, technically accurate, appropriately written for the intended audience, and designed and published in a professional manner.

This report received an informal peer review by two subject-matter experts who were not directly involved in the collection, analysis or reporting of the data presented.

Views, statements, findings, conclusions, recommendations, and data in this report do not necessarily reflect views and policies of the National Park Service, U.S. Department of the Interior. Mention of trade names or commercial products does not constitute endorsement or recommendation for use by the U.S. Government.

This report is available in digital format from the [Geologic Resources Division website](#) and the [Natural Resource Publications Management website](#). If you have difficulty accessing information in this publication, particularly if using assistive technology, please email irma@nps.gov.

Please cite this publication as:

Moore, J. R. 2018. Rainbow Bridge vibration risk assessment: Ambient vibration testing and computer modeling results for Rainbow Bridge. Natural Resource Report NPS/RABR/NRR—2018/1617. National Park Service, Fort Collins, Colorado.

Contents

	Page
Figures.....	iv
Tables.....	vi
Executive Summary	vii
Acknowledgments.....	viii
Introduction.....	1
Data Summary and Discussion	3
Vibration, tilt, and environmental data.....	3
3D numerical modal analysis	19
Helicopter noise sources.....	24
Potential helicopter-induced vibration of Rainbow Bridge.....	28
Bureau of Reclamation past studies	33
Recommendations.....	44
Maximum allowable vibration amplitudes	44
Helicopter avoidance distances	45
Future studies.....	46
Long-term monitoring	46
Hazards from Natural Vibration Sources.....	50
Data	55
Literature Cited	56

Figures

	Page
Figure 1. Overview of sensor locations on and around Rainbow Bridge.	4
Figure 2. Layout of sensors on and around Rainbow Bridge.....	5
Figure 3. Summary of meteorological conditions during the period of field testing at Rainbow Bridge.	6
Figure 4. Time-series data from seismometer RABC located on Rainbow Bridge.	8
Figure 5. Raw data spectrogram from seismometer RABC on Rainbow Bridge.	9
Figure 6. Power spectral density plots for sensor RABC on the bridge and reference sensor RABD on the canyon floor for a selected 1-hour time period exhibiting typical results..	10
Figure 7. PSD plots for seismometers RABA-RABD from coincident time periods	11
Figure 8. Variation of the fundamental frequency over time measured at RABC.....	13
Figure 9. Polarization of ground motion at different frequencies for sensors RABA, RABB, and RABC.	15
Figure 10. Polarization of ground motion in the horizontal plane at sensor RABC on Rainbow Bridge.	16
Figure 11. Rotated and band-passed data comparing RABC/B and RABC/D during the windiest period.....	17
Figure 12. Comparison of wind speed and vibration amplitude at station RABC using available wind data.	17
Figure 13. Ground motion on Rainbow Bridge (RABC) and at the nearby reference station (RABD) during two small regional earthquakes.....	18
Figure 14. Site-to-reference spectral ratios comparing ground motion on Rainbow Bridge (RABC) to the nearby reference on bedrock (RABD).....	19
Figure 15. a) Geometry and mesh of the finite-element model generated from photogrammetry	21
Figure 16. Predicted first eight modes of vibration for Rainbow Bridge with accompanying Eigen-frequencies listed.....	23
Figure 17. Spectrum of typical helicopter noise originating from different vibration sources.....	24

Figures (continued)

	Page
Figure 18a. Impulsive noise generated by a UH-1H helicopter, highlighting relative contributions from blade-slap and thickness noise phenomena.....	25
Figure 18b. Variation of noise amplitude with angle from the main-rotor.....	25
Figure 18c. Variation of main-rotor noise amplitude with forward airspeed.....	26
Figure 19. Helicopter noise data computed at a common distance.....	27
Figure 20. Four modeled modes of vibration for Rainbow Bridge.....	29
Figure 21. Partly detached slab on the underside of the eastern abutment of Rainbow Bridge.....	30
Figure 22. Partly detached slab on the western abutment of Rainbow Bridge.	31
Figure 23. Sound spectrum of a typical propeller-driven aircraft.	32
Figure 24. (a, b) Modeled principle compressive stresses with scaled orientation indicators.....	35
Figure 25. Displacement of Rainbow Bridge under the influence of gravity highlighting the tendency for northward (y) rotation (i.e. outward component of displacement vectors).....	36
Figure 26. Redrawn from Skipper (1989): displacement monitoring at Rainbow Bridge between 1986 and 1990, measurements twice per year in spring and fall.....	38
Figure 27. Cumulative in-plane (i.e. azimuth 065°) horizontal displacement of three BOR monitoring points on Rainbow Bridge.....	39
Figure 28. a) Modeled displacement at maximum deflection (summer); b) at minimum (winter).....	41
Figure 29. 2-ft BOR topographic map of Rainbow Bridge.....	42
Figure 30. Vibrating wire scissor-jack crackmeter installed in a crack in Yosemite.....	49
Figure 31. Proposed location for scissor-jack crackmeter installation, within crack at western abutment.	49
Figure 32. Pankow (2012) peak ground velocity (PGV) predictions for Utah using Chiou et al. (2010) ground-motion-prediction equations and local earthquake data.....	51
Figure 33. Earthquakes occurring within 150 km of Rainbow Bridge during the past 35 years.	52
Figure 34. Hauling monitoring equipment to the top of the bridge.	58

Tables

	Page
Table 1. Summary of key spectral and polarization data from ambient vibration measurements at RABC.....	12
Table 2. Comparison of modeled and measured modal frequencies and polarization at sensor position RABC.....	22
Table 3. Blade-pass frequency estimates for different common helicopter models.....	26
Table 4. Intact rock sample properties reported by Dames and Moore (1972).....	34
Table 5. Triaxial test data for Navajo sandstone samples reported by Dames and Moore (1972); Hoek-Brown m_i values were calculated here using Roclab software (www.roscience.com).	34
Table 6. Rock mass material properties used by Dames and Moore (1972).....	36
Table 7. Displacement data regenerated from Skipper (1989) BOR monitoring annual report. Values in gray are suspect data that may reflect settlement of the reflectors or base station monument.*	43

Executive Summary

Rainbow Bridge is an exceptionally rare natural arch with deep cultural significance. This study analyzed the potential for aircraft, specifically helicopters and fixed-wing propeller-driven airplanes, to generate noise (i.e. air pressure waves) that excites resonance of Rainbow Bridge. Helicopters in particular emit noise at frequencies between ~10-30 Hz, controlled by the blade-pass frequency of the main rotor, which is in the range of known resonant frequencies for many natural structures. This noise is maximized in the plane of the main rotor and increases with forward air speed. When a periodic air pressure pulse acts on a structure with similar natural frequency, resonance can be excited, generating large deformations, internal stresses, and potential damage.

We measured the natural frequencies of Rainbow Bridge during a field test recording ambient vibration data (i.e. no forced excitation). Using data from two broadband seismometers placed on the bridge, compared to two nearby reference stations, we distinguished several modes of vibration for Rainbow Bridge: results show strong spectral peaks at resonant frequencies of 1.1, 2.2, 2.5, 4.2, 4.4, 5.2, 6.2, 7.9, and 9.6 Hz. Each spectral peak was then processed for polarization attributes in an attempt to clarify the modes of vibration from experimental data; e.g. the fundamental mode at 1.1 Hz represents out-of-plane flexural bending of the arch. These modes were further explored through numerical modal analysis, where we used a new 3D photogrammetric model of Rainbow Bridge to predict the complete vibrational response. Results compare well with measured data, and we are able to match seven out of the first eight modes within expected margins of error. Wind generated strong vibration of the bridge, exciting resonance, while large site-to-reference spectral ratios resolved from experimental data indicate high amplification on the bridge as compared to nearby bedrock.

While the lowest modes of vibration of Rainbow Bridge appear to be insensitive to helicopter or fixed-wing propeller aircraft excitation (i.e. well below typical blade-pass frequencies), significant higher-order modes may be excited by helicopters with unknown consequences for global or local rock mass damage. Moreover, several partly detached slabs on each bridge abutment may have unique resonant frequencies capable of being excited by helicopter noise, with unknown effects. Due to the complex composition of Rainbow Bridge, combined with its exceptional cultural significance, I recommend adopting conservative guidelines for aircraft standoff distances. Specifically, I recommend prohibiting helicopter flight within a $\frac{1}{4}$ mile (1320 ft or 400 m) horizontal radius of Rainbow Bridge for elevations below 5000 ft a.s.l. (i.e. 1050 ft or 320 m above the top of the bridge). Future field testing would be required to determine if the selected avoidance distances are sufficient to limit induced vibrations below the proposed velocity threshold for damage avoidance of 2 mm/s.

I further compiled and analyzed data from several past Bureau of Reclamation reports, and conducted preliminary structural and thermal deformation analyses of Rainbow Bridge using the 3D numerical model. The results help inform proposed future studies and long-term monitoring to capture cumulative effects of natural and anthropogenic vibration sources. Wind may be one of the most damaging natural vibration sources affecting Rainbow Bridge, while a search of the USGS earthquake catalog revealed no likely damaging events have occurred in the past 35 years.

Acknowledgments

The research team thanks the following tribal organizations for motivating this study and allowing access to Rainbow Bridge: Navajo Nation, Hopi Tribe, Kiabab Paiute Tribe, San Juan Southern Paiute Tribe, White Mesa Ute, and the Pueblo of Zuni. I gratefully acknowledge field assistance, technical input, and relevant data provided by cooperating researchers, including text on supersonic flight by Randy Stanley, as well as field and technical assistance provided by GLCA and GRD staff.



Rainbow Bridge as seen from the trail looking westward. Inset is the general location of Rainbow Bridge National Monument (RABR) in the State of Utah.

Introduction

Rainbow Bridge is a sacred site of exceptional importance to neighboring Indian tribes, as well as a unique geological feature with national significance as one of the world's largest known natural bridges. Rainbow Bridge is also a prominent visitor attraction managed by the National Park Service as a National Monument (RABR). Most visitors arrive by boat and foot, while some view Rainbow Bridge from the air as part of helicopter and fixed-wing aircraft tours offered by commercial operators. Anthropogenic sources of vibration (e.g. aircraft and foot traffic) have the potential to excite resonance of sensitive rock structures like Rainbow Bridge, and in doing so may generate stresses that exceed the strength of rock resulting in internal damage. Rock masses are ubiquitously fractured with cracks and pre-existing flaws at many scales, and frequently rely on small patches of intact rock between discontinuities to maintain local and global stability. Incremental internal rock damage constitutes progressive failure, and in many cases shows no distinguishable surface signature. Vibration sources (natural and anthropogenic) can impart stresses within rock structures that promote internal damage and may ultimately contribute to partial or total failure. Investigating the potential for anthropogenic vibration-induced damage may thus help minimize physical impacts on culturally significant and irreplaceable natural resources.

The potential for vibration-induced structural damage is maximized when source vibration frequencies match the natural modes of vibration of a structure exciting resonance – displacement and force amplitudes are greatest for vibration occurring at resonant frequencies. Any man-made or geological structure has several important natural modes; the lowest is termed the fundamental but any number of higher-order modes may be significant. Source vibrations from aircraft originate primarily from noise generated by the passage of propeller or rotor blades, with the dominant energy occurring at the blade-pass frequency and its overtones. Helicopters generate noise in generally lower frequency bands than fixed-wing propeller aircraft, within the range of known natural frequencies for many civil and geological features, and are thus likely to pose the greatest threat to the structural stability of Rainbow Bridge from anthropogenic vibration sources (Volpe, 2014). A key unknown, however, are the natural frequencies of Rainbow Bridge, which cannot be adequately predicted from literature review alone and must be measured. I report on field testing conducted to measure resonant frequencies (i.e. excited natural modes), as well as numerical modeling confirming and exploring experimental data, and then compare my results to data on aircraft source noise.

The primary goal of this study was to measure the resonant frequencies of Rainbow Bridge. Field testing included measurements of ambient vibration (natural background motion, no forced excitation), which were used to experimentally resolve resonant frequencies. These were then explored using 3D numerical modal analysis, predicting the frequency and shape of vibration at different modes. This same methodology has been used by the investigator on several natural arches in southeastern Utah (e.g. Starr et al., 2015) and has proven successful in identifying resonant frequencies of geological features.

Detailed goals of this study include:

1. Measure the resonant frequencies of Rainbow Bridge from ambient vibration data. Measure background vibration amplitudes from natural sources (e.g. wind, earthquakes).
2. Conduct 3D numerical modal analysis of Rainbow Bridge to verify resonance measurements and describe important mode shapes, as well as explore higher-order resonant modes not identified in experimental data.
3. Assess the potential bridge response to air tour traffic, evaluating data for aircraft source noise compiled from existing tests and literature review. Key question: are aircraft able to excite resonance of the bridge?
4. Review past data and analysis of structural conditions at Rainbow Bridge; perform preliminary numerical structural and thermal deformation analyses.
5. Review past studies on vibration-induced damage, and recommend maximum allowable vibration thresholds for damage avoidance.
6. Suggest proposed stand-off distances for aircraft flights near Rainbow Bridge that limit induced-vibration and safeguard against adverse structural effects.
7. Inform potential management steps to prevent anthropogenic degradation of Rainbow Bridge.

Recommendations and analysis provided in this report are based on: a) literature review of past studies of aircraft-induced vibrations and potential for damage of sensitive cultural and natural resources, b) review of existing Bureau of Reclamation reports detailing previous structural studies at Rainbow Bridge, c) input and data supplied by NPS Physical Scientist / Acoustic Specialist Randy Stanley regarding noise generated by common helicopter models, d) a 3D model of Rainbow Bridge generated by NPS Geologist / Photogrammetry Specialist John Wood, and e) results of in-situ ambient vibration testing conducted by the research team on March 23 and 24, 2015.

Data Summary and Discussion

Vibration, tilt, and environmental data

We conducted a field test on March 23-24, 2015 to measure the ambient vibration of Rainbow Bridge and extract its resonant frequencies from ambient motion data. Environmental and tilt sensors were included to assess effects and response of the bridge to different environmental driving factors (e.g. temperature and wind). Sensors deployed in the test were:

Nanometrics Trillium Compact broadband seismometers (4) with Centaur data loggers, labelled RABA, RABB, RABC, RABD, sampling at 100 Hz; measuring ground vibration (velocity).

- Onset Hobo U23 Pro temperature (3) and relative humidity (1) sensors / data loggers, sampling at 1 min. interval; measuring rock temperature, air temperature, and relative humidity (RH).
- Onset wind speed smart sensor and H21 data logger, sampling at 1 min.; measuring wind speed.
- Jewell Instruments model 701-2(4X) biaxial tilt meter with Campbell Scientific CR800 data logger, sampling at 1 min. interval, measuring tilt of the arch top surface.

The layout of sensors is shown in Figures 1 and 2. Meteorological conditions at the time of the test were predominantly sunny with fair temperatures and calm winds during the day, with strong winds early in the evening settling to calm winds overnight and early morning (Figure 3).

The duration of data generated by each sensor was as follows, with the given time ranges representing ‘clean’ data blocks when the sensors were operational and all personnel had left the immediate area. Seismometer times are UTC (= MDT + 6 h), all other times are local MDT (Utah).

- Seismometer RABA: 3/23 21:00 – 3/24 19:00
- Seismometer RABB: 3/23 23:00 – 3/24 19:00
- Seismometer RABC: 3/23 23:00 – 3/24 19:00
- Seismometer RABD: 3/24 01:00 – 3/24 17:00
- Air temperature + RH: 3/23 15:00 – 3/24 13:00
- Rock surface temperature: 3/23 17:00 – 3/24 13:00
- Wind speed: 3/23 15:00 – 3/23 20:57 (sensor was blown over)
- Tilt sensor: 3/23 17:00 – 3/24 13:00



Figure 1. Overview of sensor locations on and around Rainbow Bridge. Reference seismometer is RABD. RABB and RABC are 12.5 m apart on the bridge; RABA is on the adjoining knoll. (Google Earth).



Figure 2. a) Layout of sensors on and around Rainbow Bridge, b) close-up view of sensors on bridge, c) different sensors on bridge under respective covers, d) reference seismometer 220 m from bridge. e) Overview of sensor cluster on Rainbow Bridge (view along trend of the bridge at $\sim 065^\circ$ azimuth).

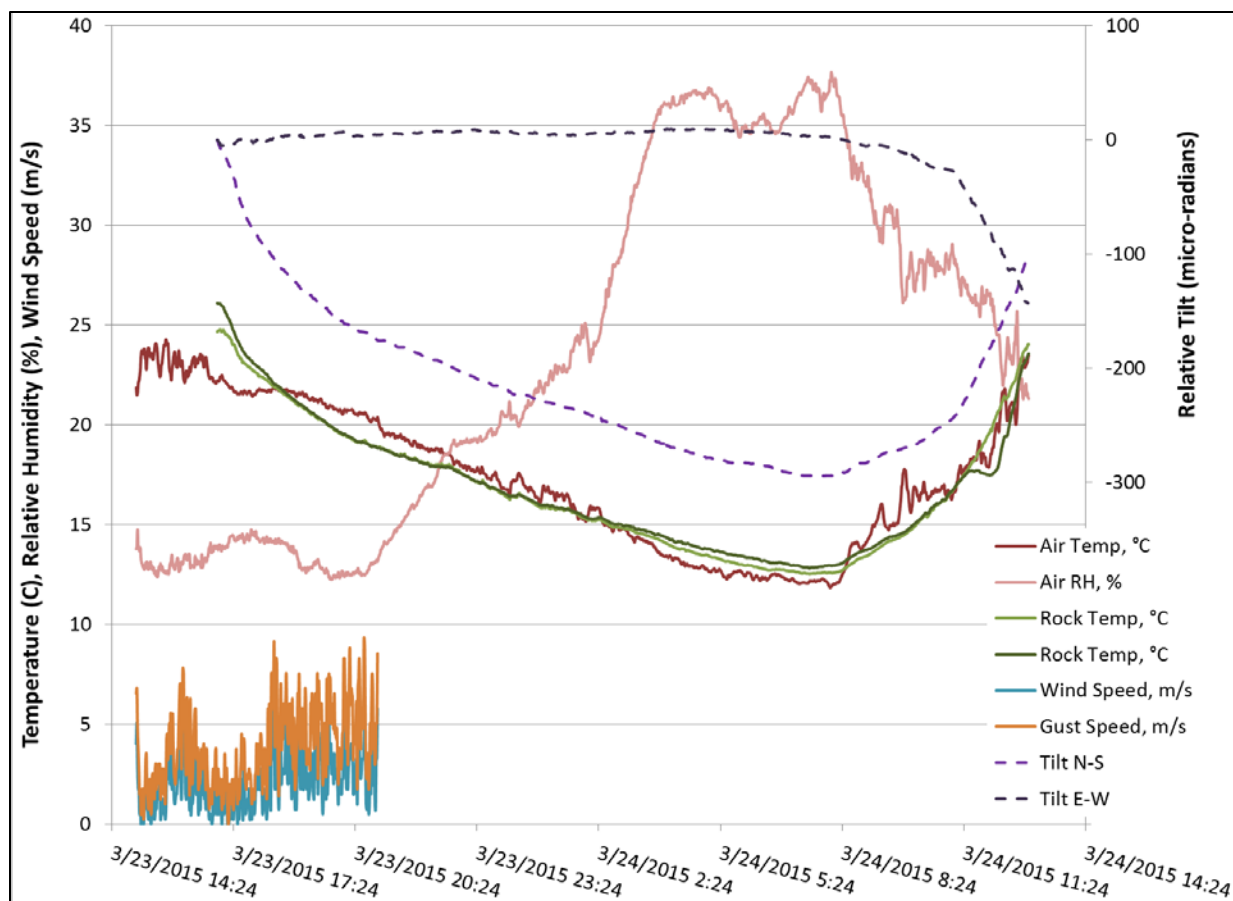


Figure 3. Summary of meteorological conditions during the period of field testing at Rainbow Bridge. Northward relative tilt data displayed on secondary vertical axis show close correspondence with rock temperature, with the bridge top surface tilting toward the south as temperatures cool overnight, and to the north as temperatures warm the next morning. Thermo-elastic effects are the suspected source, and are explored in preliminary numerical modeling in a following section. Wind data are truncated at 20:58 when the portable wind sensor tripod was blown over. Times are MDT.

Seismometers were placed on solid, bare rock surfaces, aligned to magnetic north and leveled. Each of the three sensor feet was secured from shifting using a small dab of removable ‘poster putty’, and the sensors were covered with insulating coolers to minimize temperature changes. The tilt sensor was deployed in the same manner. Rock temperature sensors were placed on the top surface of the arch in slightly different positions, affixed with tape, and covered with small stones to prevent direct sun exposure. The air temperature + RH sensor was located atop the adjoining knoll, and used an aspirated radiation shield. Wind speed was measured on a short, ~1.5 m high portable tripod, also atop the knoll. Seismometer velocity response is flat in the 0.05 – 100 Hz passband, and data were thus converted to ground velocity by multiplying by the instrument scaling factor of 3E9 counts/m/s at the chosen digitizer gain. Tilt data were corrected for sensor temperature per manufacturer’s recommendations. All raw and processed data generated during the test are available with this final report.

Figure 4 presents an overview of the complete data time series from seismometer RABC, the sensor position farthest out on the bridge lintel (see Figure 1). Data shown are ground velocity (in m/s) of three orthogonal components of motion: bridge-perpendicular, bridge-parallel, and vertical. The bridge parallel direction is defined as an azimuth of 065°. Unfiltered data are broadband as recorded, while band-passed data are filtered between 1-10 Hz showing motion at frequencies most relevant to arch resonance. Some basic information can be gleaned from this time-series:

- Winds picked up shortly after the start of the test, increasing in strength until ~23:00 local time (note the wind sensor blew over at 20:58).
- Maximum ground vibration velocities during the windiest period of the test were $\sim 1.5 \times 10^{-5}$ m/s (0.015 mm/s), with greatest vibration amplitudes in the arch-perpendicular direction.
- Band-passed filtered data show two ‘spikes’ at 11:32 and 13:26 on 3/24/15, which are two small earthquakes entered into UUSS and USGS catalogs with epicenters near Panguitch, UT.
- Unfiltered vertical component data show tilt of the sensor, which is normal and expected, but of little value given the accompanying tiltmeter data.

Figure 5 shows a spectrogram (illustrating signal frequency content over time) of raw data recorded at seismometer RABC on Rainbow Bridge. The records are in the original sensor orientation (N-S, E-W, vertical) and filtered between 0.5-40 Hz. Data show that the spectral content of ambient motion has several distinct peaks at dominant frequencies (indicated by horizontal lines in the plot). The strongest spectral peaks occur at frequencies between 1-10 Hz. These appear steady over time, and likely thus represent resonant frequencies of Rainbow Bridge and/or other nearby resonating features. The spectral content of ambient motion is further clarified in Figure 6, which shows a power spectral density (PSD) plot indicating power in the data at different frequencies for a 1-hr time block. Peaks in the PSD plot occur at specific frequencies corresponding to horizontal lines in the spectrogram, again likely indicating the resonant frequencies of Rainbow Bridge and surrounding features (e.g. the rock knoll to the south, bushes, boulders). These peaks are not observed in data from the reference seismometer RABD located 220 m away from the bridge on the canyon floor (Figure 6).

Figure 7 shows PSD plots from all four seismometers (RABA-RABD) during three coincident 1-hr time blocks: 04-05 UTC during a windy period, and 10-11 and 14-15 UTC during relatively quiet periods. Data show that prominent spectral peaks are not identical on all sensors. RABC provides the most useful data for evaluating the resonant frequencies of Rainbow Bridge, while data from RABB and RABA are valuable for comparison. RABA was located on the adjoining rock knoll, a feature with its own resonant modes that may leak into the signal on the bridge through mechanical attachment. Stations RABC and RABB show similar spectra, though peaks at RABB are muted compared to RABC due to its location at the bridge abutment.

