Annotated Bibliography – Vibroacoustic Studies for NPS Resource Impact Assessment v1.1 (9/23/2014)

Summary of selected content: This collective body of literature reflects more than 30 years of studies on the effects of vibration on cultural and natural resources in various settings, including National Park units and National Historic Landmarks. The cultural resources include historic buildings, bridges, Indian ruins, petroglyphs, and other archaeological sites. Historic buildings can include adobe structures, stone veneer frame structure, monuments, and masonry (mortar or mortar-less) structures of all sizes. Natural structures can include pinnacles, caves, and the stone faces on which petroglyphs are formed. Where text is copied, quotes are included for attribution to the author(s).

Overall Summary of References: Vibration risk assessments should include field inspection of receiver susceptibility as well as the input function and the transfer path. Specifically, what are the key transfer paths (medium or coupling) between the vibration source and the receiver? What is the vibration source and intensity? Is the vibration due to an explosive air blast, a sonic boom, helicopter rotor, aircraft propeller, vehicle motion, ground impact, or other shock wave? Because ground-borne vibration can vary greatly with the ground material and the degree of soil compaction, site-specific assessment of ground paths can also be very important.

Citation	Summary
1. Sutherland, L.C., et al., "Sonic and Vibration Environments for Ground Facilities – A Design Manual" Wyle Laboratories Report No. WR 68-2, Submitted under NASA Contract NAS8-11217, March 1968.	Author Introduction: "This manual provides a comprehensive engineering guide for the evaluation of acoustic, vibration and blast environments in the design and siting of ground facilities for the launch and testing of rocket vehicles. The manual also includes related material covering dynamic loads due to sonic booms." The manual is not only usable for engineering design of major rocket testing facilities but also has "potential value in the basic engineering data, design criteria, and analytical background presented… The manual may have value for lesser, and often just as important, sonic and vibration problems faced by the engineering specialist or designer."
2. Whiffin, A. C. and Leonard, D. R., "A Survey of Traffic-induced Vibrations," Road Research Laboratory Report LR418, Crowthorne, England, 1971.	Author Introduction: "This report summarizes existing knowledge of traffic-induced vibrations and attempts to assess their importance in relation to other sources of vibration affecting the environment. Information derived from field measurements is included together with existing scales for assessing intensity of vibrations in order to discuss the criteria which might be applied." **In this survey, the recommended upper level of vibration (peak particle velocity in vertical direction) to which ruins and ancient monuments should be subjected is 2.0 mm/sec. For normal dwelling-houses with plastered walls and ceilings, there is a risk of "architectural" damage when the ground vibrations reach the level of 5 mm/s. "If the vibrations reach the level of 10-15 mm/s, people would find them unpleasant, and there would be a risk of structural damage to buildings."**

3. U.S. Environmental Protection Agency. The Effects of Sonic Boom and Similar Impulsive Noise on Structures. EPA Report No. NTID300.12, December 31, 1971.	The EPA report constitutes an early attempt to summarize "the physical nature of sonic booms, and other impulsive noises, and the parameters… used to characterize booms," as understood from research conducted up to 1971. It includes "an overview of the response of structures – particularly buildings – to sonic booms and a review of the damage history observed due to supersonic overflights. The report concludes with a summary of the observed effects of impulsive noise on terrain and natural structures." The National Park Service is noted as the primary source of information for the effect of sonic booms on archaeological or natural structures, including cliff dwellings at Canyon de Chelly National Monument, an earth formation at Bryce Canyon National Park, and structures at Mesa Verde National Park.
4. Clarkson, B.L. and Mayes, W.H., "Sonic-Boom-Induced Building Structure Responses Including Damage," Journal of the Acoustical Society of America, Vol. 51, No. 2 (Part 3), 1972, pp. 742-757.	Author Abstract: "Concepts of sonic-boom pressure loading of building structures and the associated responses are reviewed, and results of pertinent theoretical and experimental research programs are summarized. The significance of sonic-boom load time histories, including waveshape effects, are illustrated with the aid of simple structural elements such as beams and plates. Also included are discussions of the significance of such other phenomena as three-dimensional loading effects, air cavity coupling, multimodal responses, and structural nonlinearities. Measured deflection, acceleration, and strain data from laboratory models and full-scale building tests are summarized, and these data are compared, where possible, with predicted values. Damage complaint and claim experience due both to controlled and uncontrolled supersonic flights over communities are summarized with particular reference to residential, commercial, and historic buildings. Sonic-boom-induced building responses are compared with those from other impulsive loadings due to natural and cultural events and from laboratory simulation tests."
5. Harding, S.T., King, K.W., Langer, C.J., "Near-source broad-band recording from the Yellowstone earthquake aftershock sequence of June, l975," Abstract: 49th Annual Meeting of the Seismological Society of America, Eastern Section, October 13-14, 1977, in Earthquake Notes, Vol. 48, No. 3, July-Sept. 1977. http://srl.geoscienceworld.org/content/48/3/7.full.pdf+html	Author Text: "Three sets of broad-band (0.2 to 30 Hz) seismograph systems… were used to record the ground motion from aftershocks of the June 30, 1975, Yellowstone Park earthquake. The aftershocks were located by a network consisting of five portable smoked paper recording seismographs and the broad-band instruments. Coda-length magnitudes were determined from the smoked-paper recordings at the Ice Lake station, near the earthquake source, and a log number (log N) vs magnitude (M) relationship was determined (log N = A - bM) for magnitudes between 1.0 and 3.0. A similar relationship was determined for magnitudes between 2.5 and 4.5 over the same period of time at the YVR station approximately 75 km from the source area... The extent to which the results are influenced by different average magnitudes and different magnitude thresholds is not known. However, an important contribution to the difference appears to be the fact that many of the larger events recorded at the greater distances appear to consist of a series of small events when recorded at close distances." Fourier velocity spectra of the aftershocks were analyzed for corner frequency with azimuth and distance.

6. Battis, J.C., "Seismo-Acoustic Effects of Sonic Booms on Archeological Sites, Valentine Military Operations Area," Air Force Geophysics Laboratory, Hanscom AFB, Report No. AFGL-TR-83-0304, Environmental Research Papers, No. 858, November 9, 1983.	Edited Abstract: Seismo-acoustic recordings of sonic booms were made at two sites in the Valentine Military Operations Area (MOA). This investigation was primarily directed at determining the potential for damage by sonic booms to American Indian rock shelter and petroglyph sites located within the MOA. The studies indicate that sonic booms mostly reflect off hard rock surfaces and are unlikely to cause damage to such archaeological sites. The expected motions are, at worst, 8 percent of the limits set by strict blasting codes and comparable to velocities that could be produced by local earthquakes which have occurred in the Valentine area. At these levels of motion, competent rock will be unaffected by the transmission of seismic waves. The predicted velocity levels from sonic booms are unlikely to initiate either fracture or spalling in competent rocks. However, it is possible that, in rocks where natural meteorological action has initiated these erosive mechanisms, sonic boom induced motion could accelerate the processes to some small degree.
7. Battis, J.C., "Vibro-Acoustic Forecasts for STS Launches at V23, Vandenberg AFB: Results Summary and the Payload Preparation Room," Air Force Geophysics Laboratory, Hanscom AFB, Report No. AFGL-TR-85-0133, Environmental Research Papers, No. 922, May 8, 1985.	Other Summary[i]: "This report presents a method for launch noise-induced vibration environment forecasts for locations in major structures at the Vandenberg AFB Shuttle launch facility. Forecasts were made by coupling a model for the Shuttle rocket acoustics with observed vibrations of structures due to charge detonations over the launch mount. Vibration criteria, or levels of concern, were established for this study. Various locations were assessed for excessive vibrations according to the criteria."
8. King, K.W., et al., "Seismic and Vibration Hazard Investigations of Chaco Culture National Historical Park," USGS Open-File Report 85-529, 1985. http://pubs.usgs.gov/of/1985/0529/report.pdf	Author Abstract: "The potential for damage to structures in Chaco Culture National Historical Park resulting from earthquakes, landslides, industrial blasting, road building and vehicular traffic has been investigated. The Historical Park, located in northwestern New Mexico, contains over 2,000 known archeological sites. The structures of interest… date from the 11th and 12th centuries. A **2.0 mm/sec particle velocity is recommended as the upper limit for induced motions in the structures** resulting from industrial blasting, road building and vehicular traffic. Minimum distances of these activities from the structures are recommended based on field recordings and analysis of the induced vibrations from these sources. Minimum distances of 1.2 km from blasting, 0.5 km from railroad traffic, 45 m from road building and 25 m from vehicular traffic are recommended based on normal blasting practices in the area, conventional rail traffic, usage of road building equipment and normal vehicular traffic patterns. Recommendations are also made for controlling vibrations from one road in the Historical Park considered to be too close to historical structures. Levels of expected ground motion from earthquakes… indicate that possible future earthquake damage to the structures should be considered."