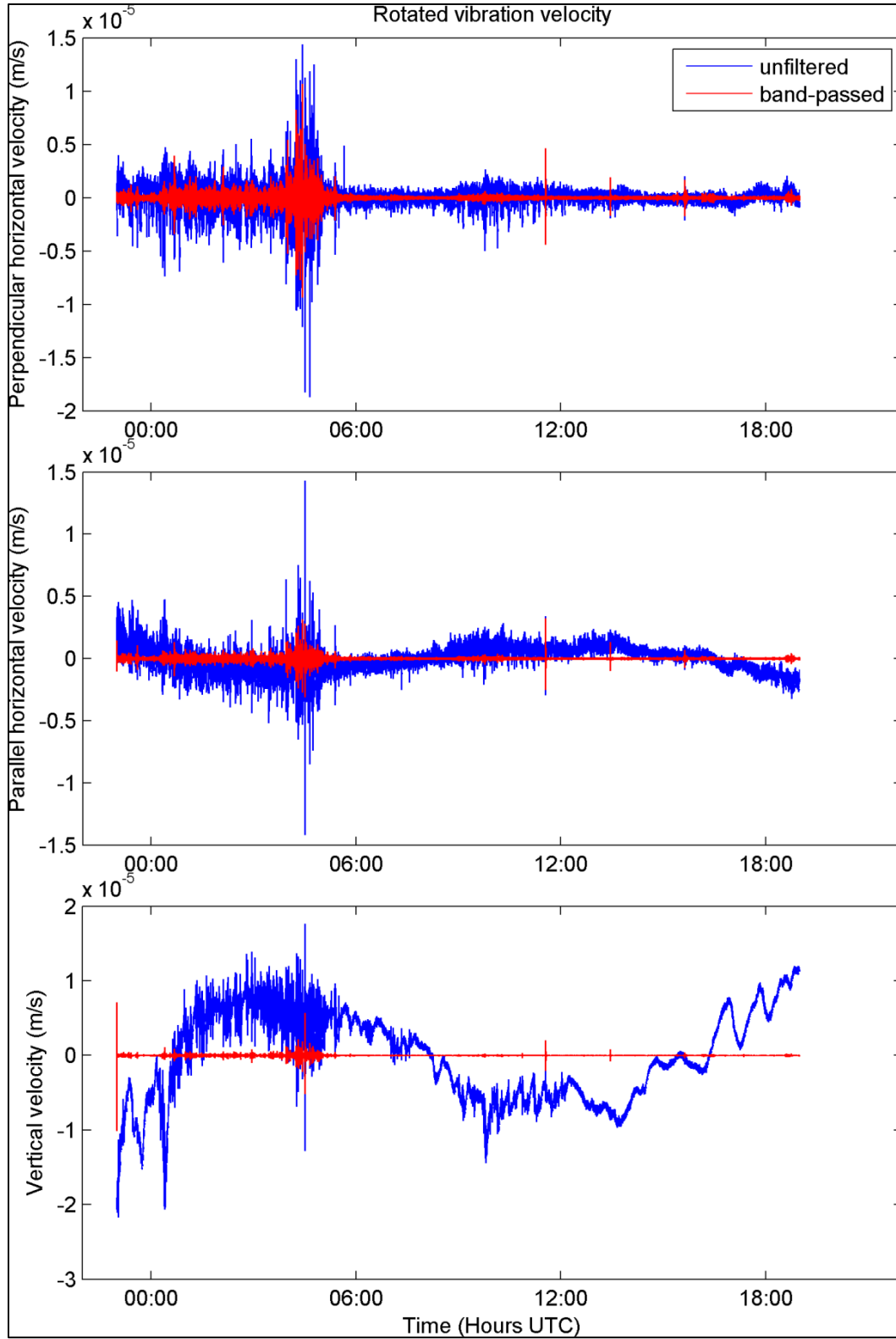


Figure 4. Time-series data from seismometer RABC located on Rainbow Bridge. Horizontal components have been rotated to bridge-perpendicular and bridge-parallel (065°) orientations. Band pass is 1-10 Hz. Available media: RABCfull.mp3, band-passed perpendicular horizontal velocity data sped up 50 times.

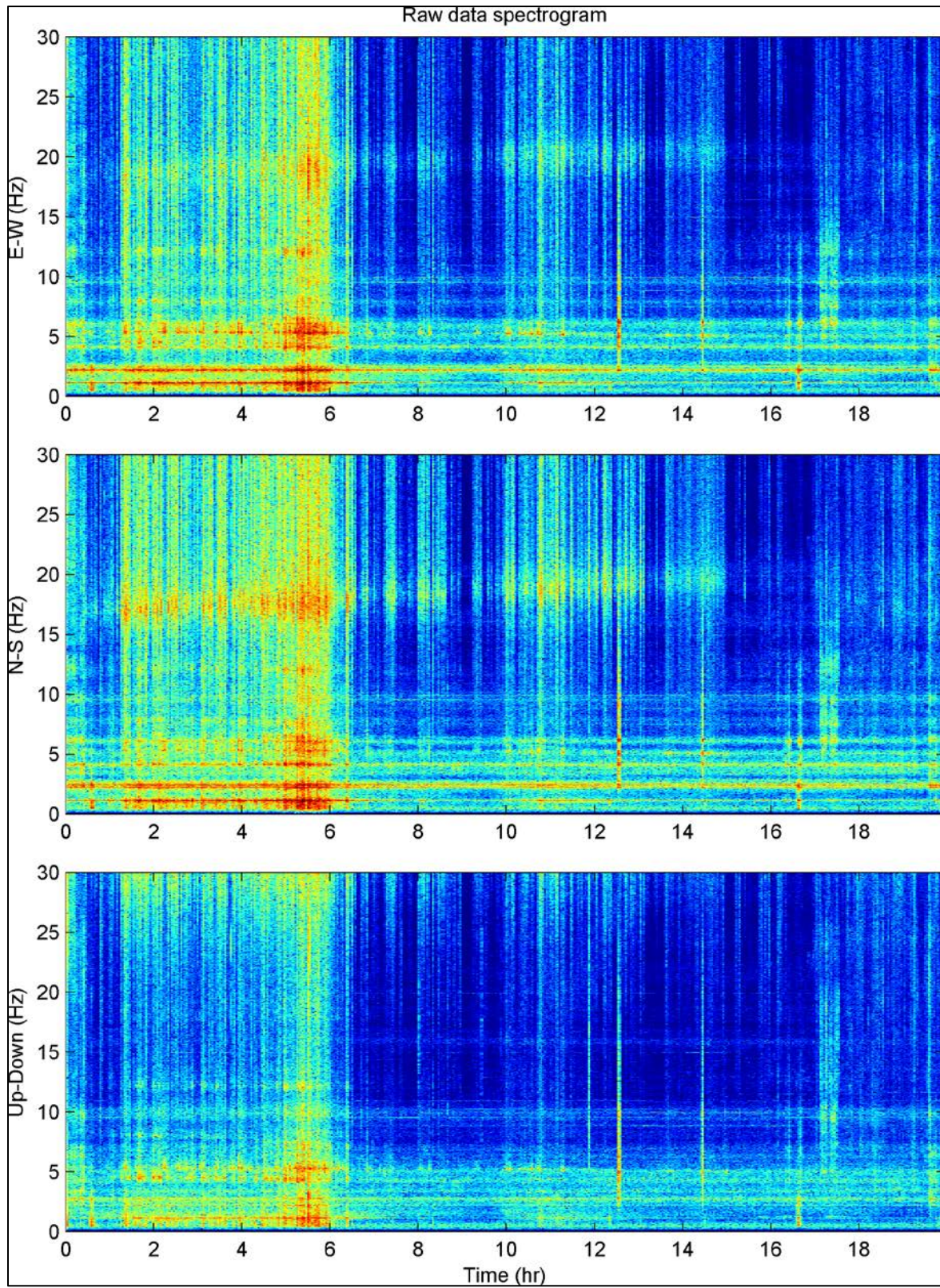


Figure 5. Raw data spectrogram from seismometer RABC on Rainbow Bridge. 0 hr is 3/23/15 23:00 UTC.

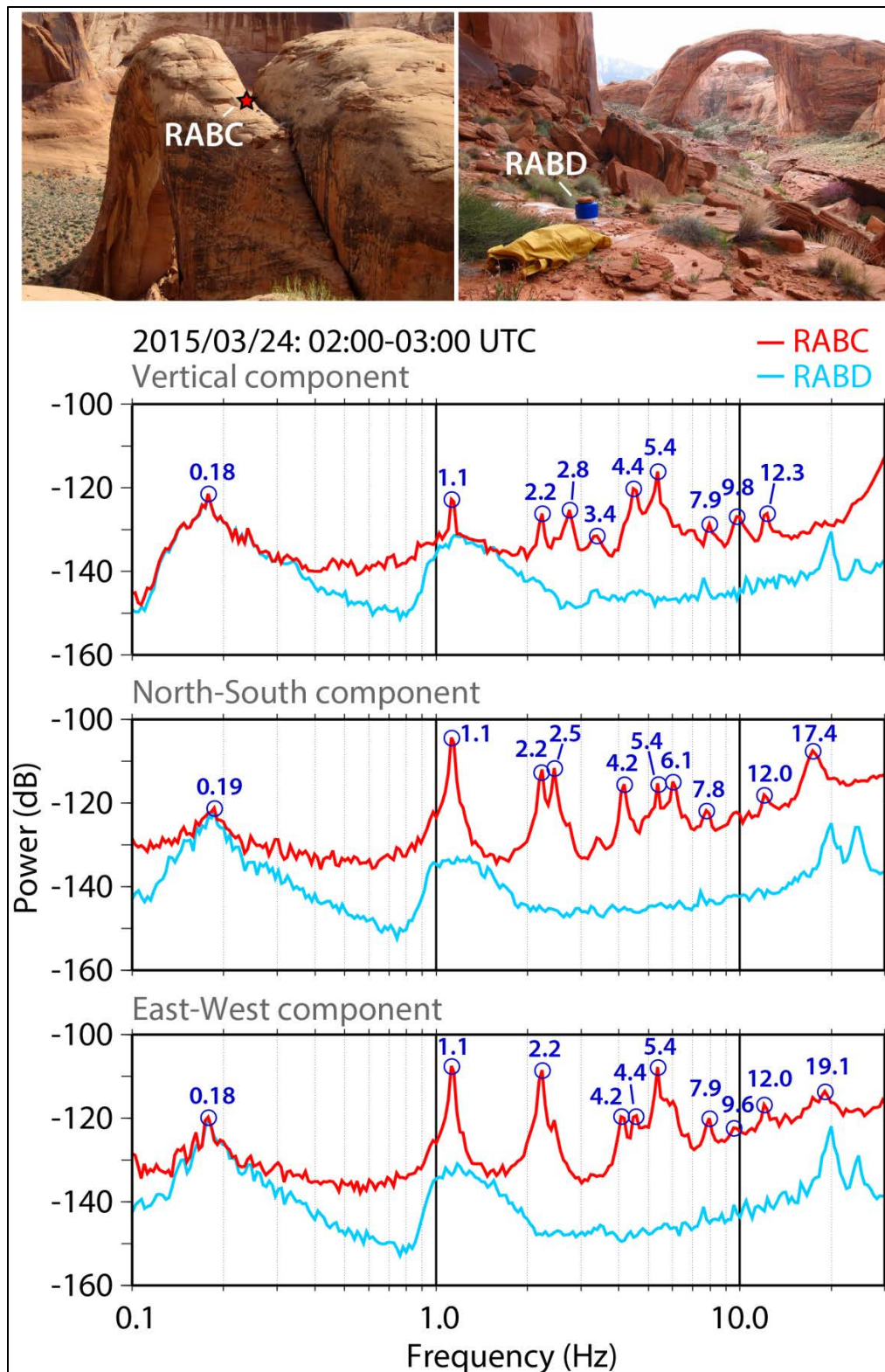


Figure 6. Power spectral density plots for sensor RABC (red) on the bridge and reference sensor RABD (blue) on the canyon floor for a selected 1-hour time period exhibiting typical results. Peak frequencies are labeled. Power is reported in decibel (dB) units of spectral ground acceleration, $10\log_{10} [\text{m}^2/\text{s}^4/\text{Hz}]$.

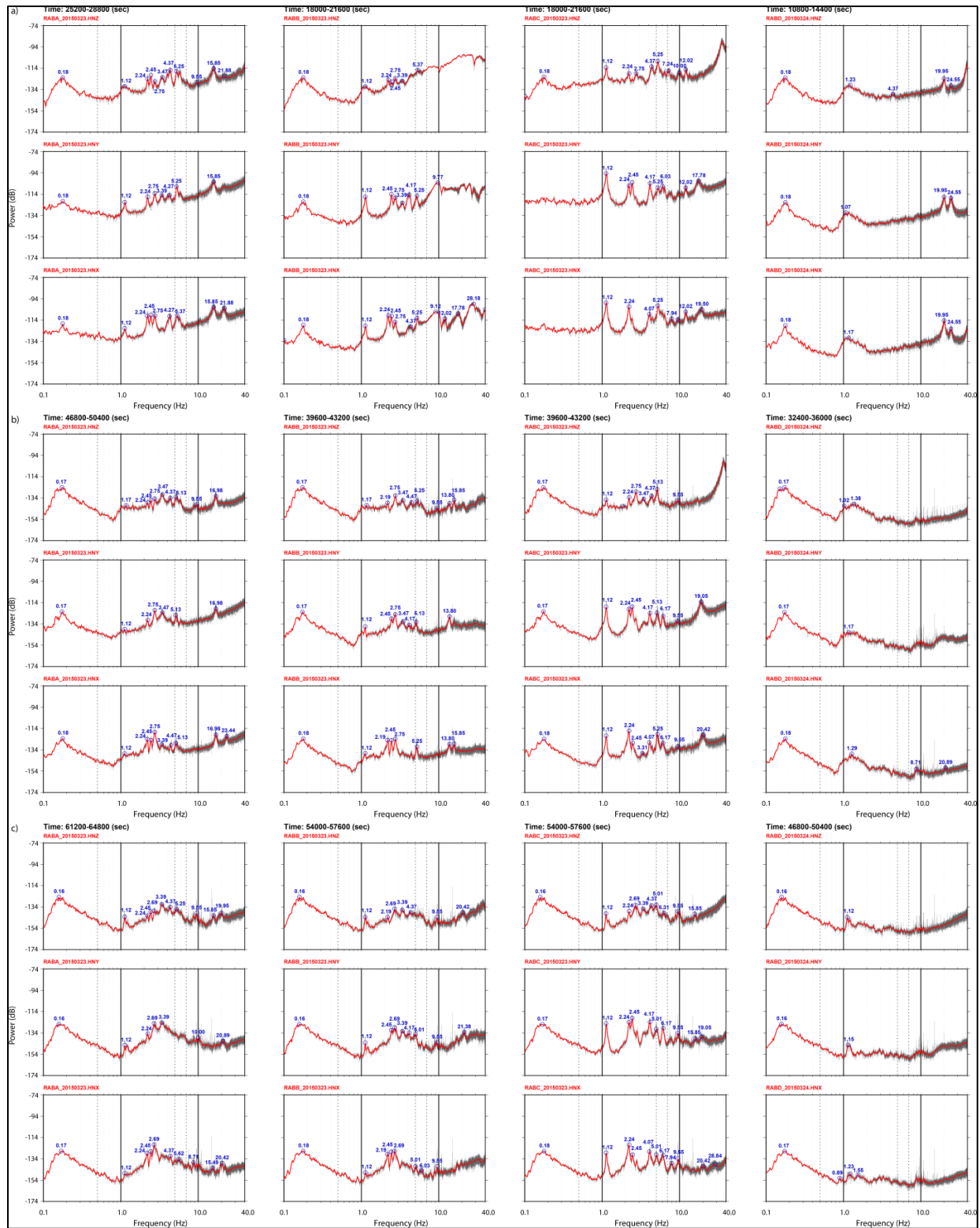


Figure 7. PSD plots for seismometers RABA-RABD (columns) from coincident time periods: a) 04-05 UTC, b) 10-11 UTC, c) 14-15 UTC on 3/24/15. RABA is located on the rock knoll, RABB is on Rainbow Bridge at the west position, RABC is west-center on Rainbow Bridge, RABD is 220 m northwest of the bridge.

Predominant spectral peaks observed at station RABC are listed in Table 1. Data reveal that the fundamental frequency of vibration of Rainbow Bridge is 1.1 Hz, the first and strongest spectral peak in most data from RABC (Figure 6). This peak appears strongest on the horizontal components, and thus likely represents out-of-plane flexure of the arch. Other notable spectral peaks at RABC that likely represent resonant modes of the bridge occur at 2.2, 2.5, 4.2, 4.4, 5.2, 6.2, 7.9, and 9.6 Hz (Figures 6 and 7). Several peaks above 10 Hz appear in our data, but lack strong power or clear signal over time making these difficult to interpret. In particular, the peak at 12 Hz noted in Table 1 was only identified during the windiest period, and may represent wind-blown vibration of a sensor cable or cover. Some spectral peaks also likely originate from the adjoining rock knoll, as apparent by increased power on station RABA (e.g. 2.8 and 3.5 Hz). Dominant peaks from RABC can also sometimes be seen on RABA, especially during windy periods when bridge vibration amplitudes are largest. A common peak at ~0.17 Hz occurs in data from all seismic stations, which represents earth noise generated by distant ocean waves known as the microseism (Shearer, 2009). Most resonant frequencies appear stable over time, not varying by more than fraction of a percent during the ~20 h period of testing. Drift of the fundamental frequency, or lack thereof, is shown in Figure 8. Exceptions are vibration at 2.5 and 5.2 Hz; these frequencies drift slightly over the test period but without clear or related pattern.

Table 1. Summary of key spectral and polarization data from ambient vibration measurements at RABC

Frequency (Hz)	Strongest station	Strongest component	Degree of Polarization	Azimuth ° from M.N.	Incidence (0 = vert)	Note
1.1	RABC	Horizontals	1.0	145	85	Mode Rainbow Bridge
2.2	RABC	Horizontals	0.9	123	84	Mode Rainbow Bridge
2.5	RABC	N-S Horizontal	0.8	20	82	Mode Rainbow Bridge
4.2	RABC	N-S Horizontal	0.8	147	78	Mode Rainbow Bridge
4.4	RABC	Vertical	0.6	132	52	Mode Rainbow Bridge
5.1-5.5	RABC	E-W Horizontal	0.5	38	57	Mode Rainbow Bridge
6.2	RABC	N-S Horizontal	0.9	141	79	Mode Rainbow Bridge
7.9	RABC	E-W Horizontal	0.8	130	77	Mode Rainbow Bridge
9.6	RABC	Vertical	0.7	131	74	Mode Rainbow Bridge
12.0	RABC	–	–	–	–	Wind noise?

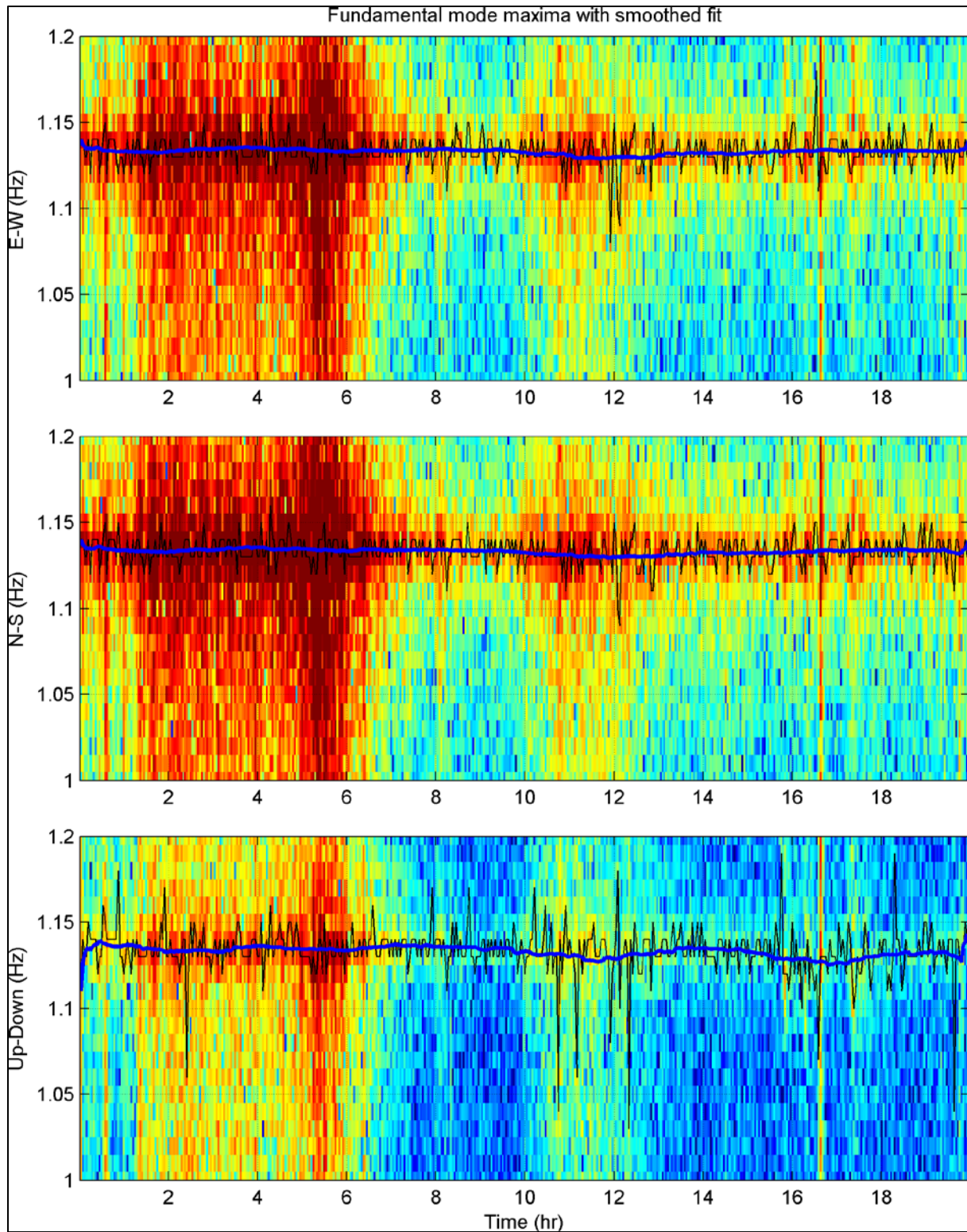


Figure 8. Variation of the fundamental frequency over time measured at RABC (0 hr is 23:00 UTC on 3/23/15); frequency remains relatively steady at 1.1 Hz over the duration of the test period, not varying systematically with time of day, rock temperature, or wind speed.

Ambient vibration data were processed for polarization attributes using methodology described by Koper & Hawley (2010), highlighting the degree of polarization (dimensionless, ranging from 0 to 1), the orientation of polarized motion in the horizontal plane (azimuth, 0° = magnetic north), and the dip of particle motion (0° = horizontal, 90° = vertical). Results are displayed in Figure 9 across all frequencies and Table 1 for select resonant frequencies. Several peaks in polarization magnitude can be seen in Figure 9, which correspond to the peaks in spectral power shown in Figures 5 and 6 and highlighted in Table 1. RABC shows strongest polarization at 1.1 Hz, which is not seen on RABA and to a lesser degree on RABB. Other polarization peaks on RABC are found at 2.2, 2.5, 3.5, 4.2, 6.2, 7.9, and 9.6 Hz. Horizontal polarization of ground motion at sensor RABC at the identified fundamental frequency of 1.1 Hz is shown in Figure 10. Raw, unfiltered data show rough alignment perpendicular to the bridge, while band-passed data around the fundamental frequency show strongly polarized, linear ground motion oriented perpendicular to the trend of the bridge.

Wind is able to excite resonance of structures (e.g. Boggs and Dragovich, 2006), and our test data show that vibration amplitudes increase markedly during windy periods (Figures 4 and 7). Figure 11 shows band-passed (1-10 Hz) vibration data from seismometers RABB, RABC, and RABD during the windiest portion of the test. Maximum vibration amplitudes of $\sim 1.5 \times 10^{-5}$ m/s occur around 04:25 UTC. In comparison, vibration amplitudes at RABB, located 12.5 m west on the bridge, are smaller, while vibration at RABD is scarcely visible at the selected scale. Vibration amplitudes from RABC are compared with available wind speed data in Figure 12. Unfortunately the wind sensor blew over before the period of maximum wind velocity. Figure 12 shows wind gust speed along with band-passed (1-10 Hz) and unfiltered vibration amplitude data. A trend is visible suggesting that vibration velocity scales with gust speed according to a quadratic relationship. However, the details of this trend cannot be fully resolved because of missing data at high wind speeds.

Figure 13 shows vibration data from station RABC and reference RABD generated by two small, regional earthquakes. These events were respectively: EQ1: 15/03/24 11:32:43 M_L (local magnitude) =1.7; EQ2: 15/03/24 13:26:27 M_L =1.4, and were both centered at 37.53N 112.31W near Panguitch, Utah. The epicenters are thus ~ 130 km away from Rainbow Bridge, and the earthquake magnitudes are very small, nevertheless both were recorded clearly in our seismic data at Rainbow Bridge. Band-passed (1-10 Hz) peak vibration amplitudes at station RABC are ~ 2 -4 $\mu\text{m/s}$, or 0.002 – 0.004 mm/s. Large amplification of ground motion is observed, however, for these small earthquakes on Rainbow Bridge as compared to the nearby reference on the canyon floor. Peak velocity amplitudes (in the 1-10 Hz band) occur on the bridge-perpendicular horizontal component, and are amplified 15-25 times as compared to ground motion at reference RABD. Meanwhile, peak horizontal velocity at RABC is amplified 3-6 times as compared to nearby station RABB on the west end of the bridge.

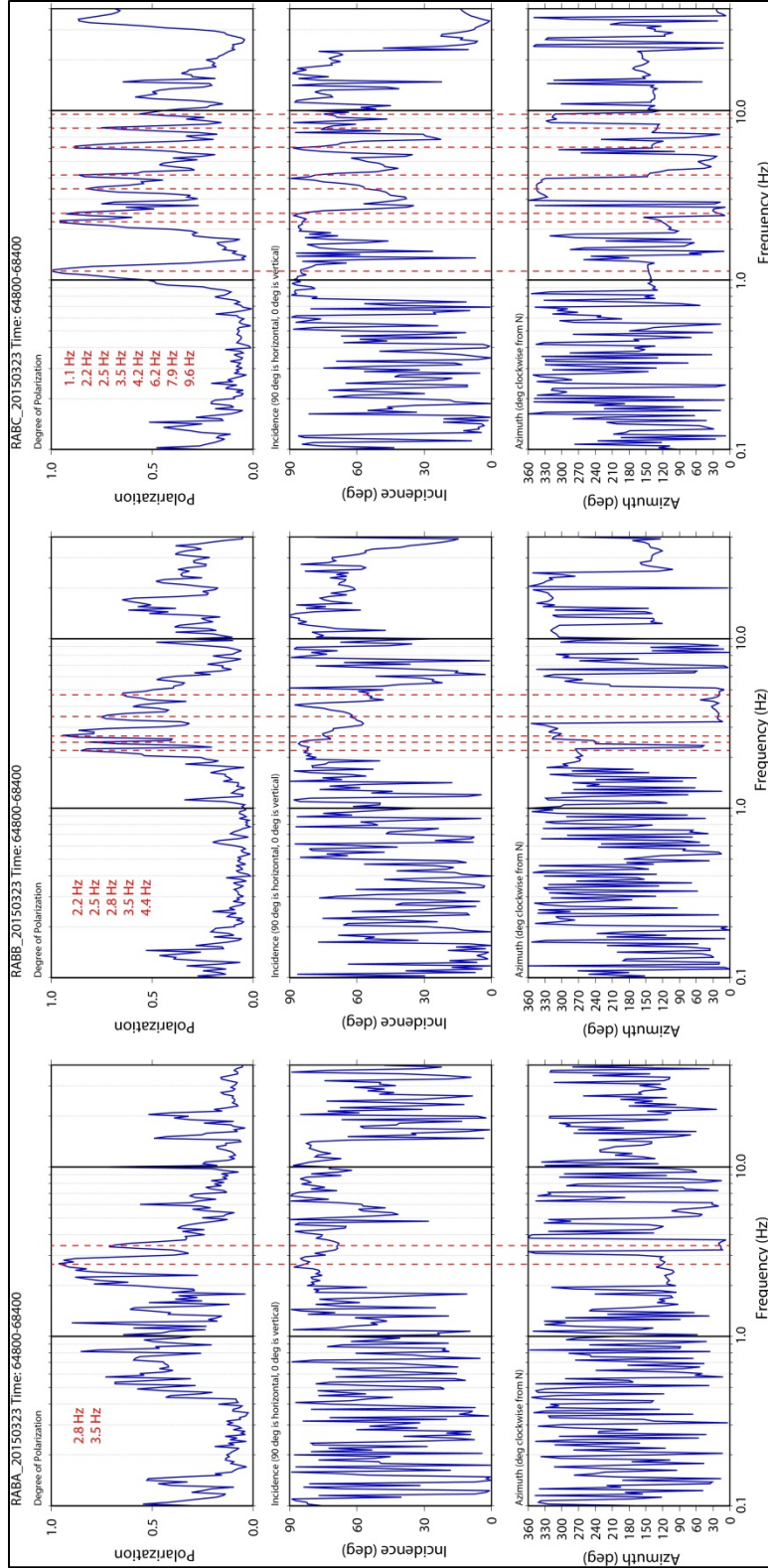


Figure 9. Polarization of ground motion at different frequencies for sensors RABA, RABB, and RABC. Peaks in polarization (1 = perfectly polarized motion) are seen at the frequencies highlighted in Figures 6 and 7. Incidence is angle from the horizontal, azimuth is degrees from magnetic north.

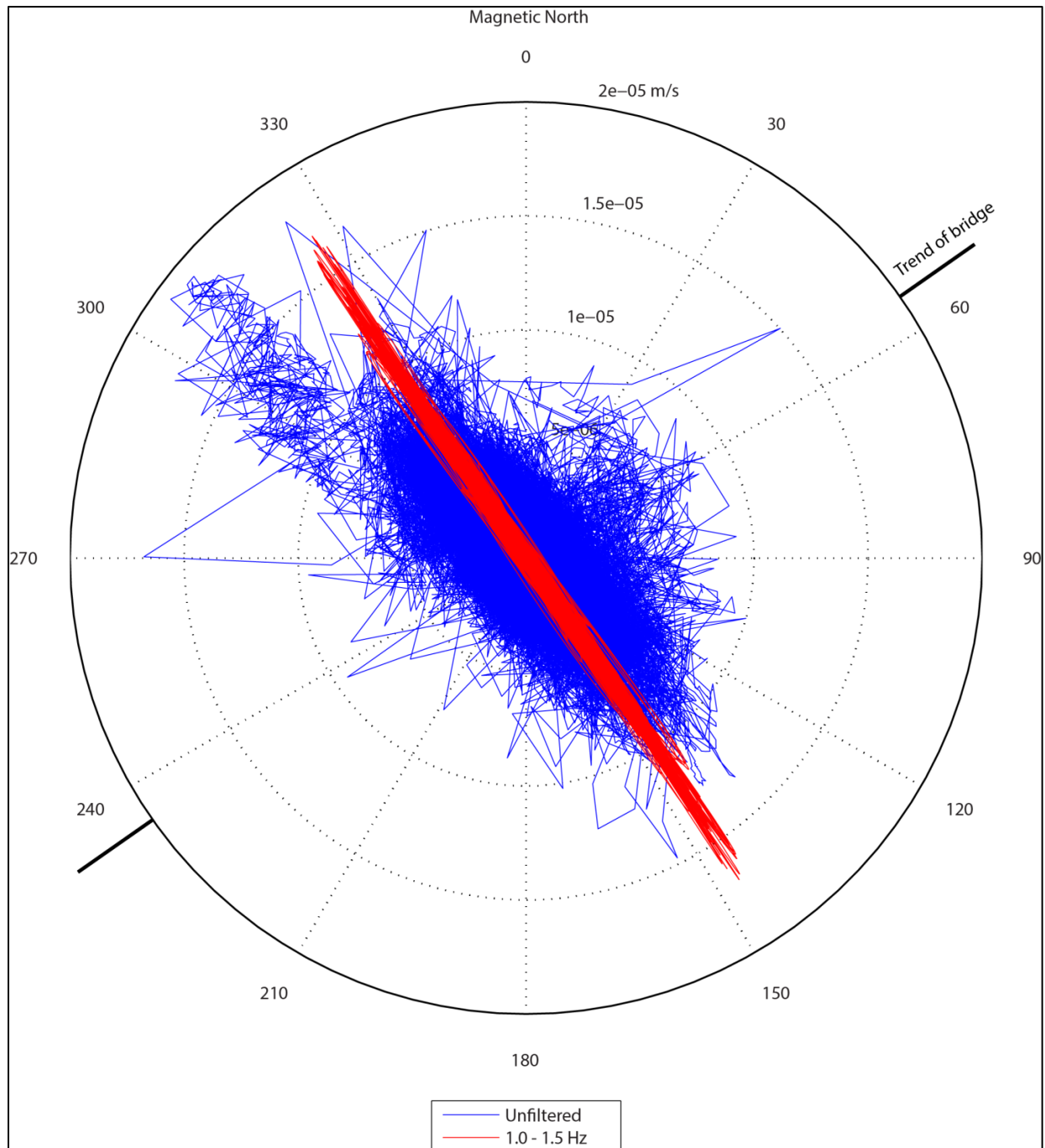


Figure 10. Polarization of ground motion in the horizontal plane at sensor RABC on Rainbow Bridge. Unfiltered velocity data in blue show rough alignment perpendicular to the bridge, while band-pass filtered data around the fundamental frequency (1.1 Hz) show strong polarization with ground motion oriented perpendicular to the trend of the bridge. Data are from the windiest period exhibiting strongest vibration amplitude. Figure 8 and Table 1 summarize polarization results at other frequencies.

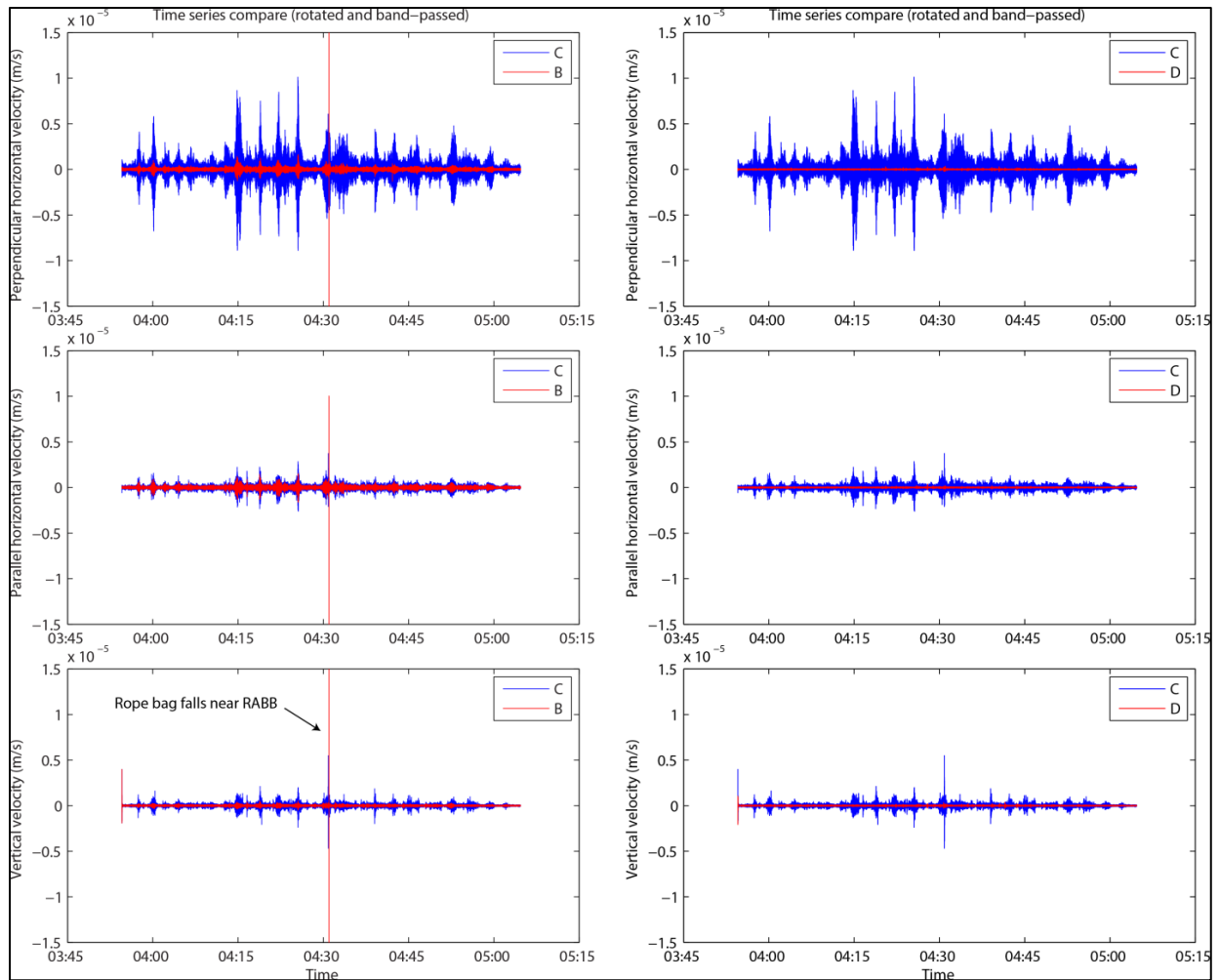


Figure 11. Rotated and band-passed data comparing RABC/B and RABC/D during the windiest period.

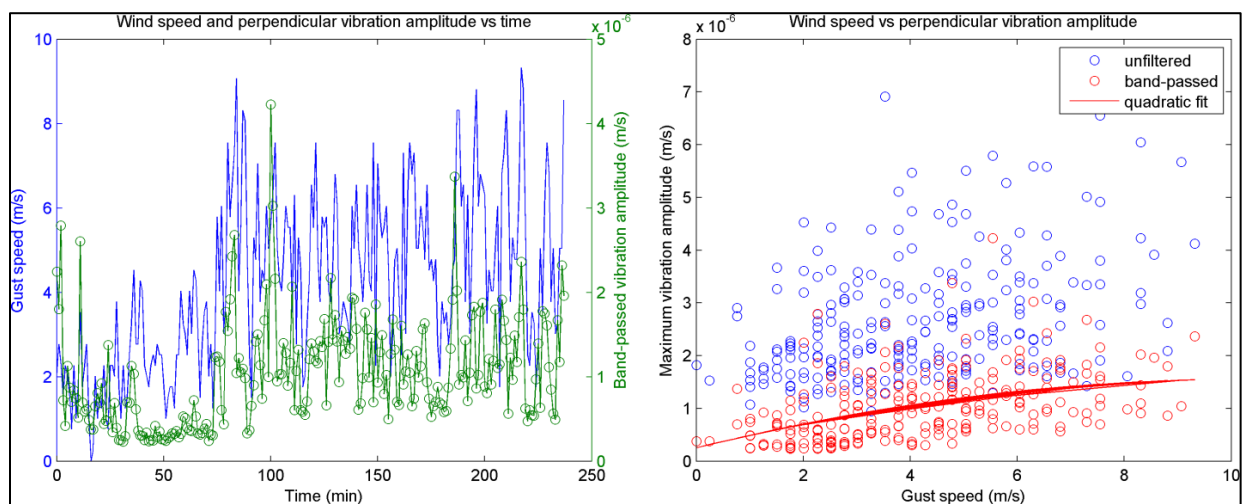


Figure 12. Comparison of wind speed and vibration amplitude at station RABC using available wind data.

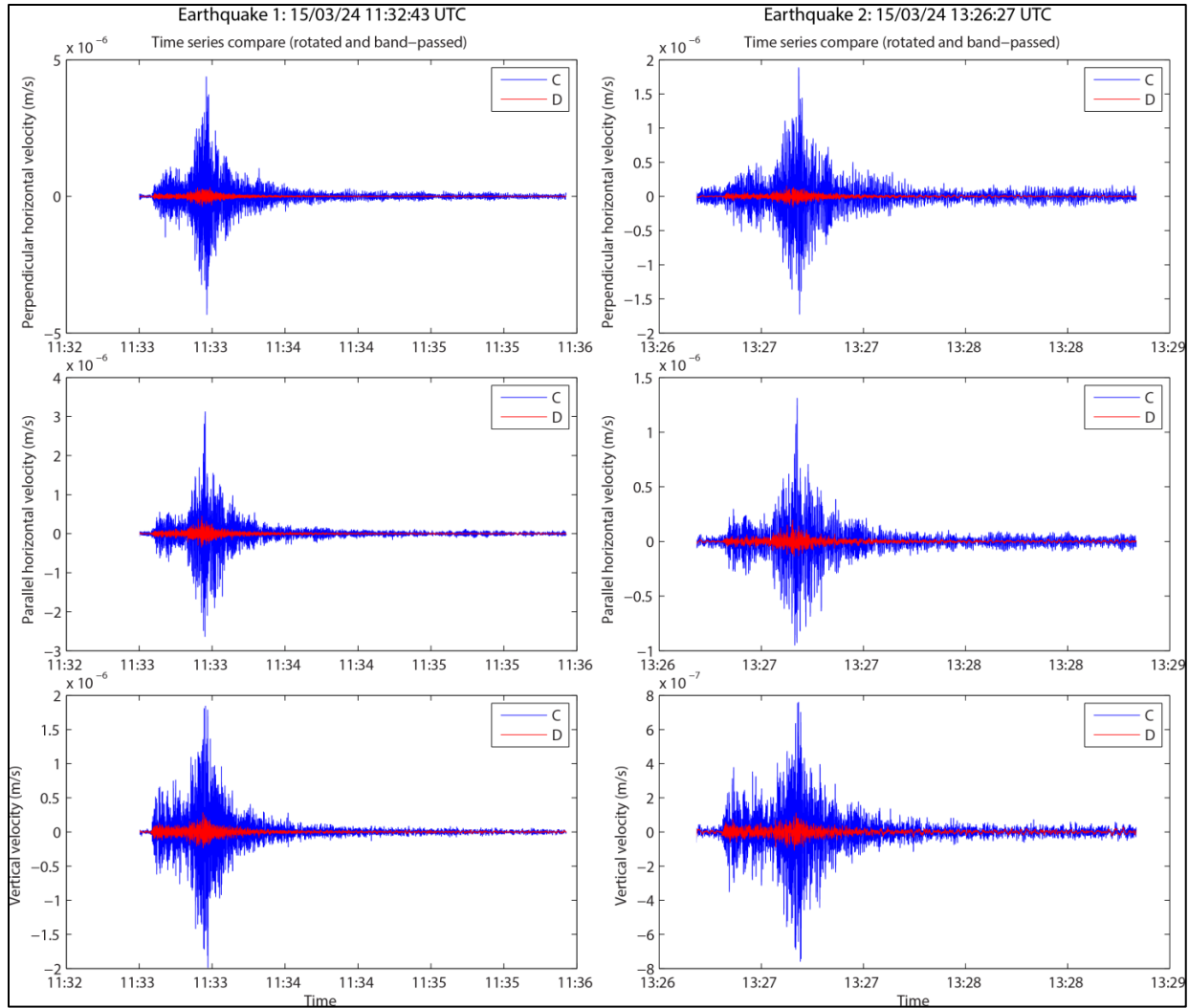


Figure 13. Ground motion on Rainbow Bridge (RABC) and at the nearby reference station (RABD) during two small regional earthquakes: EQ1: 15/03/24 11:32:43 M_L 1.7; EQ2: 15/03/24 13:26:27 M_L 1.4, both centered at 37.53N 112.31W, ~34 km south-southeast of Panguitch, Utah.

Ambient vibration data can be compared between a site (RABC) and a reference (RABD) station, creating so-called site-to-reference spectral ratios (e.g. Burjanek et al., 2012). Results illustrate the amplification of ground motion at distinct frequencies. We processed data only from calm, wind-free periods, as wind excites the arch differently than surrounding ground. Ambient vibration data at station RABC on Rainbow Bridge were compared with the reference station RABD using 10 h of data from quiet overnight hours. Resulting site-to-reference spectral ratios are shown in Figure 14, illustrating the ratio of vibration amplitude (as opposed to power shown in PSD plots) at the two stations. Data are rotated to bridge perpendicular and parallel for clarity. Results show strong spectral amplification at the resonant frequencies of Rainbow Bridge: vibration at the fundamental frequency is amplified ~13 times as compared to the reference sensor, while higher-order modes are amplified by factors of >40. These high amplification factors are generally larger than those measured on soil

sites and rock slope instabilities (e.g. Moore et al., 2011a). They result from the great flexibility of Rainbow Bridge caused in part by its slenderness.

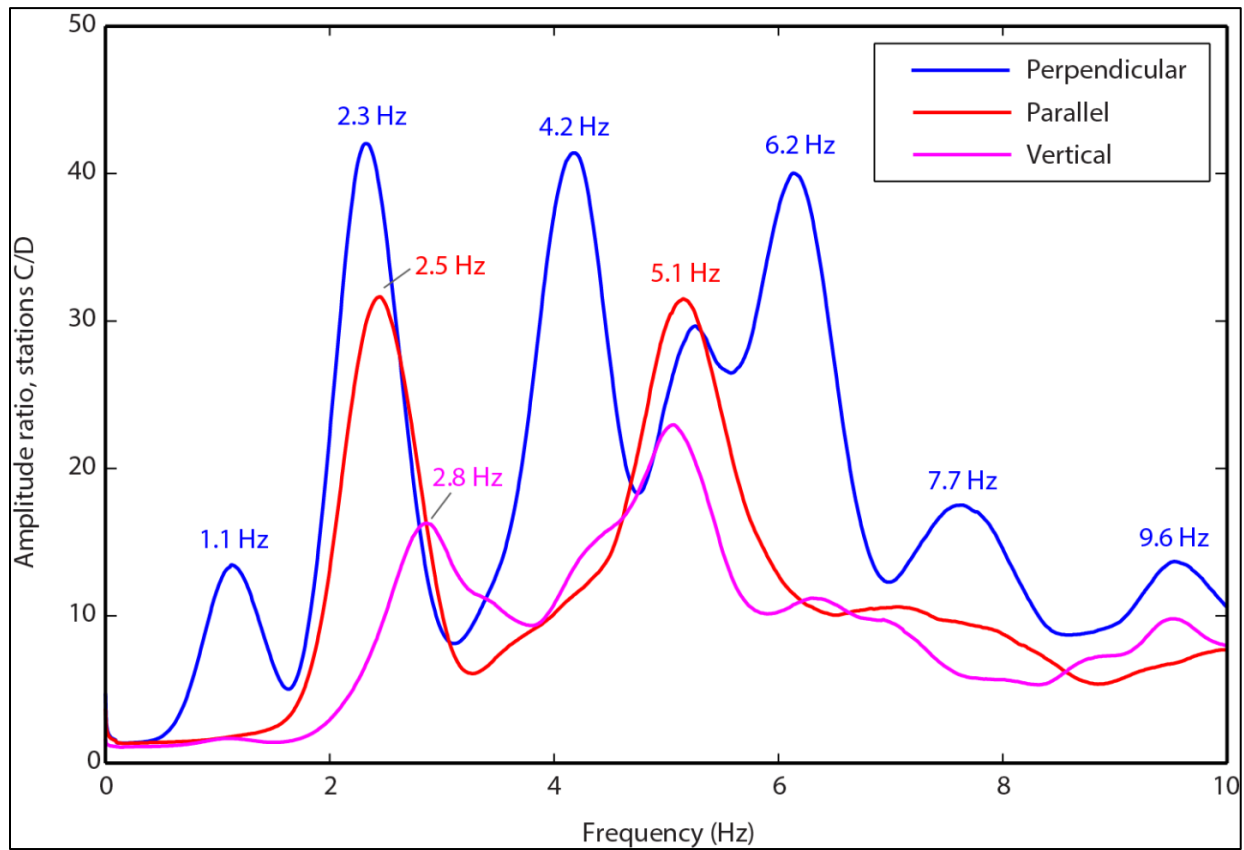


Figure 14. Site-to-reference spectral ratios comparing ground motion on Rainbow Bridge (RABC) to the nearby reference on bedrock (RABD). Spectral ratios up to ~40 indicate strong spectral amplification at the resonant frequencies of Rainbow Bridge. Data include the two earthquakes shown in Figure 13.

3D numerical modal analysis

Numerical modal analysis (i.e. Eigenfrequency analysis) of Rainbow Bridge was performed using the finite-element software COMSOL Multiphysics (<http://www.comsol.com/>). The goal was to match experimental data, calibrate key mechanical properties of the model, and view the complete set of predicted, significant resonant modes for Rainbow Bridge. Our experimental data highlighted several important modes, including the fundamental frequency of vibration; however, the ability to measure resonant modes depends on sensor location, which is in turn dependent on access, so modeling also helps ascertain whether important modes can be distinguished from other available sensor positions. Moreover, small-amplitude vibrations at higher-order modes may be difficult to detect in ambient seismic data, while some modes have nearly coincident frequencies that be impossible to distinguish. Numerical modal analysis allows for more complete description of the vibration of Rainbow Bridge.

Input data for the numerical model include: 1) geometry of the bridge, 2) mechanical boundary conditions, and 3) material properties. Geometry was provided by the 3D photogrammetric model

created by NPS specialist John Wood (Figure 15). Boundary conditions were determined from field assessment; most of the model boundaries are free to move, while the bases of the bridge are fixed. The crack separating the bridge from the knoll is the largest unknown mechanical boundary condition, i.e. where it is closed and where open, which was evaluated through field assessment. Fixed boundaries in the model are illustrated in Figure 15b. For material properties, I assumed a uniform density (ρ) for Navajo sandstone of 2000 kg/m^3 based on past reported values from Rainbow Bridge test specimens (Dames and Moore, 1972), and then varied Young's modulus (E) to achieve the best fit with measured resonant frequencies. $E = 4.7 \text{ GPa}$ was found to provide optimum match to several measured frequencies, which is within the range of nominal values for a weathered sandstone rock mass (Hoek and Diederichs, 2006). Note that Dames and Moore (1972) assumed $E = 4.1 \text{ GPa}$ in their earlier structural analysis, which is very close to my value determined through Eigenfrequency matching, and we used $E = 5.5 \text{ GPa}$ in previous analysis of another arch composed of Navajo Sandstone (Starr et al., 2015). Poisson's ratio was held constant at 0.3 (Dames and Moore, 1972).

Eigenfrequency analysis predicts the frequency and displacement field associated with each mode of vibration. Displacements are relative for each mode, and cannot be compared between modes in an absolute sense. However, the displacement field does serve to highlight areas of maximum vibration (and force) amplitude for each mode, and can guide sensor placement in experimental design or prediction of potential damage locations. Frequency matching is approximate, typically values within $\pm 10\%$ of each other can be considered a match, however results rely on underlying assumptions of uniform material properties and lack of cracks or other discontinuities, so matching especially at higher-order modes may be less precise. Finally, the analysis assumes Rainbow Bridge is a singular solid feature, and thus does not model superposed vibration from near-surface slabs or other partly detached portions. Good resolved match between field data and numerical results indicates that key model assumptions (e.g. uniform material properties, fixed boundaries) are appropriate, validating the implemented geological model. Mass participation factors provide the basis to judge whether a mode of vibration is significant; here I assume that if $>2\%$ of the total bridge mass ($1.0 \times 10^8 \text{ kg}$ or 110,000 short tons!) participates in a given mode in any cardinal direction, the mode is significant.

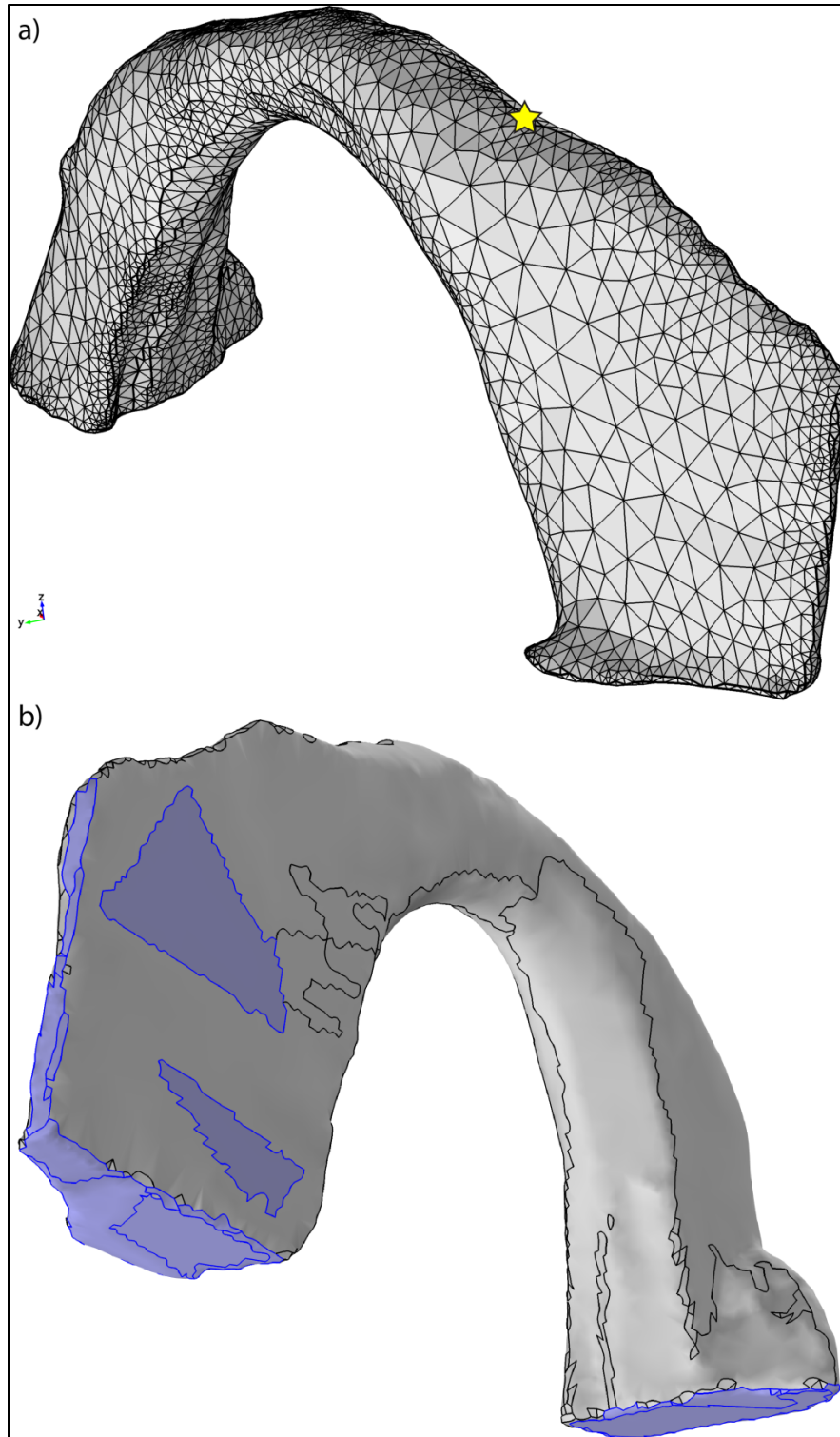


Figure 15. a) Geometry and mesh of the finite-element model generated from photogrammetry; star shows location of seismometer RABC. Orientation: $y = N$, $x = E$, $z = \text{up}$. b) Rotated view showing boundaries selected as fixed in the modal analysis (blue), all other boundaries were free to move.

Table 2. Comparison of modeled and measured modal frequencies and polarization at sensor position RABC.

Mode	Measured Frequency (Hz)	Degree of Polarization [0-1]	Measured Azimuth ^A (°)	Measured Incidence ^B (°)	Modeled Frequency (Hz)	Modeled Azimuth ^A (°)	Modeled Incidence ^B (°)	Mass Particip. (max %)
1	1.1	1	145	85	1.0	141	87	29.3
2	2.2	0.9	123	84	2.3	133	86	2.0
3	2.5	0.8	20	82	3.0	22	76	28.8
4	4.2	0.8	147	78	4.1	140	87	9.1
5	4.4	0.6	132	52	4.4	127	73	26.5
6 ^C	–	–	–	–	5.0 ^C	153 ^C	89 ^C	3.9 ^C
7	5.2	0.5	38	57	5.6	65	52	5.2
8	6.2	0.9	141	79	6.1	135	86	0.2
9 ^C	–	–	–	–	6.5 ^C	47 ^C	42 ^C	3.1 ^C
10 ^C	–	–	–	–	7.0 ^C	14 ^C	47 ^C	10.3 ^C
11 ^C	–	–	–	–	8.3 ^C	54 ^C	14 ^C	4.1 ^C
12	7.9	0.8	130	77	8.8	150	65	4.2
13	9.6	0.7	131	74	9.8	106	76	1.2
14 ^C	–	–	–	–	10.5 ^C	49 ^C	50 ^C	14.5 ^C

^A Degrees from magnetic north

^B Degrees from vertical

^C Gray text indicates predicted modes not identified in experimental data

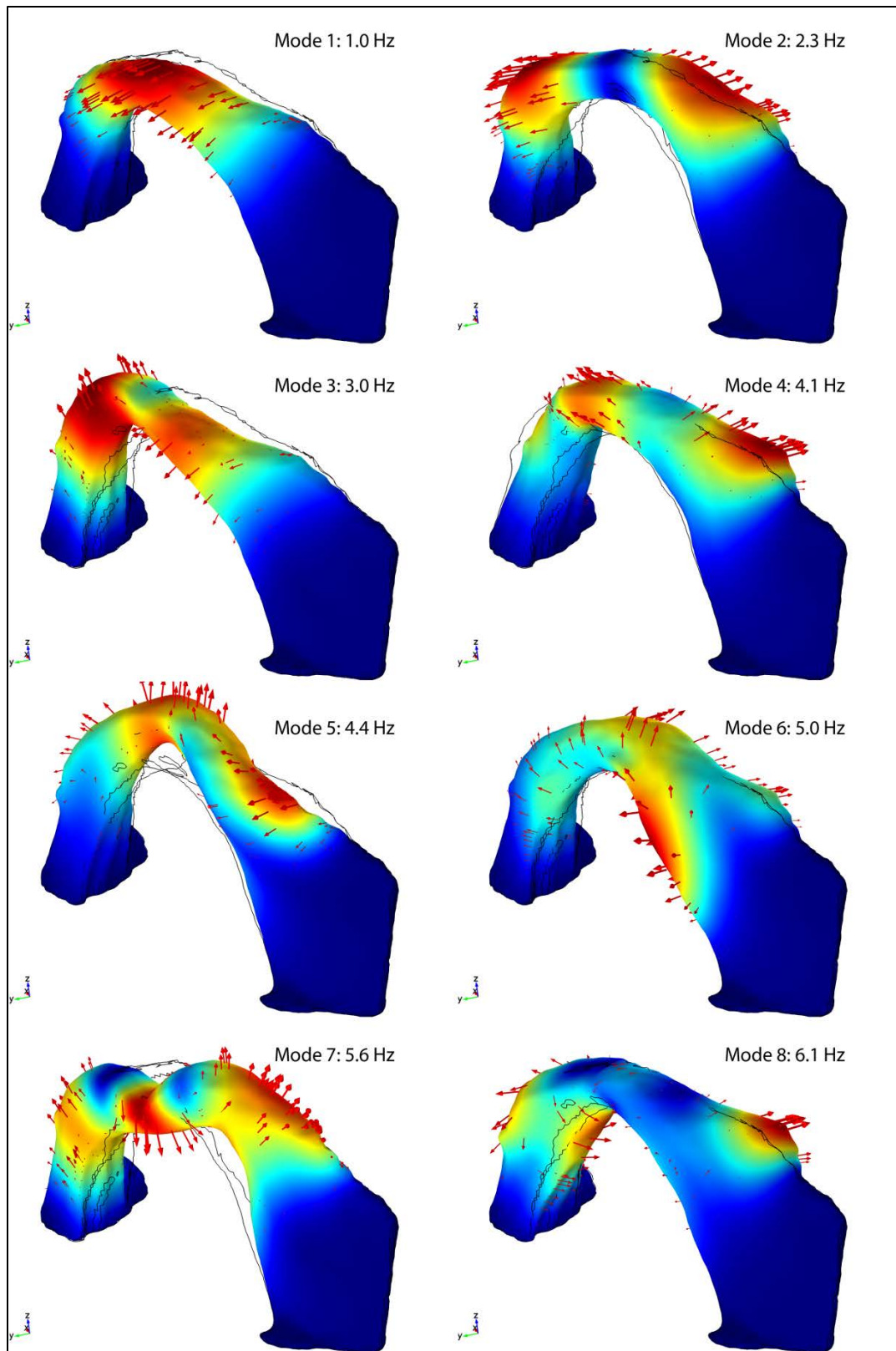


Figure 16. Predicted first eight modes of vibration for Rainbow Bridge with accompanying Eigen-frequencies listed. Electronic supplement available: animation of first eight resonant modes.

Helicopter noise sources

Helicopters produce noise (i.e. air pressure waves) from different sources (Figure 17) (Hanson et al., 1991; King, 1996). Low frequency noise ($\sim 10\text{--}50\text{ Hz}$), most relevant for structural excitation, is produced by the helicopter's main rotor and consists of two primary phenomena: blade-vortex interaction (BVI; also called blade slap) and thickness noise. The former, blade slap, is generated as an advancing blade strikes the vortex produced in the wake of the previous blade; it is audible and of relatively low pressure amplitude. Thickness noise, on the other, is generally not audible but produces a considerable net pressure pulse at the blade-pass frequency; it is associated with the physical thickness of an advancing rotor blade producing pressure peaks and troughs that arrive at an observation point at slightly different times and interfere constructively. Thickness noise produces the greatest net pressure pulse, with spectral content near the resonant frequencies of many civil and natural structures, and is thus the phenomenon of most interest when evaluating potential helicopter-induced vibration (Figures 18a, 18b, and 18c) (Hanson et al., 1991; King, 1996, 2001, Volpe, 2014). Thickness noise is strongest in the plane of the main rotor, and pressure levels increase with forward air speed (increasing rotor tip speed) (Schmitz & Yu, 1983). Noise produced by a helicopter's tail rotor occurs at higher frequencies ($\sim 80\text{ Hz}$), which are generally too high to excite resonance of most structures of concern.

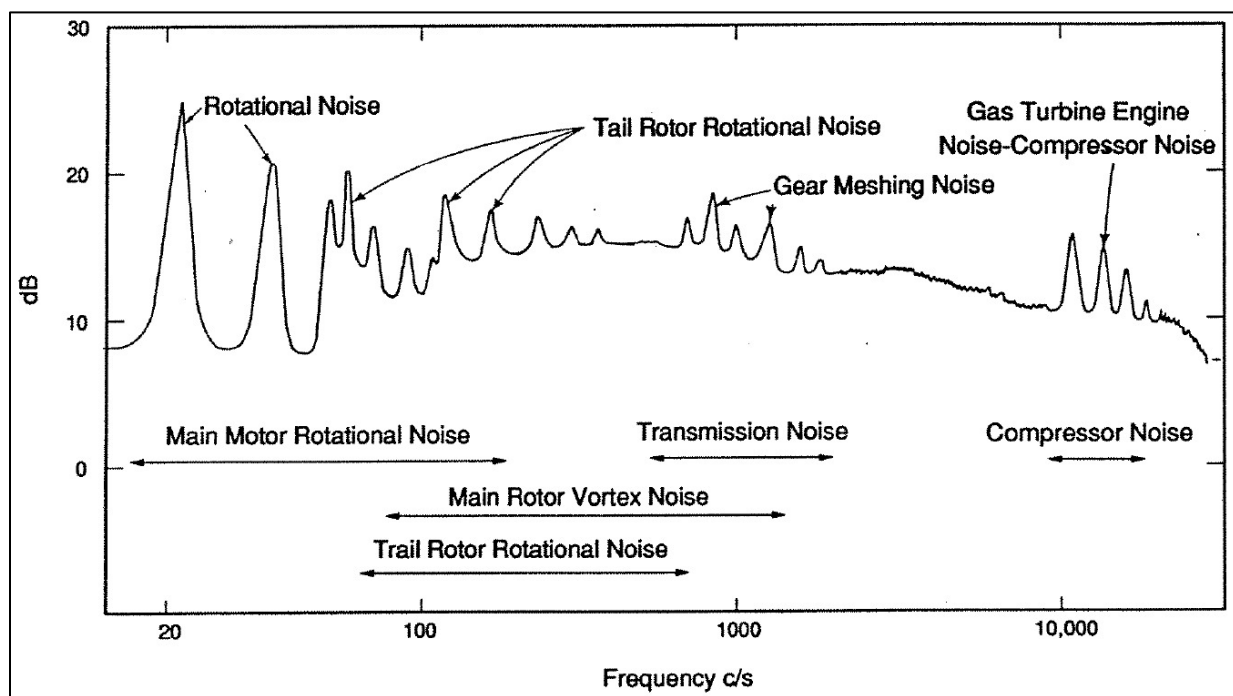


Figure 17. Spectrum of typical helicopter noise originating from different vibration sources (reproduced from Hanson et al., 1991).

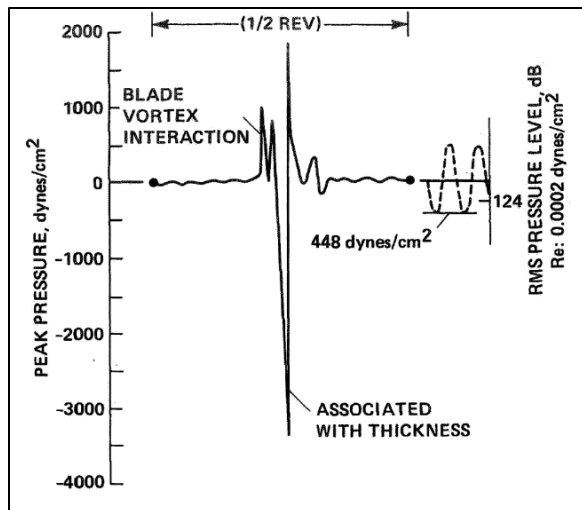


Figure 18a. Impulsive noise generated by a UH-1H helicopter, highlighting relative contributions from blade-slap and thickness noise phenomena. Figure reproduced from Schmitz & Yu (1983).

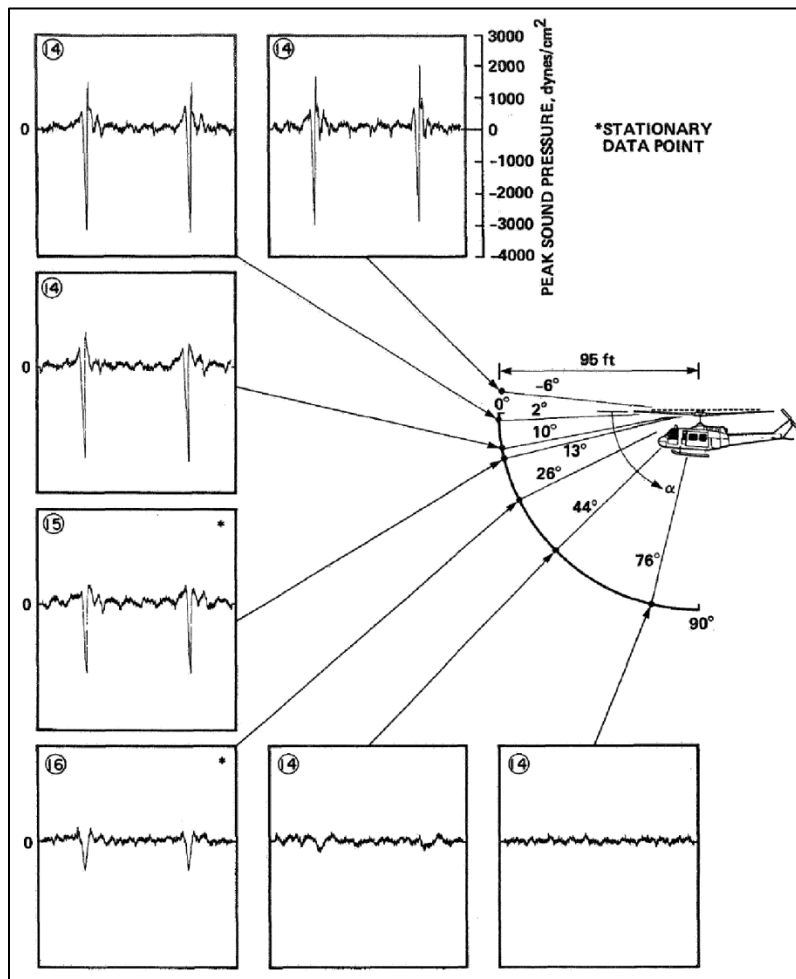


Figure 18b. Variation of noise amplitude with angle from the main-rotor. Figure reproduced from Schmitz & Yu (1983).

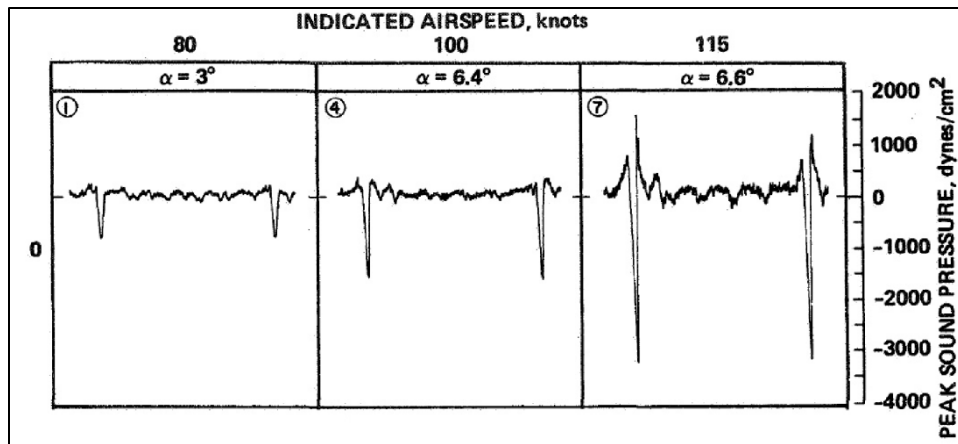


Figure 18c. Variation of main-rotor noise amplitude with forward airspeed. α is angle from the plane of the rotor; data for level flight. Figure reproduced from Schmitz & Yu (1983).

Thickness noise and blade slap are generated at the blade-pass frequency (BPF) of a helicopter (plus overtones), and thus depending on the BPF, certain model helicopters have the potential to excite resonance of nearby structures. BPF is simply the product of the number of blades times the revolution rate of the main rotor. Most light-duty civil helicopters have 2, 3 or 4 blades, and once in operation the main rotor revolution rate does not vary significantly. Therefore the BPF for different model helicopters is relatively predictable. Table 3 shows my compiled estimates of BPF for several common helicopters, some known to currently fly in the Rainbow Bridge area (Bell UH-1 included for reference). Revolution rate data in Table 3 have been compiled from literature research and personal communication with pilots, and may vary slightly (<5%) between operators or within specific helicopter models. Most of the models listed in Table 3 have a tail-rotor BPF in the range of 70-80 Hz, while the EC 130 features a fenestron tail rotor to alleviate this noise source.

Table 3. Blade-pass frequency estimates for different common helicopter models.

Helicopter make and model	Number of main rotor blades	Revolution rate (RPM)	Main rotor blade-pass frequency (Hz)	Maximum weight (lbs.)
Bell 407	4	413	27	5000
Bell 206	2	394	13	3200
EC AS350	3	401	20	5225
EC 130	3	394	20	5350
Robinson R44	2	400	13	2400
MBB Bo 105	4	424	28	5280
Bell UH-1	2	320	11	9000

Figure 19 shows data compiled by NPS Physical Scientist / Acoustic Specialist Randy Stanley providing estimates of sound pressure level at a common distance of 500 ft (~150 m), for helicopters approaching an observer at ~105 knots (195 km/hr) at an elevation of 100-300 ft (30-90 m). Frequencies are corrected for Doppler shift. Data were recorded under slightly different test

conditions in each case, so the comparison is not absolute. Nevertheless, the results show useful relative comparison of noise generated by the different helicopter models, and allow for a few general conclusions: a) Lowest stimulated sound frequencies occur at the BPF, and are in good agreement with predictions in Table 3; b) Helicopters with fewer blades generate lower-frequency vibrations and thus have the potential to excite structural resonance at frequencies relevant to many civil and natural structures; and c) Heavier helicopters produce higher sound pressure levels. Not included in this compilation is the Robinson R44 helicopter, an inexpensive and common 2-blade model; its sound spectrum is predicted to be similar to that of the Bell 206. Meanwhile the EC 130 and AS 350 are very similar helicopters, and are expected to produce similar sound spectra. The main difference between these models is the EC 130 incorporates a fenestron tail rotor with multiple enclosed blades, and will thus lack much of the noise associated with an open 2-blade tail rotor as featured on the AS 350. The Bell 407 is predicted to have a similar sound spectrum as the Bo 105, both models having 4-blade main rotors.

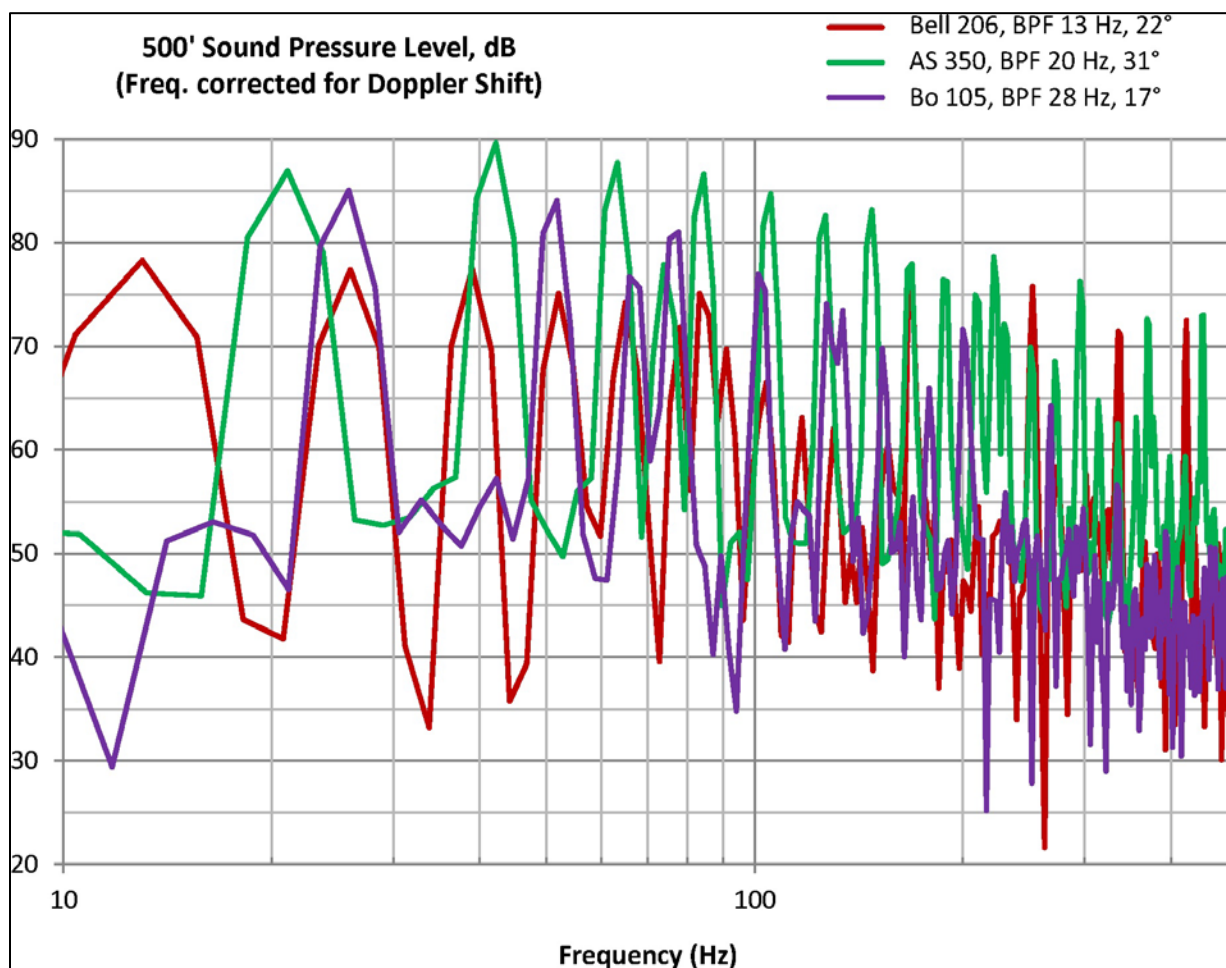


Figure 19. Helicopter noise data computed at a common distance; frequencies have been corrected for Doppler shift; observation angles from main rotor plane are provided (figure prepared by NPS Physical Scientist / Acoustic Specialist Randy Stanley; data courtesy of NASA).

Potential helicopter-induced vibration of Rainbow Bridge

All resonant modes of vibration for Rainbow Bridge conclusively identified from experimental data occur at frequencies below 10 Hz (Tables 1 and 2), with the fundamental frequency at 1.1 Hz. Meanwhile the lowest blade-pass frequency of common helicopter models currently flying in the area (Robinson R44 and Bell 206) is ~13 Hz (Table 3). Comparing these values shows that helicopter source-energy generally occurs at frequencies greater than the first several resonant frequencies of the bridge, and is thus unlikely to excite resonance at these modes. Several of these resonant modes have high dynamic mass participation >25% (e.g. modes 1, 3, and 5) and are thus among the most significant for structural excitation (i.e. contain a significant proportion of vibrational energy).

Results of numerical modal analysis, however, indicate that several significant vibrational modes (mass participation >2%) coincide with the main rotor blade-pass frequency of common helicopter models (Table 3), or are within the anticipated Doppler-shifted range, and may thus be excited by helicopters operating near the bridge. Thickness noise, generating pressure pulses of greatest amplitude, is strongest in the plane of the main rotor and at high air speeds, so level flight at elevations near the top of the bridge (~3950 ft), specifically flight past the bridge at or near this elevation, is likely to be the worst-case scenario for thickness noise generation. Such flight would produce a horizontal pressure pulse acting on the bridge at different possible incidence angles, and may be able to excite resonant modes with corresponding frequency. Some of these modes are highlighted in Figure 20. In particular, mode 14 at ~11 Hz includes 15% of the vertical mass participation and is significant, while modes 19, 29, and 30 each contribute ~5% of the total dynamic mass participation. It thus appears that while the lowest modes of vibration for Rainbow Bridge may be insensitive to helicopter excitation, higher-order modes can be excited, with unknown consequences for global or local damage.

Moreover, Rainbow Bridge contains several partly detached surficial slabs of rock, which are not included in the preceding modal analysis, and which may have natural frequencies similar to helicopter source noise. Helicopters may thus be able to excite resonance of these slabs, generating localized stresses that possibly lead to internal failure. Two such slabs are shown in Figures 21 and 22. In both cases, failure of these slabs may be simply cosmetic (i.e. not affecting global stability but still generally unacceptable) or potentially worse, where failure of the slab promotes nearby crack propagation with global effects (both features were previously monitored by the Bureau of Reclamation). Especially the western slab, highlighted in Figure 22, may affect global stability of Rainbow Bridge; failure of the slab could promote crack propagation and basal shear at this abutment. Archeological resources are also located in the vicinity that might be affected by slab falls. Independent, simplified models of these slabs were created based on the photogrammetric model of Rainbow Bridge, and input into COMSOL for modal analysis. Identical material properties were used as in the preceding analysis. Fundamental resonant frequencies for the eastern and western slabs are predicted to be around 4 Hz, with important horizontal bending modes between 10 and 30 Hz. These latter resonant frequencies are within the range of blade-pass frequencies for common helicopter models (Table 3), suggesting that helicopters flying near the bridge may be able to excite resonance of these slabs. Note that this analysis is approximate, and there are other similar features on Rainbow Bridge not independently analyzed here.

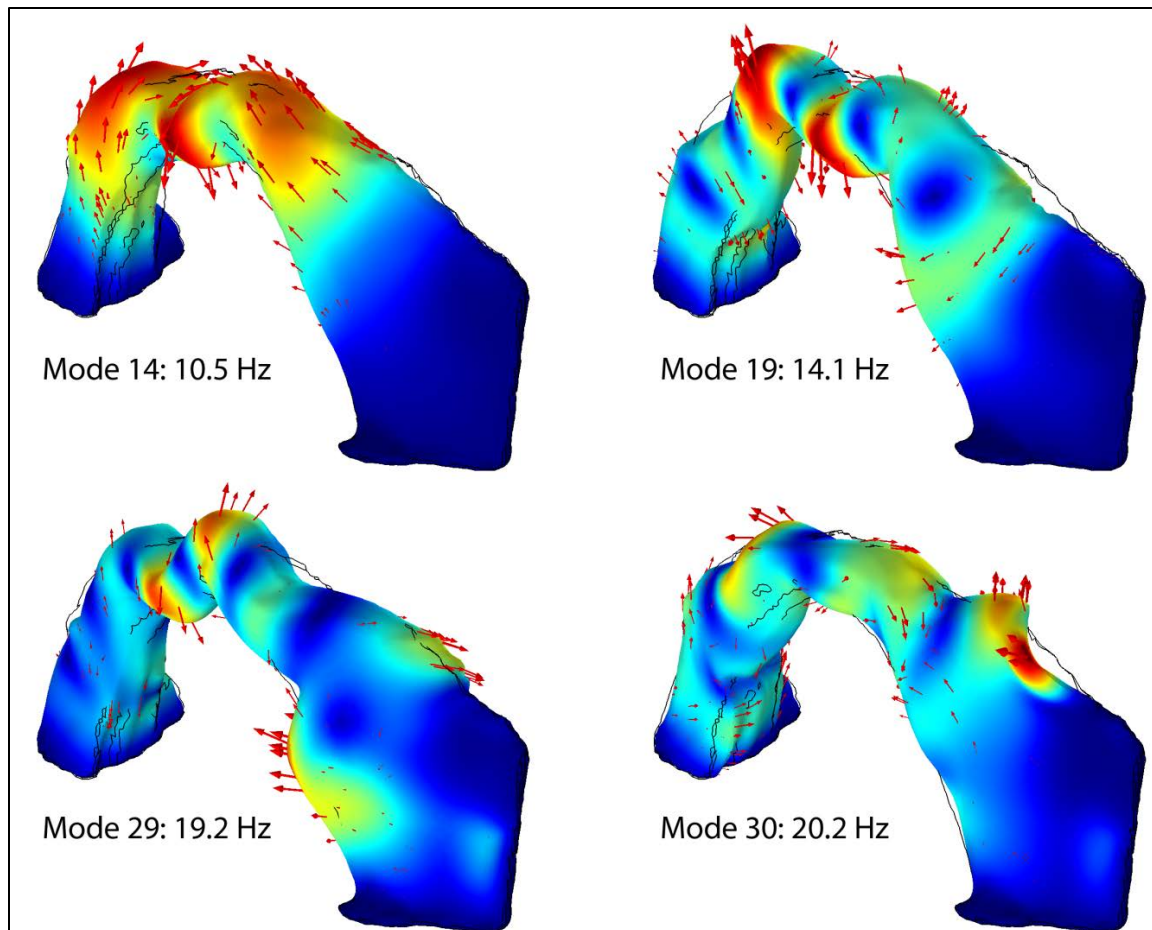


Figure 20. Four modeled modes of vibration for Rainbow Bridge that may be stimulated by helicopters operating in proximity; in each case the modal frequencies are nearly coincident with the blade-pass frequency of common helicopter models. Each mode has mass participation >4% in at least one cardinal direction; mode 14 includes 15% of the vertical mass participation.

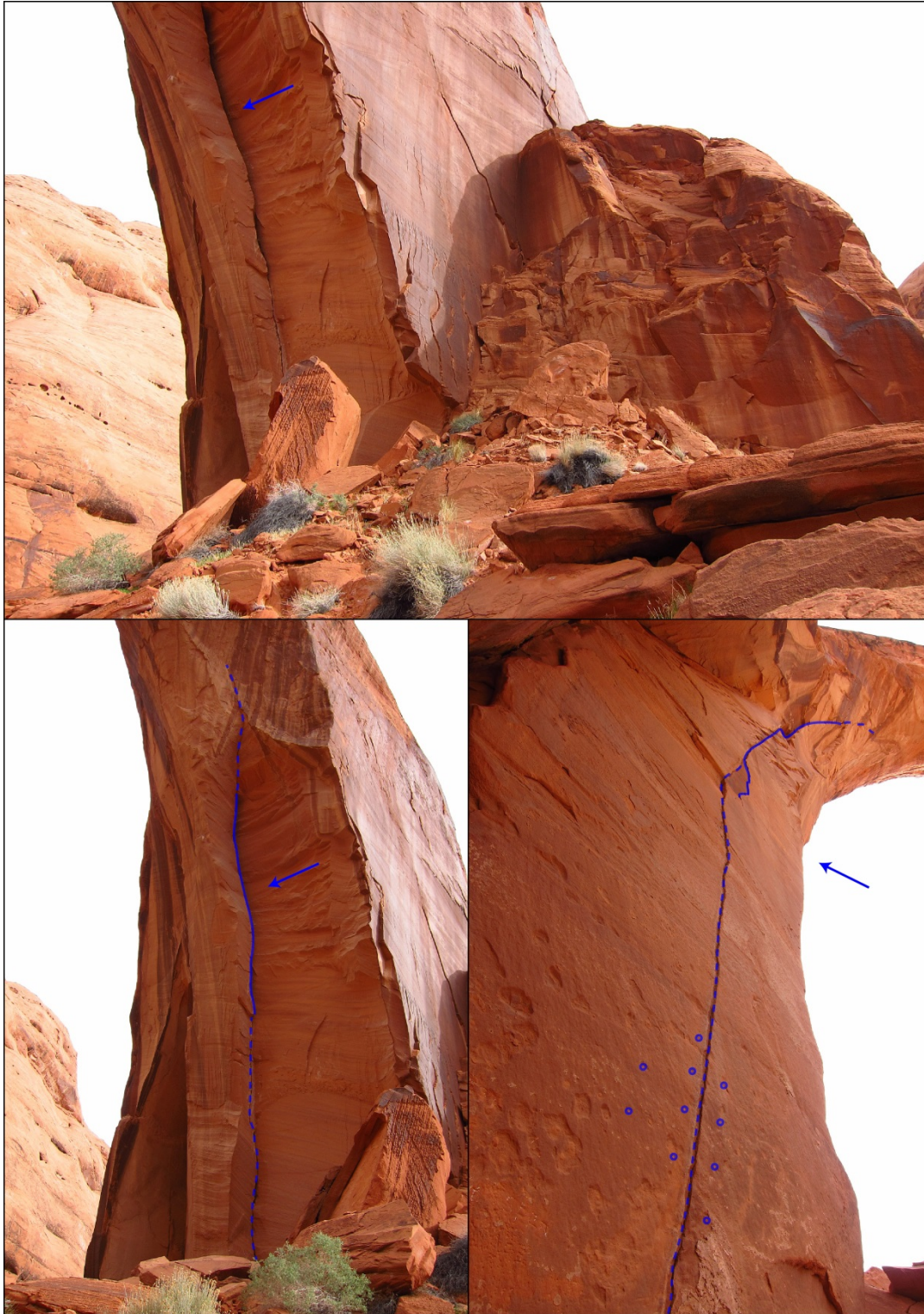


Figure 21. Partly detached slab on the underside of the eastern abutment of Rainbow Bridge. Arrows indicate the same location of the open crack. Solid lines indicate open crack, dashed partly-closed. Circles are crack monitoring points installed by the Bureau of Reclamation (BOR). Failure of this slab would impact archeological resources at the base of the bridge and potentially affect global stability.

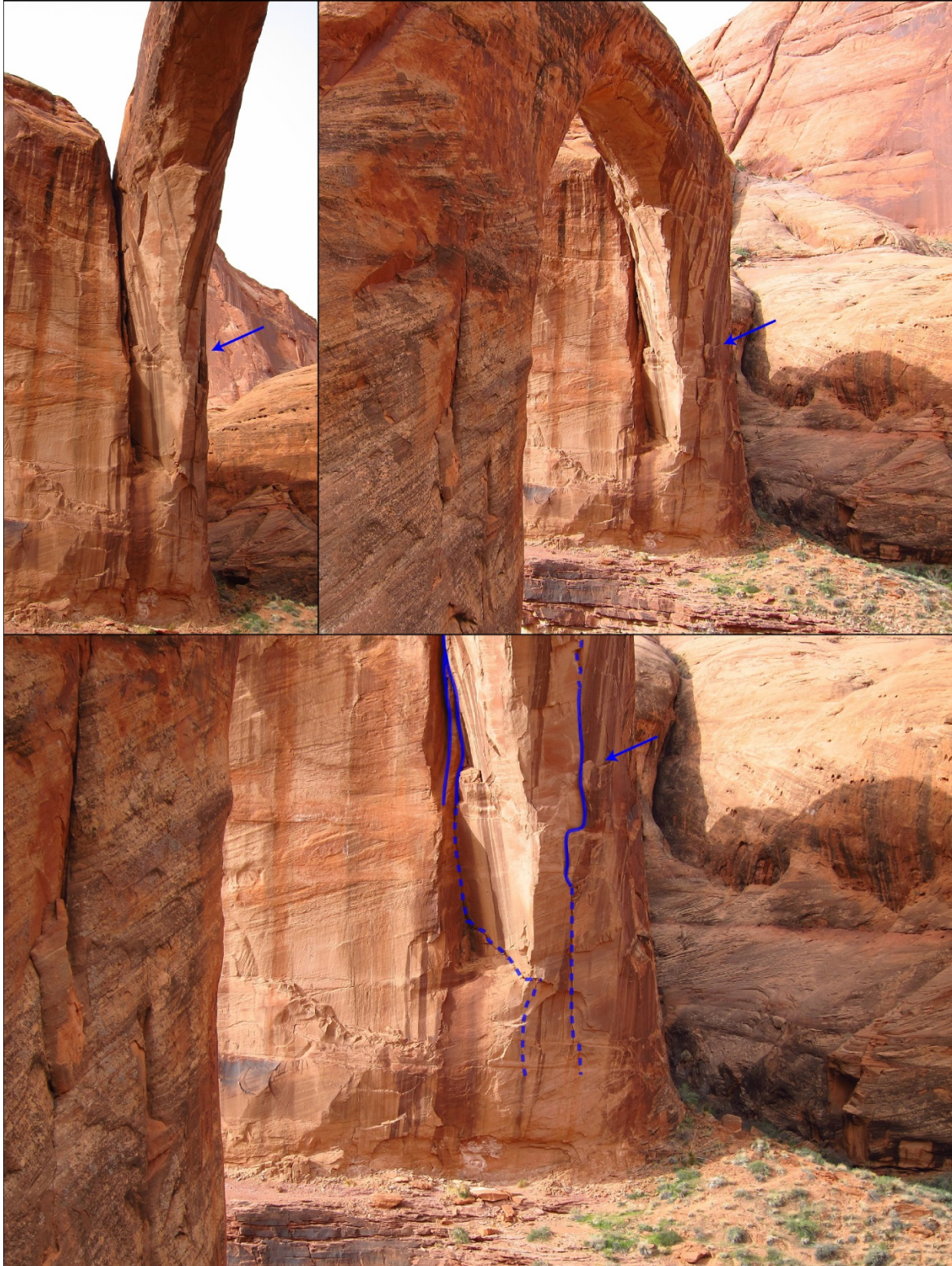


Figure 22. Partly detached slab on the western abutment of Rainbow Bridge. Arrows indicate the same location of the open crack. Solid lines indicate open crack, dashed partly-closed. Failure of this slab may impact global stability of Rainbow Bridge allowing crack propagation and basal shear failure.

Potential induced vibration from fixed-wing propeller aircraft

Several air tour operators in the Rainbow Bridge area operate fixed-wing propeller-driven aircraft. These airplanes produce noise (i.e. air pressure waves) from each propeller at the blade pass frequency (BPF) and above, in a similar manner as helicopter rotors (Hanson et al., 1991). However, due to the small size of these propellers, the revolution rate is typically high, in the range of ~2500 rpm. A 2-blade propeller spinning at 2500 rpm generates noise at a BPF of 83 Hz, with additional overtones (e.g. Figure 23). Energy in the sound spectrum thus occurs at frequencies far above the measured and modeled significant resonant frequencies of Rainbow Bridge, making the potential for excited resonance very low. Even analyzing the preceding numerical model results to 100 modes only brought resonant frequencies up to ~40 Hz, making it unlikely that Rainbow Bridge has significant global resonant modes near the BPF of most propeller-driven aircraft. Again, Rainbow Bridge is not a perfect solid and has several partly detached slabs; however these too are unlikely to have resonant frequencies in the range of 70-80 Hz. It is thus unlikely that noise produced by fixed-wing propeller-driven aircraft poses a vibration threat to the structural stability of Rainbow Bridge.

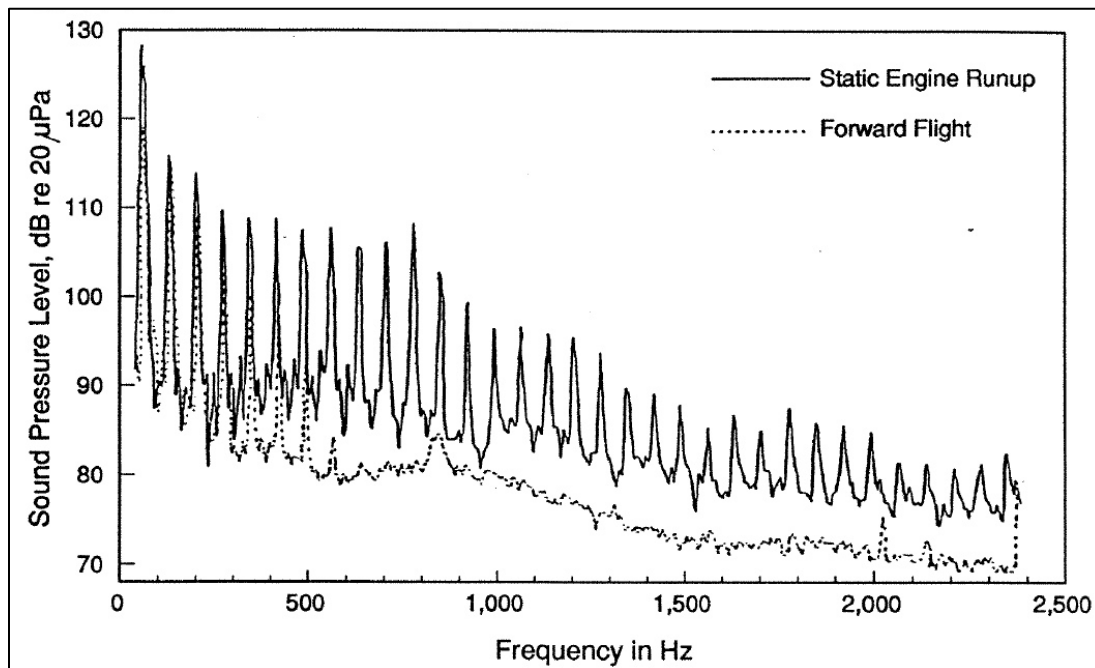


Figure 23. Sound spectrum of a typical propeller-driven aircraft (reproduced from Hanson et al., 1991). The first frequency peak occurs at the blade-pass frequency, here about 80 Hz, with repeated overtones at higher frequencies.

Potential induced vibration from supersonic flight

Although supersonic flight by military aircraft over Rainbow Bridge is uncommon, and supersonic flight by civilian aircraft is currently prohibited over the U.S. (since 1973), there is the potential that supersonic overflight of aircraft could occur at Rainbow Bridge in the future. Supersonic overflight is of concern and is discussed here due to the potential for sonic booms that can produce strong pressure disturbances and thus pose substantial risk to structures within their area of influence (Hanson et al., 1991).

Sonic booms are intense pressure waves with an "N-shaped" time history of pressure above and below ambient. A sonic boom waveform is generally impulsive, with a "push-pull" forcing function that is more effective at exciting structural resonance than a typical impulsive air blast, i.e. an explosion (Hanson et al., 1991). A sonic boom contains energy over a broad range of frequencies associated with the typical natural frequencies of structures, including the natural frequencies of Rainbow Bridge identified here.

Sonic boom avoidance areas are specified to protect communities and other sensitive areas within military airspace. Inside the sonic boom avoidance areas, only subsonic flight is allowed (e.g. Holloman AFB, 2012). To protect the weakest elements of Fort Jefferson (Dry Tortugas National Park) from sonic boom induced damage, a buffer of 20,000 feet (vertical) and 12 nautical miles (horizontal) was recommended (James et al., 2009). If supersonic flight over Rainbow Bridge or other sensitive natural structures is anticipated, a substantial avoidance distance should likewise be incorporated to protect those structures from vibration damage.

Bureau of Reclamation past studies

The Bureau of Reclamation (BOR) performed several past studies between 1974 and 1990 at Rainbow Bridge, including material testing, precision surveying, repeat photography, and displacement monitoring, to investigate effects of Lake Powell's rising water levels (which can and have passed under the bridge). In a previous related study, Dames and Moore (1972) performed material testing, geological investigations, and finite-element stress and stability analysis for Rainbow Bridge. While several reports from these investigations remain accessible from BOR libraries, few contain actual data that may be independently analyzed. I reviewed several of these reports, and summarize some key information here together with data I was able to retrieve.

Dames and Moore (1972) performed a range of structural and geological analyses for Rainbow Bridge; most relevant for the current investigation was material testing for the engineering properties of constituent rocks. Two bulk samples of Navajo and Kayenta Sandstone were retrieved from the eastern and western abutments of Rainbow Bridge (recall that the bridge consists of Navajo Sandstone while the Kayenta Formation provides the footings). One sample of Kayenta was ultimately too small for strength testing, while other testing results are reproduced in Tables 4 and 5. Some of these values appear suspicious, however, e.g. the eastern Navajo sample has very low Young's modulus compared to typical values for intact rock, while both Navajo samples have relatively weak uniaxial compressive strength (UCS) as compared to other existing test data (e.g. Goodman, 1989) – possibly the result of the samples being taken from available loose pieces which were highly weathered.

Table 4. Intact rock sample properties reported by Dames and Moore (1972).

Material	Sample location	Dry density (kg/m ³)	Young's modulus (GPa)	Poisson's ratio	UCS (MPa)
Navajo	east abutment	2195	1.9	0.26	38
Navajo	west abutment	2098	10.3	–	41
Kayenta	east footing	2114	–	–	–
Kayenta	west footing	2563	25.7	0.19	108

Table 5. Triaxial test data for Navajo sandstone samples reported by Dames and Moore (1972); Hoek-Brown m_i values were calculated here using Roclab software (www.roclab.com).

Navajo East abutment		Navajo West abutment	
σ_3 (MPa)	σ_1 (MPa)	σ_3 (MPa)	σ_1 (MPa)
0.0	38.5	0.0	40.9
13.8	131.0	13.8	127.6
27.6	197.9	27.6	168.9
Hoek-Brown m_i	25.461	Hoek-Brown m_i	16.713

When conducting finite-element structural analysis, Dames and Moore (1972) scaled the intact rock test values to account for the reduced bulk strength of a rock mass (incorporating discontinuities and scale effects). While conceptually appropriate, they provide few details on how these properties were derived (this is still a challenging aspect of rock engineering). Table 6 summarizes rock mass material properties used by Dames and Moore (1972) for structural analysis of Rainbow Bridge. The finite-element analysis predicting areas of maximum stress performed by Dames and Moore (1972) is easily reproduced with modern software (see Figure 24, generated using COMSOL and our 3D model). However, the selection of failure criterion for the intact rock and rock mass remains challenging, and the presence of non-persistent discontinuities complicates interpretation of continuum model (i.e. finite-element) results. Thus, while it is difficult to predict the precise degree of criticality of Rainbow Bridge in a quantitative manner, areas of high compressive or tensile stresses do serve to indicate regions of the rock mass that may be most susceptible to failure. Moreover, preliminary structural analysis highlights an interesting result: under gravitational self-weight, Rainbow Bridge compresses downward but also tends to lean outward to the north (Figure 25), creating horizontal tensile stresses in the main crack system where the bridge connects to the adjoining knoll. This mechanical connection thus appears to help restrain the bridge from northward rotation and toppling. Propagation of this crack, and/or loss of strength to resist this movement, may result in further rotation.

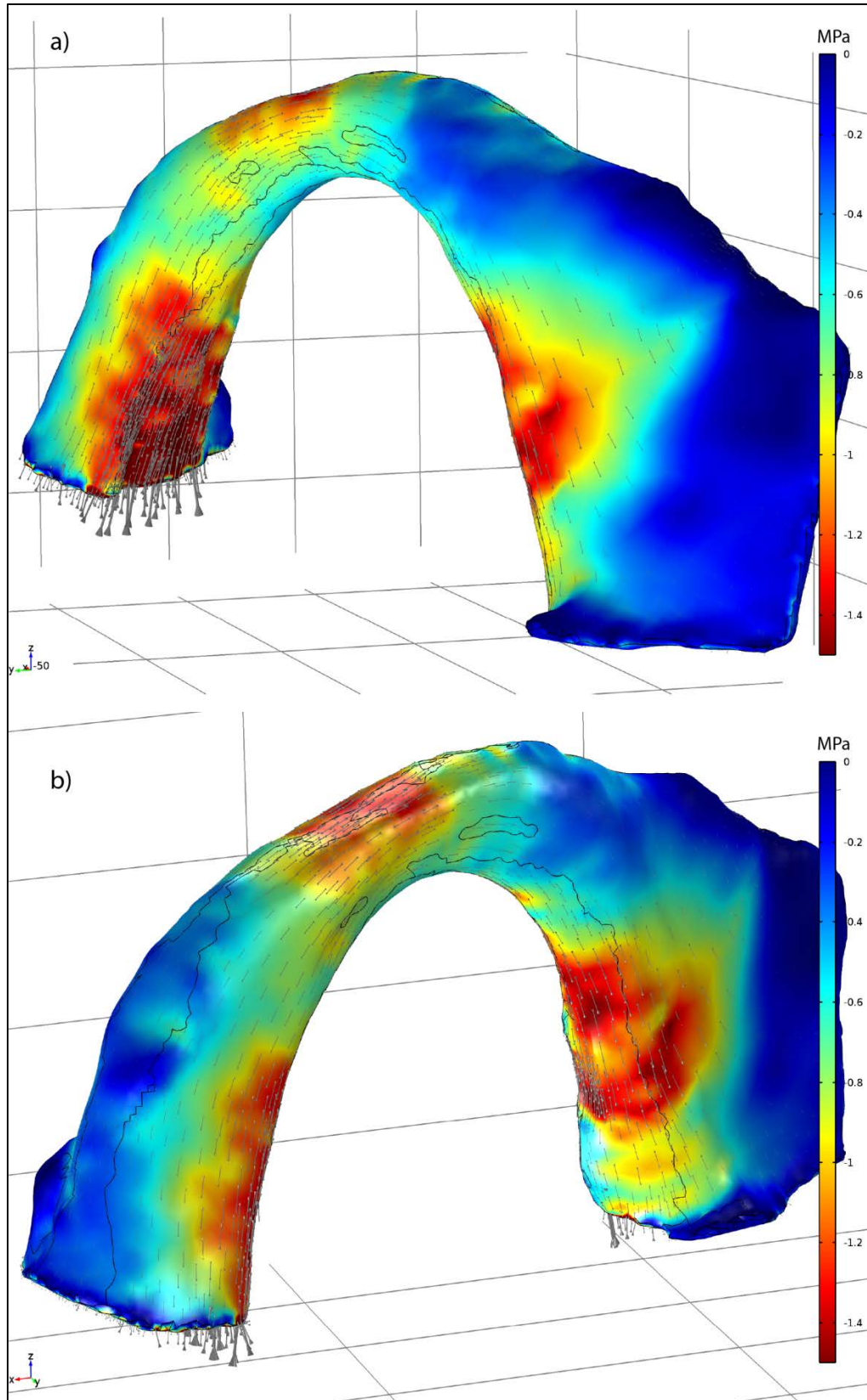


Figure 24. (a, b) Modeled principle compressive stresses with scaled orientation indicators (gray bars).

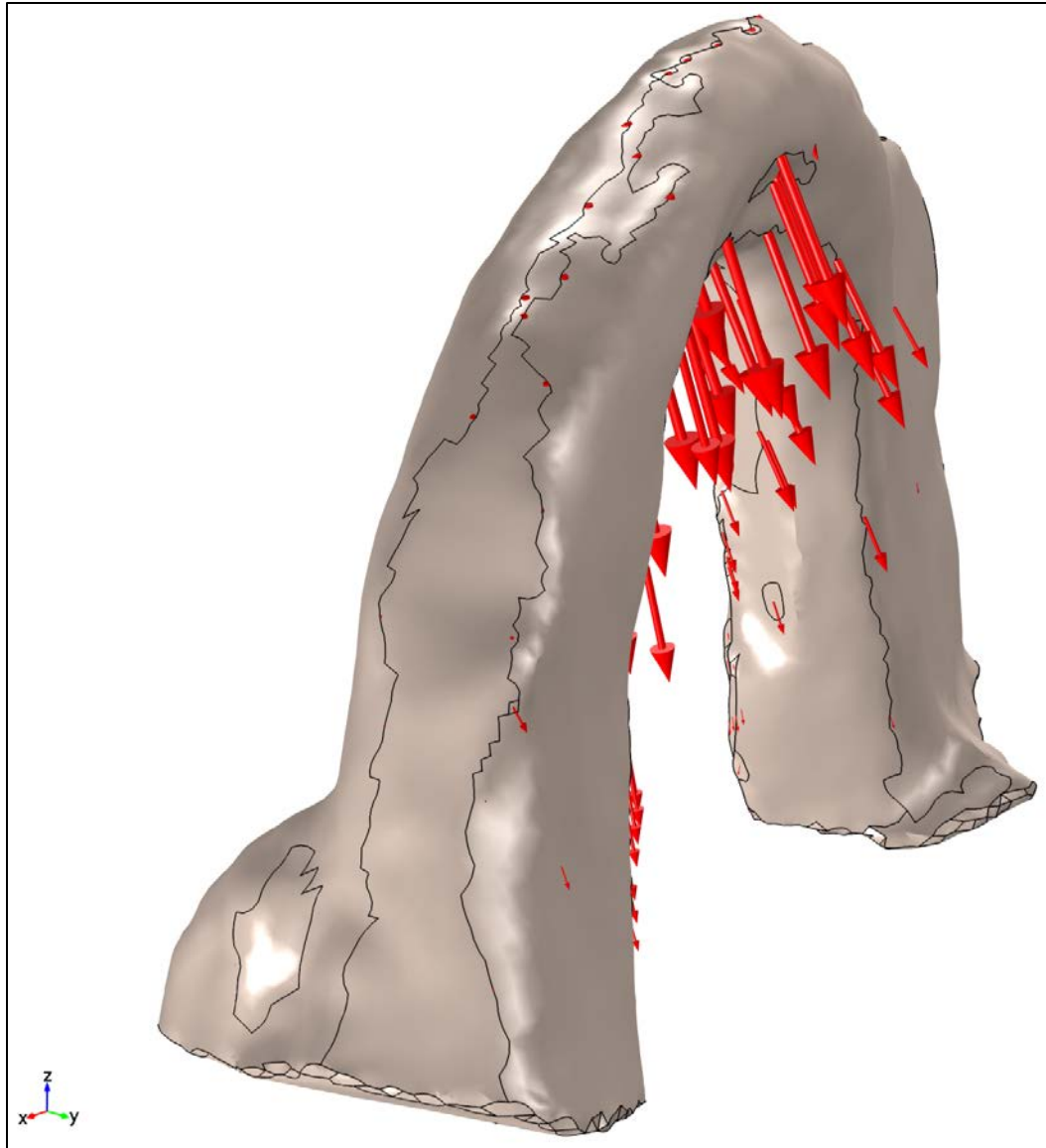


Figure 25. Displacement of Rainbow Bridge under the influence of gravity highlighting the tendency for northward (y) rotation (i.e. outward component of displacement vectors). Tensile strength of intact rock linkages at the western abutment help resist this rotation supporting the stability of Rainbow Bridge. Bending of the bridge also helps resist outward rotation, facilitated by the compressive strength of the rock mass. The partly detached slab on the western abutment shown in Figure 22 likely reflects high compressive stresses created by bending strains (see Figure 23b).

Table 6. Rock mass material properties used by Dames and Moore (1972).

Material	Dry density (kg/m ³)	Young's modulus (GPa)	Poisson's ratio	UCS (MPa)	Shear strength (MPa)
Navajo	2162	4.1	0.25	31	15.5
Kayenta	2243	6.9	0.2	41	20.7

The Bureau of Reclamation deformation monitoring program included two basic measurements: 1) crack gauges monitoring crack aperture at several select locations (including those identified in Figures 21 and 22); and 2) precision distance and elevation surveying to measure the seasonal and annual displacement of several points on Rainbow Bridge. Cracks were observed to “close as the rock expands in summer and open as the surrounding rock contracts in winter,” with “no apparent accumulated movement evident” (Skipper, 1985), however no actual data on crack displacement were included in any reviewed report. Between 1974 and 1984, BOR precision surveying utilized Quadrilateral arrays, and while it was reported that “Expansion and contraction of the bridge occur as a result of seasonal temperature fluctuations, and changes in other weather conditions,” again no data from these surveys appear in any report I was able to obtain (Skipper, 1985).

In 1986, the surveying system was modernized to include three reflector prisms installed on Rainbow Bridge, allowing direct measurement of seasonal and annual displacements. Eight such ‘trilateration’ surveys were performed between fall 1986 and spring 1990 (twice per year), and while no raw data were found in any reviewed report, one annual report (Skipper, 1989) reproduced a scaled map showing horizontal and vertical movement of three reflector points. I digitized and generated a new version of that figure in order to measure the displacements and thus back-calculate seasonal movement data. My results are shown in Table 7, and Figures 26 and 27. Data reveal that the bridge appears to move approximately 6 mm (1/4 inch) seasonally, while vertical displacements are minimal. Skipper (1989) writes: “bridge movements occur as a result of seasonal temperature fluctuations and changes in other weather conditions,” and “this motion continues to be cyclical and no accumulated movement has occurred.” However, I note that the seasonal pattern of movement is counterintuitive: the bridge appears to move outward (to the east) in spring and inward (to the west) in fall. These movements are opposite to my expectations for seasonal thermo-elastic expansion and contraction, which would have the bridge contracting through winter to attain minimum expansion (westerly movement) and then heating and expanding throughout the summer to produce maximum expansion (easterly movement). Moreover, displacement of each point is remarkably similar, rather pointing to potential seasonal movement of the survey base station/s.

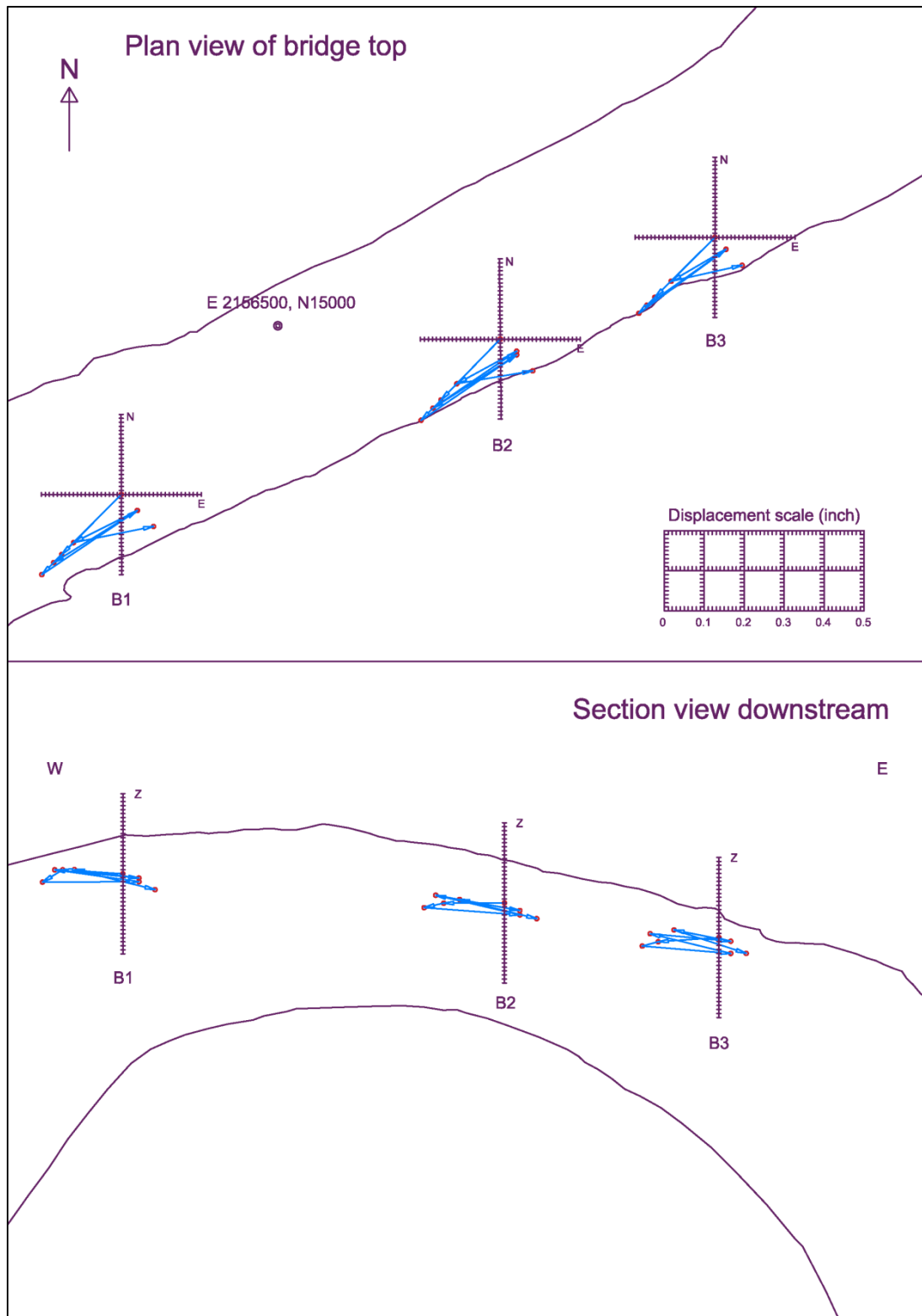


Figure 26. Redrawn from Skipper (1989): displacement monitoring at Rainbow Bridge between 1986 and 1990, measurements twice per year in spring and fall. Arrows indicate point tracking. (Electronic supplement available: scaled Autocad .dwg file).

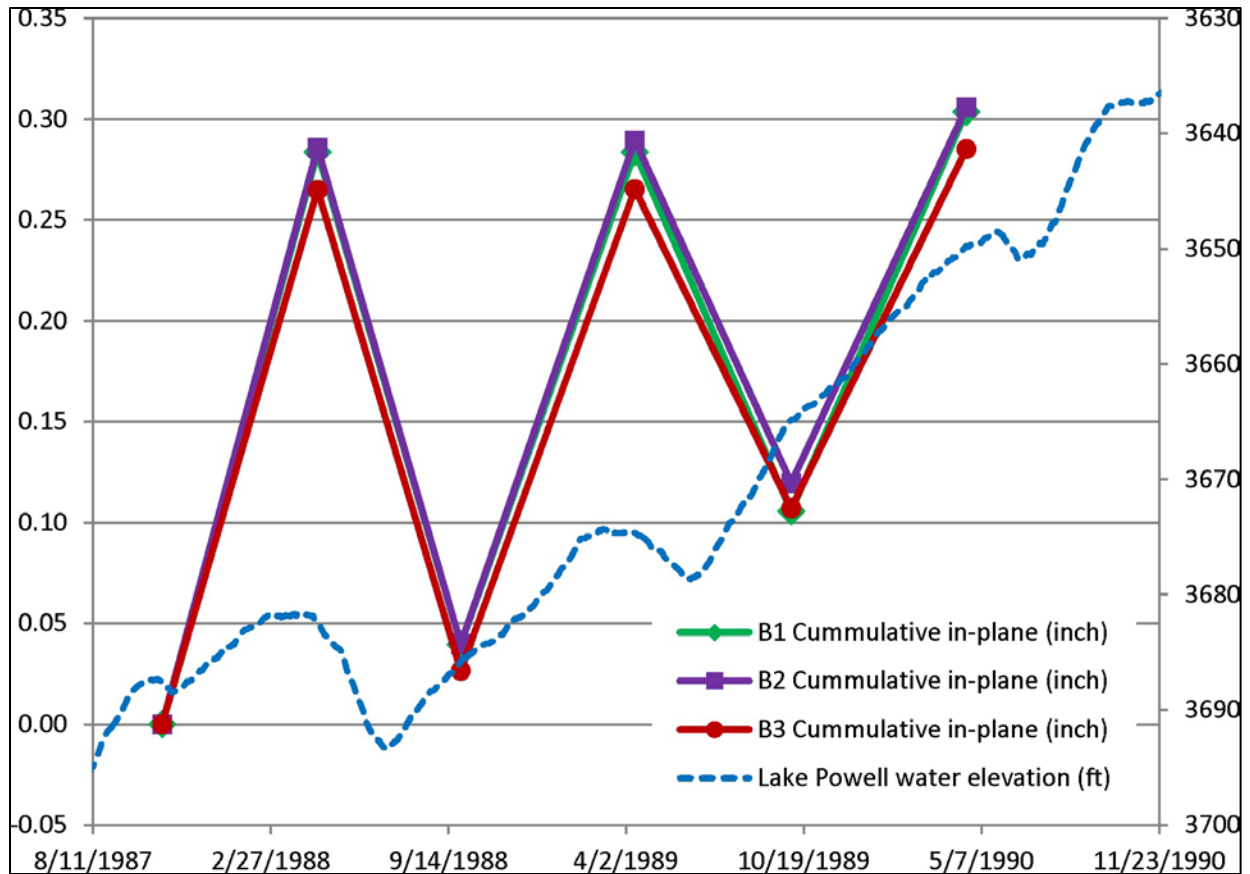


Figure 27. Cumulative in-plane (i.e. azimuth 065°) horizontal displacement of three BOR monitoring points on Rainbow Bridge. Data generated from Figure 26 (Skipper, 1989). Initial measurements have been omitted, which show a different trend potentially related to settling of the survey points or base station. (Electronic supplement available: Excel data file containing raw data and plot).

To further evaluate potential movement of Rainbow Bridge by seasonal thermo-elastic effects, I created a preliminary transient thermo-mechanical coupled model in COMSOL using the 3D geometry provided by the photogrammetric survey and material properties determined through Eigenfrequency analysis. In addition, I had to assume thermal properties and a thermal expansion coefficient for Navajo Sandstone; with few precise values available for the material in literature, I chose typical values for thermal conductivity = 2.3 W/mK, heat capacity = 920 J/kgK, and thermal expansion coefficient = 1×10^{-5} (Moore et al. 2011b). I applied an annual cyclic temperature boundary condition (T) to the outside of all exposed rock surfaces in the form of (where t is time):

$$T = 20 + 15 \times \sin(t)$$

which assumes a mean rock mean temperature of 20 °C and annual amplitude of 15 °C. This method contains several simplifications, nonetheless allows first approximation of seasonal displacements. Results are shown in Figure 28, which provides views of the displacement field at maximum and minimum intervals (summer and winter, respectively). The predicted pattern of movement includes outward (easterly) expansion in summer as the bridge warms, and inward (westerly) movement of the

top of the bridge in winter as it cools, as expected, with strong corresponding vertical inflation and deflation. Predicted total annual displacement amplitude is in the range of 10 mm. These movements are generally opposite to those measured by BOR surveying between 1986 and 1990, suggesting the latter may be in error (e.g. reflecting thermal movement of a survey monument base station). Moreover, the BOR measurements lack the predicted vertical component of movement, which is dominant in my preliminary model. I also note the dates of BOR surveying were not well timed to capture seasonal thermo-elastic displacements.

Scans of additional BOR maps, cross-sections, and reports are available as electronic supplements to this report, while Figure 29 reproduces a useful 2-ft BOR topographic map (Skipper, 1985).

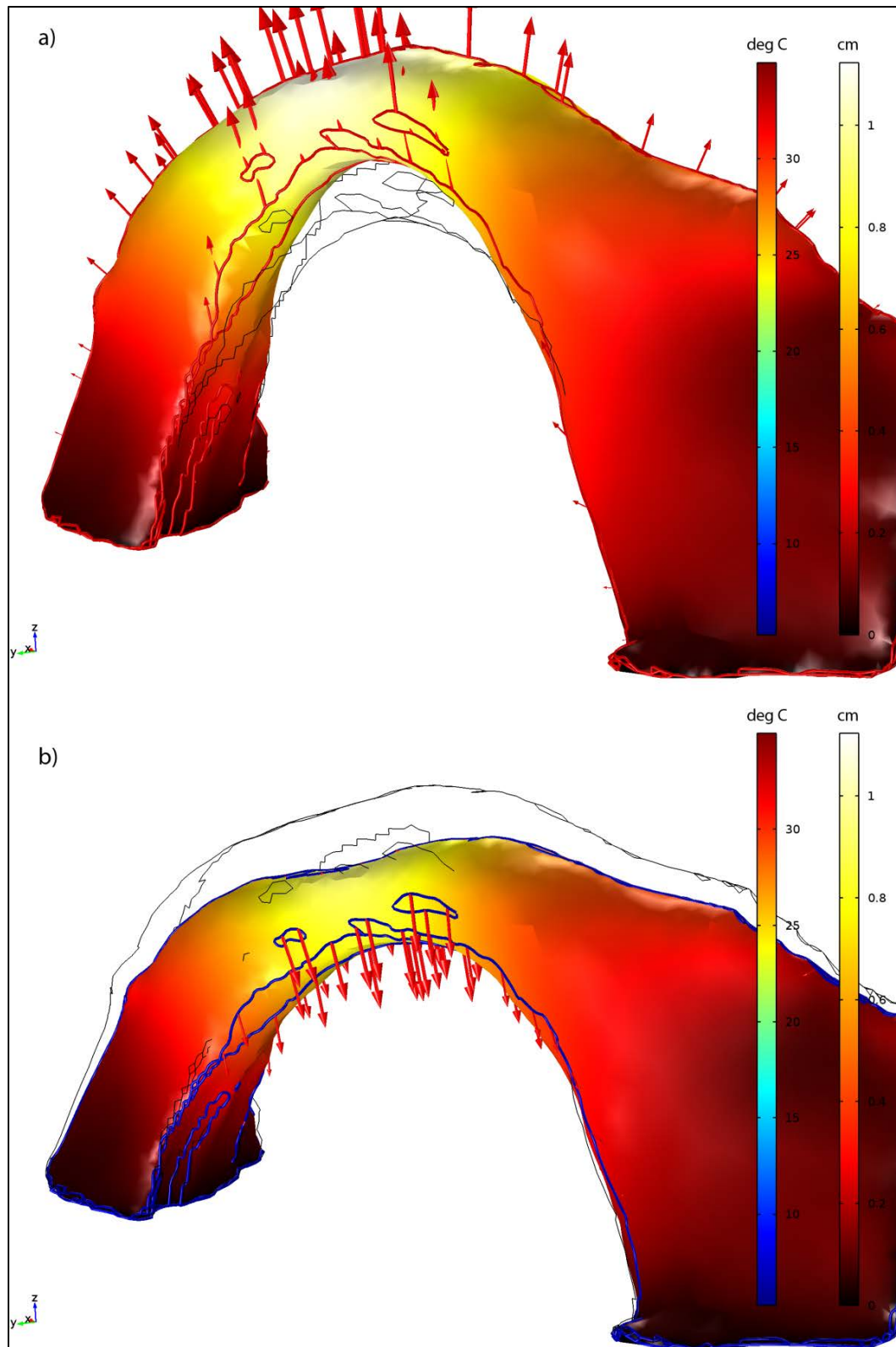


Figure 28. a) Modeled displacement at maximum deflection (summer); b) at minimum (winter). Colored wireframe indicates temperature, arrows and surface color show displacement; deformed body shape is highly exaggerated. Electronic supplement: animation of seasonal thermo-elastic displacements.

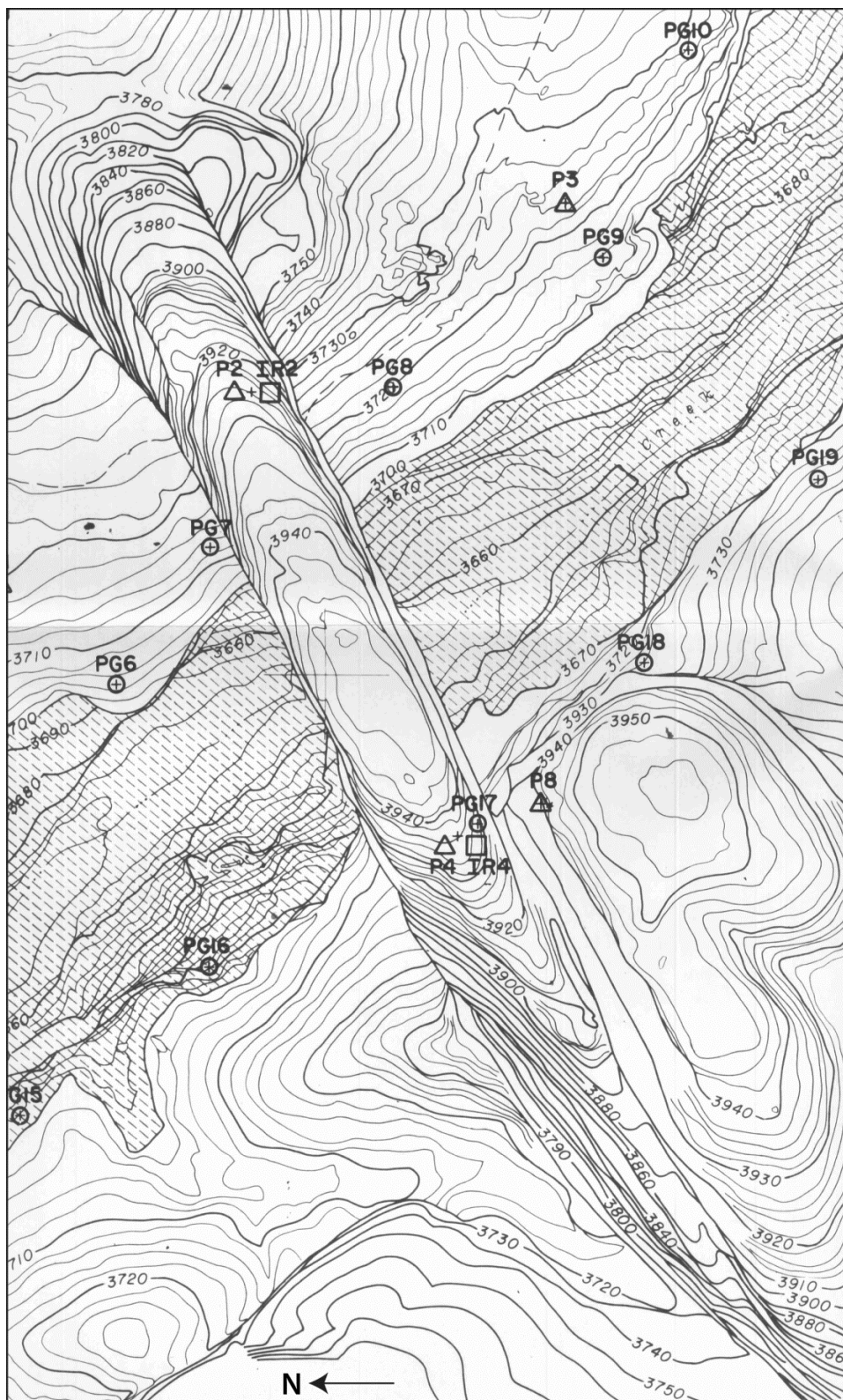


Figure 29. 2-ft BOR topographic map of Rainbow Bridge (Skipper, 1985). PG refers to photo-geology.

Table 7. Displacement data regenerated from Skipper (1989) BOR monitoring annual report. Values in gray are suspect data that may reflect settlement of the reflectors or base station monument.*

Monitoring Point	Measurement date	Horizontal movement (inch)	Azimuth (degrees)	Vertical movement (inch)	Dip (degrees)	In-plane movement (inch)	Cumulative horizontal in-plane (inch)
Point B1	Nov. 5-7, 1986*	—	—	—	—	—	—
	April 28-30, 1987*	-0.2116*	225*	0.0103*	3*	-0.1988*	—
	October 27-29, 1987	-0.0705*	225*	-0.0308*	-26*	-0.0662*	0.0000
	April 19-21, 1988	0.2872	56	0.0009	0	0.2837	0.2837
	Sept. 27-29, 1988	-0.2459	238	0.0297	7	-0.2441	0.0396
	April 11-13, 1989	0.2459	58	-0.0205	-5	0.2441	0.2837
	October 4-6, 1989	-0.1781	243	0.021	7	-0.1780	0.1057
	April ?-?, 1990	0.2041	79	-0.05	-14	0.1980	0.3037
Point B2	Nov. 5-7, 1986*	—	—	—	—	—	—
	April 28-30, 1987*	-0.2125*	224*	-0.00035*	0*	-0.1984*	—
	October 27-29, 1987	-0.0711*	224*	-0.0112*	-9*	-0.0664*	0.0000
	April 19-21, 1988	0.2895	56	-0.0179	-4	0.2859	0.2859
	Sept. 27-29, 1988	-0.2480	238	0.0489	11	-0.2462	0.0398
	April 11-13, 1989	0.2528	56	-0.0382	-9	0.2497	0.2895
	October 4-6, 1989	-0.1702	241	0.0277	9	-0.1698	0.1197
	April ?-?, 1990	0.1926	80	-0.048	-14	0.1860	0.3057
Point B3	Nov. 5-7, 1986*	—	—	—	—	—	—
	April 28-30, 1987*	-0.2121*	225*	-0.0106*	-3*	-0.1993*	—
	October 27-29, 1987	-0.0566*	225*	-0.0108*	-11*	-0.0532*	0.0000
	April 19-21, 1988	0.2699	54	-0.0185	-4	0.2649	0.2649
	Sept. 27-29, 1988	-0.2420	235	0.0493	12	-0.2383	0.0266
	April 11-13, 1989	0.2424	55	-0.0188	-4	0.2387	0.2653
	October 4-6, 1989	-0.1588	240	0.0284	10	-0.1582	0.1071
	April ?-?, 1990	0.1821	77	-0.0586	-19	0.1781	0.2853

Recommendations

Maximum allowable vibration amplitudes

King et al., summarized by Volpe (2014), recommendations for peak particle velocity (PPV) limits for natural structures and ancient/historical dwellings:

- Vibration at or near the fundamental frequency has the greatest potential for damage.
- Maximum peak particle velocity of 2 mm/s provides a conservative limit to avoid vibration-induced damage of sensitive, irreplaceable sites.
- PPV measurement location, value, and frequency band not consistently specified – King (1996) measured peak horizontal velocity transverse/radial to source, at top of structure, all frequencies.

National building and construction codes (including only relevant recommendations):

PPV limits to avoid damage to sensitive structures including historical buildings, monuments and temples, with vibration sources caused by construction activities (e.g. blasting, equipment):

- Swiss norm SN 640312a: 3 mm/s (max. value of absolute velocity vector), frequency <8 Hz
- German norm DIN 4150-3: 2.5 mm/s (highest value of two horizontal components), all freq.
- Indian DGMS guidelines: 2 mm/s (velocity component not specified), <8 Hz
- Australian standard A-2183: 2 mm/s (velocity component not specified), no frequency given
- Hungarian standard: 2 mm/s (velocity component not specified), no frequency given
- US FTA 2006 (after Swiss norm): 3 mm/s (velocity component unknown), no frequency given

Summary of selected most relevant values:

- German and Swiss norms give most precise definitions, similar PPV values, both widely used.
- German norm 4150-3 (“long-term”) considers resonance of structure and potential for fatigue (cumulative effects of many cycles), specifies the place of measurement (top of structure), as well as the value recorded and monitored in the field (highest horizontal velocity). PPV limit is for all frequencies.
- German norm 4150-3 (1999) specifies 2.5 mm/s PPV threshold for sensitive structures of “great intrinsic value”, e.g. listed buildings under preservation order, stating: “Experience has shown that if these values are complied with, damage will not occur.”

Suggested maximum allowable PPV limit for anthropogenic induced vibrations at Rainbow Bridge:

- 2.0 mm/s, measured on the top surface of Rainbow Bridge (center point or preferably multiple locations), as the highest value of arch-orthogonal horizontal velocity components, across all frequencies. Arch-perpendicular horizontal vibration likely maximum.

- Rainbow Bridge is a one-of-a-kind, irreplaceable structure; use of the most conservative available guidelines is recommended; value may need updated from further study.

Helicopter avoidance distances

Rainbow Bridge is a unique and irreplaceable natural structure with deep cultural significance. From a geological standpoint, it is an exceptionally rare and delicate landform, representing a fragile balance between forces of erosion and resistance, and revealed to us through chance intersection at a unique moment in Earth's history. Arches form and evolve over millennia (and longer) in response to and in balance with erosional forces imposed by their surroundings. Humans represent a new condition in the life-cycle of an arch, capable of applying forces that can be relatively strong and frequent. Rainbow Bridge did not evolve in equilibrium with human activities, and has an unknown ability to withstand anthropogenic stresses; the utmost care should be taken to minimize adverse effects.

Past related studies on potential damage arising from helicopter-induced vibrations focused primarily on historic or ancient structures, such as adobe pueblos and cliff dwellings (e.g. Schoemer & Neathammer, 1985; King 1996; King & King 1996a; King & King 1996b; King & King, 1998, see also Volpe 2014). Due to the brittle nature of the building materials, the results of these studies are believed to be also relevant for vibration-induced damage of natural rock structures, and indeed I recommend nearly identical allowable vibration limits for Rainbow Bridge in the preceding section. Past relevant studies ultimately recommend prohibiting helicopter flight within varying distance between 200 – 1000 ft of sensitive cultural resources (values vary depending on the site and selected permissible vibration level). One study in particular explored helicopter-induced vibration of several natural rock pinnacles, each having a first resonant frequency in the range of 2-4 Hz (King, 2001). Based on field testing with helicopter flights at close distances, the study recommended a minimum horizontal standoff distance of 200 ft (~60 m) for helicopter flight around the pinnacles. However, King (2001) also adopted a less conservative vibration limit for the pinnacles of 10 mm/s when developing this guideline.

In a preceding section, I point out that while the lowest modes of vibration of Rainbow Bridge appear to be insensitive to helicopter noise energy, higher-order modes may be excited with unknown consequences for local or global damage. Due to the anticipated complex and poorly known structural composition of Rainbow Bridge, as well as the potential for localized failure that may affect global stability, combined with its exceptional cultural significance, I recommend adopting conservative guidelines gleaned from relevant literature for helicopter standoff distances. I thereby recommend prohibiting helicopter flight within a ¼ mile (1320 ft or 400 m) horizontal radius of Rainbow Bridge for elevations below 5000 ft a.s.l. (1050 ft or 320 m above the top of the bridge). Pass-bys and hover at or near the elevation of the bridge within the ¼ mile standoff distance should be expressly prohibited.

These recommendations are based on my analysis of experimental field data and structural assessment combined with a review of relevant literature for light-duty civil helicopters under the particular conditions of each test. Test data collected in the present experiment cannot directly inform

or confirm the validity of these standoff limits since no actual helicopter flight around Rainbow Bridge was performed. Other helicopter makes and models may produce different source excitation and have different effects. Medium- and heavy-duty class helicopters will likely require different provisions. Additional field testing would be necessary to determine whether the selected avoidance distances are sufficient to limit induced vibrations below the proposed thresholds for damage avoidance.

Future studies

In order to conclusively identify whether the proposed horizontal and vertical standoff distances are adequate to limit induced vibrations at Rainbow Bridge below the designated threshold, additional field testing would be necessary. Specifically, Rainbow Bridge should be instrumented with at least 3-4 broadband seismometers, distributed along the length of the top surface of the span, recording vibration data during a test flight along a proposed air tour route. If induced vibration levels fall below the proposed threshold for damage, the air tour route could be deemed permissible from a structural standpoint; if not further revision of standoff distances would be necessary. If additional field testing is not possible, I recommend adopting the most conservative standoff values available, which may require updating the distance limits should new data or test results arise. Flight testing at the level of the bridge and within a few hundred feet is not recommended. Testing for potential damage to each partly detached slab or individual surficial feature on Rainbow Bridge is impractical, while installation of sensors in difficult to reach areas would be overly intrusive, and is similarly not recommended. Additional ambient vibration testing may allow us to better constrain some of the higher-order resonant modes predicted in the numerical analysis, which had slight ground motion at station position RABC and were not resolved in existing experimental data.

Additional numerical modelling may be used to further explore natural and anthropogenic vibration effects on Rainbow Bridge. The numerical model is set up, based on an excellent 3D geometrical model, and has basic material properties calibrated through matching experimental resonance data. Future studies could explicitly model helicopter air pressure sources and their potential effects on Rainbow Bridge, wind-induced vibration and resonance, as well as earthquake response and potential seismic damage. Moreover, the preliminary thermal and structural analyses presented here can be extended to analyze thermal- and hydro-mechanical coupled stress cycles, or effects of rising lake waters beneath the bridge. Each of the above analyses, however, is fairly intensive to perform, so should be driven by a clear scientific question or management need. Nonetheless, the capability exists to extend the numerical modeling significantly beyond the scope of the current work. Such modeling studies could also be supplemented by additional field campaigns, e.g. collecting simultaneous wind and vibration data, or daily thermal movement of the bridge. Select options for future monitoring of long-term effects and structural state of health are detailed in the following section.

Long-term monitoring

Cumulative effects of natural, as well as potential anthropogenic damage sources affecting Rainbow Bridge may be studied through long-term monitoring. In general, we distinguish continuous monitoring from repeat monitoring, the former meaning a sensor is placed at the site over a

continuous period, while in the latter, a reading is made and sensors then removed until the next measurement. Continuous monitoring offers the ability to detect and analyze individual drivers of damage, e.g. permanent change associated with an individual rain storm or earthquake, but is more costly and requires greater infrastructure to be installed on site (e.g. power and permanent mounting). Repeat occupation monitoring is less able to sense direct effects of individual drivers, rather can only capture cumulative change (or lack thereof) over the monitoring interval. Repeat monitoring is typically less expensive and less invasive.

Based on my field assessment of Rainbow Bridge, and with due attention to avoid detractions in visitor experience and minimize permanent installation effects on Rainbow Bridge, I propose two options for long-term monitoring. Several other options or variants of these are also possible, and could be developed according to specific scientific or management data requirements.

1. *Repeat ambient seismic resonance measurements at specified regular intervals, e.g. 1 year.*

The natural frequencies of a structure, here Rainbow Bridge, are a function of two key material properties: mass and elastic modulus, as well as the mechanical boundary conditions (e.g. cracks at attachment points). Monitoring resonance characteristics over time can thus provide evidence of mechanical change, which is a core principle of the field of structural health monitoring now prevalent in civil engineering. Such monitoring is non-invasive and able to sense changes in bulk material properties or boundary conditions over time through repeat or continuous measurements. The method is relative meaning a baseline is needed to which later measurements are compared. Internal cracking and damage, for example, manifest as a decrease in elastic modulus over time – i.e. a material becomes softer as it accumulates damage, and resonant frequencies drop. Meanwhile, a change in boundary conditions, e.g. an elongating or opening crack, will affect the total resonating mass and again result in a change in resonant frequencies over time. Our experimental data at Rainbow Bridge indicated stable resonant frequencies on daily scales, while seasonal changes not related to damage may be anticipated (e.g. rainy periods, ice). Therefore, our detection threshold of permanent resonant frequency change is likely in the range of a few percent, as also suggested by past related studies (Starr et al., 2015). We have already accessed a suitable monitoring position on the bridge, location RABC, which is ideal for repeat monitoring. RABC is not ideal for continuous monitoring, however; continuous measurements if desired may be performed at location RABB, which is nearly invisible to visitors but with less clear resonance characteristics, and the sensor would require a solar panel for continuous operation. Therefore, as a simple measure capable of sensing bulk change over a specified time interval, repeat ambient resonance measurements are advisable. My group currently performs similar measurements at other prominent natural rock arches in Utah. I would suggest measuring the resonance properties of Rainbow Bridge once or twice per year over a period of three years as an initial study. One outcome might be that permanent change is detected during this period, and thus more intensive study is necessary, while another outcome might show no net change in the mechanical properties of the bridge over this time; either outcome is likely useful to guide management decisions. We would require only two seismometers set at locations RABC and RABD (site and reference) for a period of several hours, simplifying the experimental procedure. Safety and access considerations have already been addressed, and the measurement

position validated with modal analysis. Experimental data collected in the current study thus serve as the baseline for future assessment of relative change in resonance properties.

2. Continuous monitoring of crack movement using an in-situ sensor placed within western abutment.

In-situ monitoring of crack displacement (i.e. opening and closing) is an essential measurement in most landslide hazard investigations. The author has used several such systems in different configurations in past studies to monitor crack displacement and landslide movement. Modern crackmeters based on vibrating wire sensors are inexpensive and accurate, and the technology is well-established. Most, however, require permanent mounting using anchor bolts on either side of a crack, which is technically feasible in some areas of Rainbow Bridge but might be intrusive for the sensitive rock structure. Moreover, such an instrument should be well-hidden at Rainbow Bridge so as not to be visible to visitors. In light of these considerations, and after field reconnaissance, I recommend use of a new type of crackmeter, a so-called scissor-jack meter. The device, shown in Figure 30, consists of a vibrating wire displacement sensor attached to a spring-driven jack, and is placed inside a narrow crack and glued to the crack walls. The sensor was developed by USGS and NPS personnel for use in Yosemite National Park (Collins and Stock, 2016). Since it is placed inside a crack, it is nearly invisible from most viewing angles, and it features the same sensor as well-established crackmeters, sensing crack aperture changes of <0.05 mm. Such an instrument once installed operates continuously, attached to a small field data logger (Figure 30) that stores readings on-site until data retrieval. Continuous crack opening data would allow us to measure the response of the crack to short-term environmental conditions, e.g. thermal cycles, as well as identify any long-term opening trends. I would propose to place one scissor-jack crackmeter within the broad crack on the south-western abutment of Rainbow Bridge (Figure 31). Preliminary modeling shows that the bridge tends to pull away from the adjoining knoll under gravity, with key tensile resistance provided by the adhered portions of this abutment. As this crack continues to elongate, the overall tensile strength is reduced, and cumulative deformation of the bridge could result in localized and potentially eventual global failure. A single crackmeter measurement provides a good starting point to assess any long-trends in global deformation (or lack thereof), without large costs or intrusive installations. A suitable position within the crack would need to be identified through future field assessment, i.e. where the crack is narrow enough for the scissor-jack meter, but wide enough to be accessed for installation. The sensor would be installed on rappel from the adjoining rock knoll south of the bridge. Data stored on site could be retrieved at intervals of twice per year (for example), and batteries checked and changed as needed. Solar power is likely not required.

The two methods recommended above may also be used in conjunction to create a more robust monitoring program, where continuous, localized crackmeter measurements help characterize the response of the bridge to individual driving forces, while seismic resonance data provide a view of global change. Additional in-situ and remote monitoring technologies could also be incorporated.



Figure 30. Vibrating wire scissor-jack crackmeter (image: Geokon Inc.) installed in a crack in Yosemite.

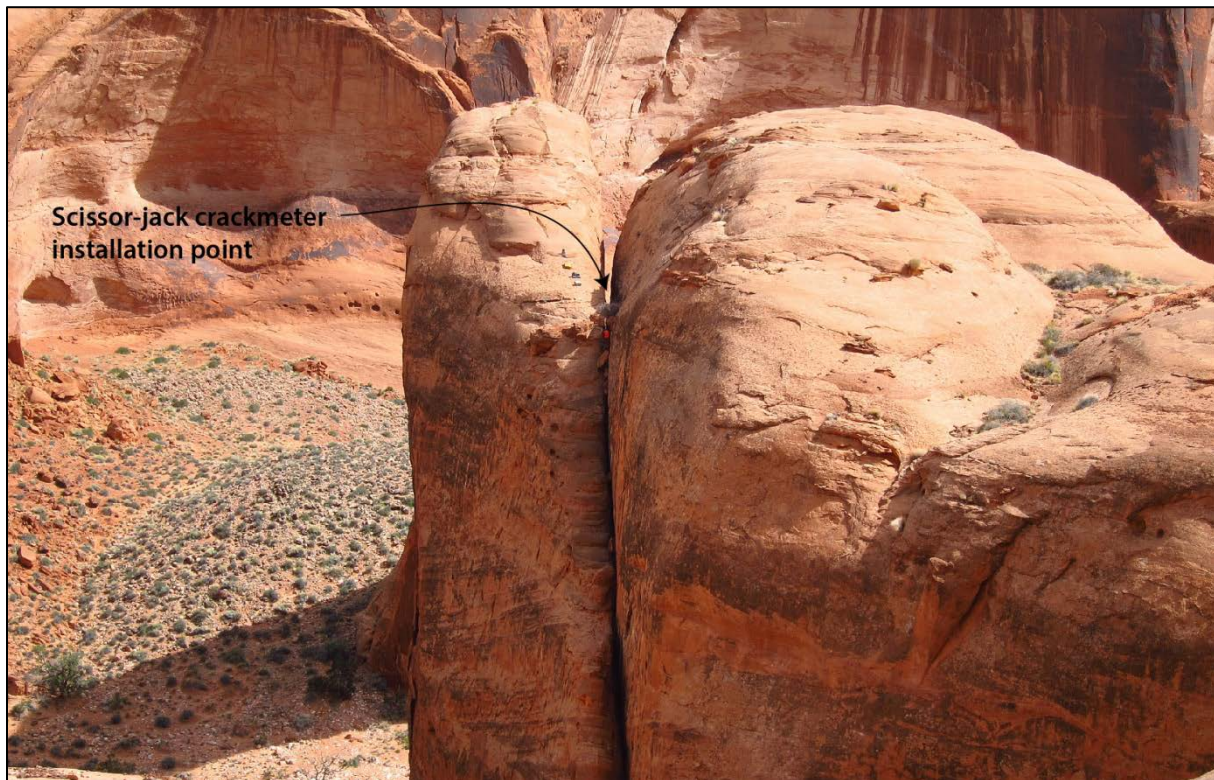


Figure 31. Proposed location for scissor-jack crackmeter installation, within crack at western abutment.

Hazards from Natural Vibration Sources

In addition to anthropogenic vibration sources, such as helicopter and fixed-wing aircraft discussed previously, as well as human (and animal) footfalls not discussed here (for more information see Volpe, 2014), several natural vibration sources may stimulate resonance of Rainbow Bridge and potentially result in damaging vibration levels. Here I briefly discuss possible effects of earthquakes and wind.

Our experimental ambient vibration data highlighted strong spectral amplification on Rainbow Bridge as compared to nearby bedrock on the canyon floor. Amplification was strongest at the resonant frequencies of the bridge, and site-to-reference spectral ratios exceeded 40. These are very high amplification values that result from slenderness and flexibility of the bridge. Past related studies on landslides have revealed similar albeit lower spectral ratios (Burjanek et al., 2012; Moore et al., 2011a). The ramification is that Rainbow Bridge is significantly more sensitive to earthquake ground shaking than surrounding bedrock; ground motion is amplified by at least an order of magnitude depending on the frequency content of the source. This finding must be taken into account in any future efforts to evaluate the seismic stability of Rainbow Bridge.

Pankow (2012) analyzed data from 163 earthquakes occurring within 200 km of Utah to develop a set of ground motion prediction equations estimating peak ground velocity (PGV) as a function of epicentral distance. The results are shown in Figure 32, highlighting the predicted variation of PGV with distance for a magnitude (M) 3 and 4 earthquake assuming both rock and soil conditions (the latter accounts for amplification in soft soil deposits). The plot can be used to roughly predict earthquake scenarios that might result in PGV at Rainbow Bridge exceeding the identified potential damage threshold of 2 mm/s. Accounting for the strong suspected site amplification at Rainbow Bridge, I refer primarily to the 'soil' curve in Figure 32. Magnitude 4 earthquakes at distances $< \sim 30$ km may thus produce damaging vibrations with PGV > 2 mm/s at Rainbow Bridge, while an estimated M 3.5 earthquake at $< \sim 10$ km distance may also exceed the 2 mm/s PGV threshold. Meanwhile, M > 5 earthquakes are expected to produce PGV levels in excess of 2 mm/s at distances less than approximately 100 km (Campbell & Bozorgnia, 2008). It should be noted that these predictions are extremely simplified and do not account for the dynamics of the structure, and moreover our data suggest amplification factors > 10 while the 'soil' amplification in Figure 32 is only a factor of ~ 2 ; smaller or more distant earthquakes may generate motions > 2 mm/s at the top of Rainbow Bridge.

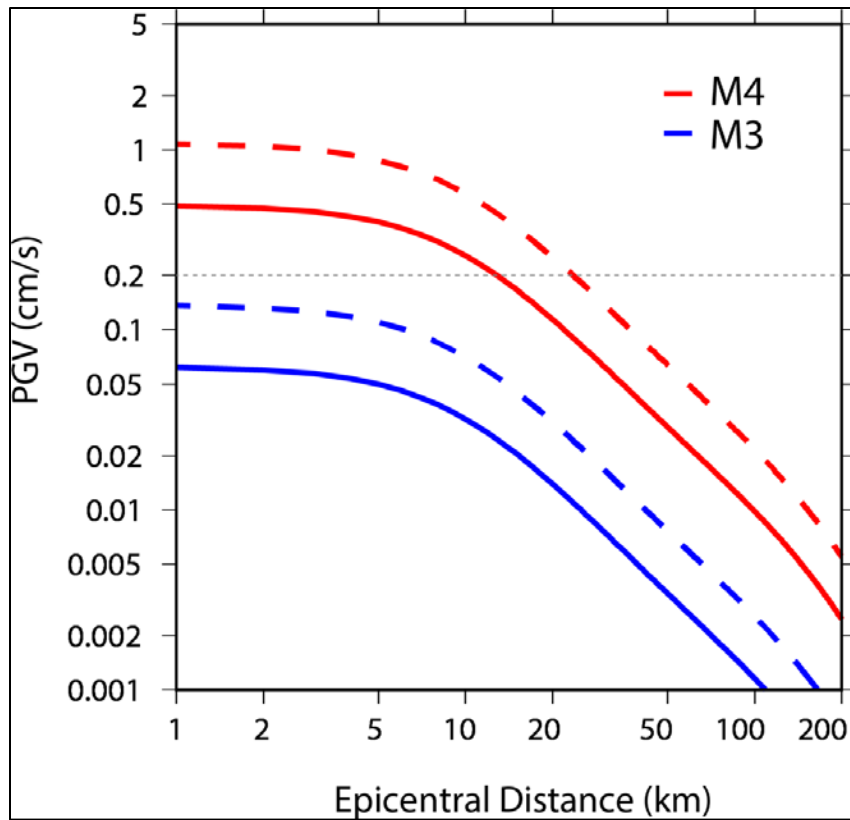


Figure 32. Pankow (2012) peak ground velocity (PGV) predictions for Utah using Chiou et al. (2010) ground-motion-prediction equations and local earthquake data (courtesy of Pankow, 2015 pers. comm.). PGV are given as a function of epicentral distance for two earthquakes (M 3 and M 4), and for rock (solid lines) or soil (dashed) site conditions. Strong amplification of ground motion at Rainbow Bridge may exceed site amplification for soil conditions. 2 mm/s PGV threshold for potential damage highlighted by the horizontal dashed line. Magnitude 4 earthquakes at distances $< \sim 30$ km may produce damaging vibrations at Rainbow Bridge, while estimated M 3.5 earthquakes at $< \sim 10$ km distance may also exceed the 2 mm/s PGV threshold for damage.

A search of the USGS catalog (<http://earthquake.usgs.gov/earthquakes/search/>) for earthquakes occurring within a 150 km radius of Rainbow Bridge with $M > 3$ during the past 35 years identified several $3 < M < 4$ events and two $M > 4$ earthquakes (Figure 33). No $M > 5$ events occurred during this time, nor are entered into the USGS catalog for the past 100 years within this search area. Comparing the magnitude and epicentral distance of the identified earthquakes with the distance-attenuation plot of Pankow (2012) (Figure 32), illustrates that none of these events are predicted to have generated $PGV > 2$ mm/s at Rainbow Bridge (the selected threshold for potential damage). The largest earthquake is highlighted in Figure 33, an M 4.0 event in 1986 located roughly 50 km from Rainbow Bridge. Accounting for soil amplification predicted by Pankow (2012), this earthquake may have generated an estimated PGV of ~ 1 mm/s at Rainbow Bridge. The value could be higher if amplification values are larger as suggested by our data. The nearest earthquake, located east of Navajo Mountain, was an M 3.3 event in 2009, and had epicentral distance of ~ 20 km from Rainbow Bridge. Such an earthquake may have generated PGV at the bridge of ~ 0.5 -1 mm/s. Both events are

thus probably unlikely to have caused structural damage to Rainbow Bridge, and no other earthquake identified in the USGS catalog exceeds these estimated PGV values.

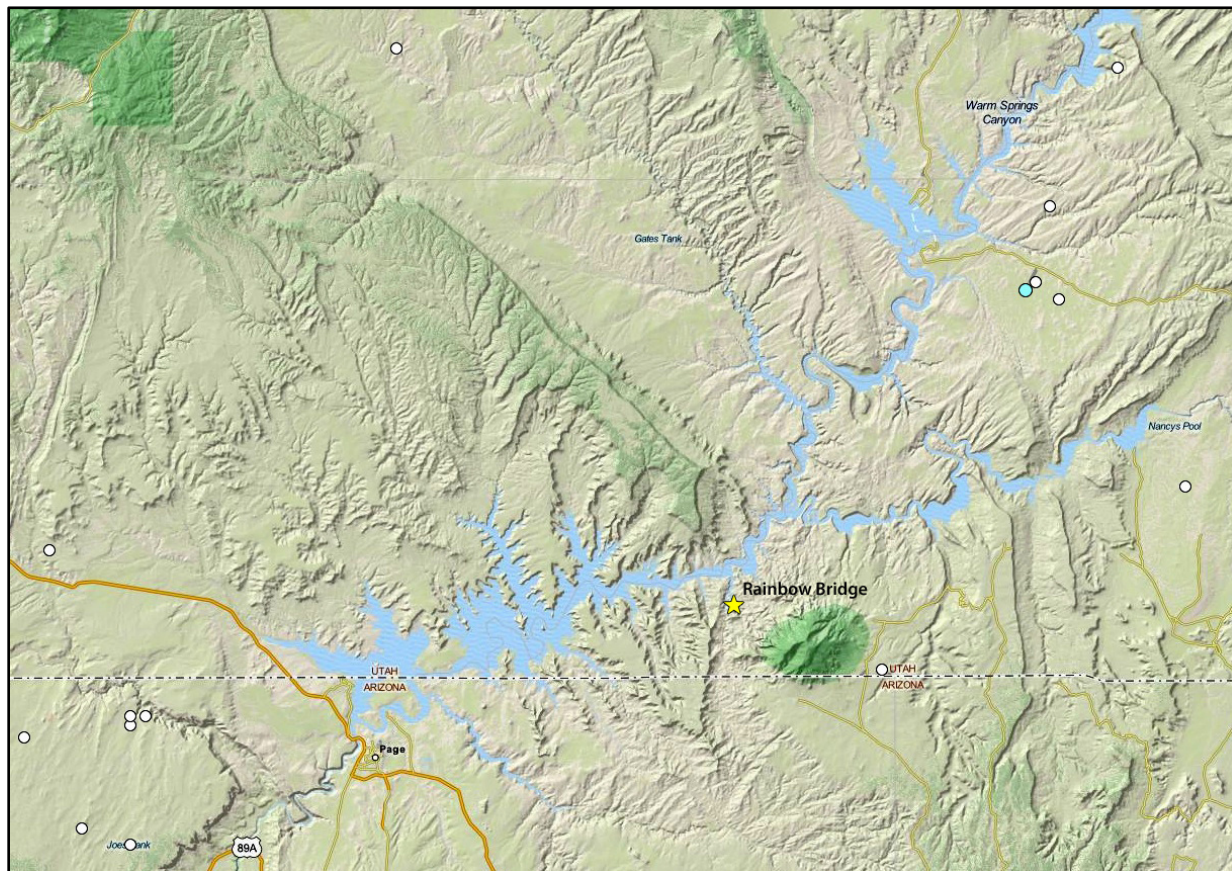


Figure 33. Earthquakes occurring within 150 km of Rainbow Bridge during the past 35 years (source: USGS). White circles are M 3-4, blue circle is the largest earthquake on this map: 1986 M 4.0, located ~50 km from Rainbow Bridge. None are likely to have produced damaging levels of vibration.

Wind is capable of exciting resonance of structures (Boggs & Dragovich, 2006), and strong winds may be one of the most damaging natural vibration sources regularly affecting Rainbow Bridge. Our experimental data highlighted a strong increase in vibration velocity during a windy period of the test, and indeed our maximum observed vibration amplitudes occurred during the windiest time (Figure 4). However, due to failure of the wind sensor, I am unable to quantitatively predict the variation of vibration amplitude with wind speed. We observe that vibration amplitudes triple as compared to those near the beginning of our experiment when gust speeds were 10 m/s or less. However, correlating gust speed with vibration amplitude for the period of coincident test data (Figure 12) was inadequate to generate meaningful extrapolations for high wind speeds. I note that due to our sensor location, we almost certainly did not measure the maximum wind-induced vibration amplitude at Rainbow Bridge, which will likely occur near the center of the bridge or at an anti-node of a particular resonant mode (Figure 16).

Vortex shedding is one phenomenon through which wind can generate structural resonance and potentially damaging vibrations (Giosan, 2000). Low-pressure vortices are created on the downwind side a structure as incident wind flows around the body, and the structure bends into the low-pressure area. The result is an oscillating force oriented perpendicular to the direction of the wind. The frequency at which vortex shedding takes place is a function of wind speed, and the size and shape of the body, and when the vortex shedding frequency matches a resonant frequency of a given structure, strong vibration can result. Many civil structures (e.g. smokestacks) have engineered components that introduce turbulence and mitigate vortex shedding, features which natural structures lack. However, vortex shedding may not explain the observed increase in vibration amplitudes during the windiest period of our data. We observe maximum vibration amplitude on the horizontal component of motion oriented perpendicular to Rainbow Bridge. In order for vortex shedding to induce resonance in this direction, the wind would have to be moving parallel to the trend of the bridge, i.e. across the canyon, which is unlikely. More likely is that wind directions are predominantly oriented up or down Bridge Canyon, which could produce vortex shedding vibration effects in the bridge-parallel and/or vertical directions. Neither of these components were strongly amplified in our experimental data, however, indicating that vortex shedding effects may not have been significant during our test period.

Data

All data and results produced in this analysis shall be electronically appended with the final report. They are organized in the following folders according to content:

- **BOR:** Bureau of Reclamation past studies: scans of obtained monitoring reports and key maps and cross-sections. Digitized displacement monitoring map, and recalculated displacement data. Material properties tested by Dames and Moore.
- **Comsol:** Results of numerical modal analysis, gravitational stress and thermo-elastic deformation analyses. Figures and movie animation outputs. Table listing the first 100 modes of vibration for Rainbow Bridge with mass participation and comparison to field data.
- **Heli_RS:** Helicopter noise data compiled, processed, and provided by NPS Physical Scientist / Acoustic Specialist, Randy Stanley.
- **Meteo:** Rock temperature, air temperature and relative humidity, as well as wind speed data from the March 2015 field test at Rainbow Bridge.
- **Photogram_JW:** 3D model used for numerical modeling created by NPS Geologist and Photogrammetry Specialist, John Wood.
- **Pics:** My photographs from the March 2015 field test at Rainbow Bridge, included annotated photos of cracks on the eastern and western abutments.
- **Seism:** Seismic data generated during the March 2015 field test at Rainbow Bridge. Tables and processed figures. Subfolders contain data from each sensor RABA-RABD in native miniseed format and generated ascii format, in addition to spectra and polarization analysis results. EQ folder contains extracted data and analysis for the two small earthquakes recorded.
- **Tilt:** Tilt data and temperature-corrected relative tilt results for the March 2015 field test.

Literature Cited

- Boggs, D., & Dragovich, J. 2006. The nature of wind loads and dynamic response, ACI Special Publication, 240.
- Burjanek, J., Moore, J.R., Yugsi-Molina, F.X., & Faeh, D. 2012. Instrumental Evidence of Normal Mode Rock Slope Vibration, *Geophysical Journal International*, 188, 559-569.
- Campbell, K.W. & Bozorgnia, Y. 2008. NGA Ground Motion Model for the Geometric Mean Horizontal Component of PGA, PGV, PGD and 5% Damped Linear Elastic Response Spectra for Periods Ranging from 0.01 to 10 s, *Earthquake Spectra*, 24, 139–171.
- Collins, B.D. & Stock, G.M. 2016. Rockfall triggering by cyclic thermal stressing of exfoliation fractures, *Nature Geoscience*, 9, 395–400.
- Chiou, B., Youngs, R., Abrahamson, N., & Addo, K. 2010. Ground-motion attenuation model for small-to-moderate shallow crustal earthquakes in California and its implications for regionalization of ground-motion prediction models: *Earthquake Spectra*, v. 26, p. 907–926.
- Dames and Moore 1972. Geological and structural evaluation of Rainbow Bridge, Rainbow Bridge National Monument, Utah.
- German norm DIN 4150-3 1999. Structural vibration, part 3: effects of vibration on structures, 11 pages.
- Giosan, I. 2000. Vortex shedding induced loads on free standing structures. *Structural Vortex Shedding Response Estimation Methodology and Finite Element Simulation*, 1-20.
- Goodman, R.E. 1989. *Introduction to rock mechanics*, New York: Wiley.
- Goulet, J.-A., Michel, C., & Smith, I.F.C. 2013. Hybrid probabilities and error-domain structural identification using ambient vibration monitoring, *Mechanical Systems & Signal Processing*, 37, 199–212.
- Hanson, C.E., King, K.W., Eagan, M.E., & Horonjeff, R.D. 1991. Aircraft noise effects on cultural resources: review of technical literature, NPOA Report No. 91-3 (HMMH Report No.290940.04-1).
- Hoek, E., & Diederichs, M. S. 2006. Empirical estimation of rock mass modulus, *International Journal of Rock Mechanics and Mining Sciences*, 43(2), 203-215.
- Holloman Air Force Base 2012. Instruction 11-250, Airfield Operations Instruction: Flying Operations, 10 August 2012.
- James, M., Downing, M., Bradley, K., & Garrelick, J. 2009. Sonic boom structural damage potential for Fort Jefferson at Dry Tortugas National Park, Key West Range Complex DRTO Sonic Boom Study.

- Keefer, D. K. 1984. Landslides caused by earthquakes. *Geol. Soc. Am. Bull.* 95, 406-421.
- Keefer, D. K. 2002. Investigating landslides caused by earthquakes – a historical review. *Surveys in Geophysics*, 23(6), 473-510.
- King, K.W. 1996. Investigation of Helicopter Induced Vibrations at Balcony House, Mesa Verde, unpublished report.
- King, K.W. 2001. Chiricahua Pinnacle Vibration Investigation, Preliminary Report for Chiricahua National Monument.
- King, K.W. & King, E. 1996a. Pipe Springs National Monument Vibration Investigation, Report.
- King, K.W. & King, E. 1996b. Vibration Investigation of Taos Pueblo, Taos, New Mexico, Report for Taos Council.
- King, K.W. & King, E. 1998. Tonto National Monument Vibration Investigation, Report for Tonto National Monument, National Park Service.
- Koper, K.D. & Hawley, V.L. 2010. Frequency dependent polarization analysis of ambient seismic noise recorded at a broadband seismometer in the central United States, *Earthquake Science*, 23, 439-447, doi: 10.1007/s11589-010-0743-5.
- Moore, J.R., Gischig, V., Burjanek, J., Loew, S., & Fäh, D. 2011a. Site Effects in Unstable Rock Slopes: Dynamic Behavior of the Randa Instability (Switzerland), *Bulletin of the Seismological Society of America*, 101, 3110-3116.
- Moore, J.R., Gischig, V., Katterbach, M., & Loew, S. 2011b. Air Circulation in Deep Fractures and the Temperature Field of an Alpine Rock Slope, *Earth Surface Processes and Landforms*, 36, 1985-1996.
- Pankow, K.L., 2012, Instrumentally recorded ground motions in the Utah Region since 2000, in Hylland, M.D., and Harty, K.M., editors, *Selected topics in engineering and environmental geology in Utah: Utah Geological Association Publication 41*, 1–8.
- Schomer, P.D. & Neathammer, R. 1985. The Role of Vibration and Rattle in Human Response to Helicopter Noise, U.S. Army CERL tech. report N-85/14.
- Schmitz, F.H & Yu, Y.H. 1983. Helicopter Impulsive Noise: Theoretical and Experimental Status, NASA Technical Memorandum 84390 USAAVRADCOT Technical Report 83-A-2.
- Shearer, P.M. 2009. *Introduction to Seismology*, 2nd ed., 396 pp., Cambridge University Press, NY.
- Skipper, K. 1985. Rainbow Bridge National Monument monitoring program: final status report, U.S. Bureau of Reclamation.

Skipper, K. 1989. 1989 Annual report of investigations for Rainbow Bridge National Monument monitoring program, U.S. Bureau of Reclamation.

Starr, A.M., Moore, J.R., & Thorne, M.S. 2015. Ambient Resonance of Mesa Arch, Canyonlands National Park, Utah, *Geophysical Research Letters*, 42, 6696–6702, doi: 10.1002/2015GL064917.

Swiss norm SN 640 312a 1992. Erschütterungen – Erschütterungseinwirkungen auf Bauwerke (Vibration effects on buildings).

United States Federal Transit Administration 2006. Transit noise and vibration impact assessment, report FTA-VA-90-1003-06, Hanson, C.E., Towers, D.A., and Meister, L.D., 274 pages.

Volpe National Transportation Systems Center, Department of Transportation, 2014. Literature Review: Vibration of Natural Structures and Ancient/Historical Dwellings, Internal Report for National Park Service, Natural Sounds and Night Skies Division, August, 21, 2014.



Figure 34. Hauling monitoring equipment to the top of the bridge.

The Department of the Interior protects and manages the nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its special responsibilities to American Indians, Alaska Natives, and affiliated Island Communities.

NPS 118/144349, April 2018

National Park Service
U.S. Department of the Interior



[Natural Resource Stewardship and Science](#)

1201 Oakridge Drive, Suite 150
Fort Collins, CO 80525