9. King, K.W., et al., "Engineering Seismic Investigation of the Village of Paguate, New Mexico," USGS Administrative Report, August 29, 1986.	Author Introduction: "This report summarizes the investigation of the levels of ground motion in the village of Paguate, New Mexico, associated with contained explosions detonated near an open-pit mine adjacent to the village… The objective of the project is to investigate the possibility of building damage from man-made seismic sources, the probable distribution of the induced ground motion, and the areas of high potential risk from vibration damage in the future." Author Discussion and Conclusions: "The damage survey in the village of Paguate shows an overall intensity pattern that is irregular in areal distribution and not related to distance from the Jackpile open-pit mine…. The seismic data analyses from the Paguate investigation show that (a) sites at greater distances from the source than many other sites in the village have larger and longer duration shaking at several frequencies due to the site ground-motion response, (b) the buildings' structural response to the induced ground shaking is within the site-response bandwidth, (c) there is no clear evidence of differential compaction under the foundations of the building at most of the sites, (d) the vertical ground-motion attenuation function used by many investigators and mining companies ($R^{-1.6}$) is suitable for vertical ground-motion attenuation for sites on rock in the Paguate area, and (e) the peak horizontal ground motion in the Paguate area attenuates as $R^{-1.15}$." Specific recommendations are made for future blasting for mining, reclamation, and (or) industrial development.
10. Raba-Kistner Consultants, Inc., "Report on Vibration Monitoring," Prepared for Transplan, Inc., Project No. 786-024, September 29, 1986.	Author Introduction and Conclusion: "As part of the Environmental Impact Statement (EIS) currently being prepared for the Stinson Municipal Airport in San Antonio, Texas, vibration monitoring was required to be undertaken within the San Antonio Missions National Historic Park. The objective of this effort was to ascertain the extent, if any, of vibration created on various mission structures within the Park, as a result of aircraft overflights from adjacent Stinson Municipal Airport. Vibration monitoring was conducted at three (3) predetermined locations for a number of single-event situations. Vibration monitoring equipment was mounted, using plaster-of-paris, as approved by the National Park Service on… mission structures." In conclusion, the "vibration levels measured for each mission and for all forms of aircraft did not exceed 0.02 in/sec which is far below even the most stringent vibration levels for historic structures. Air overpressure, less than 100 dB is also far below any damaging criteria."

11. King, K.W. and Algermissen, S.T., "A Vibration Study of the Archeological Ruins, Hovenweep National Monument, Utah-Colorado," USGS Open-File Report 87-181, 1987. http://pubs.usgs.gov/of/1987/0181/report.pdf	Author Introduction: "Hovenweep National Monument contains six groups of unique, ancient, stone-adobe structures" that the Hovenweep Anasazi people began building around 1200 A.D. "at the head of small draws and on the rims of box canyons. The Hovenweep ruins are unlike any other Anasazi structures of the southwest in architecture and general setting." Author Discussion: Assuming "that the National Park Service will not permit the Hovenweep National Monument ruins to be subjected to larger amplitude of induced ground motions than they do at the Chaco Culture National Historic Park… the suggested **maximum induced-vibration level is 2.0 mm/sec," a conservative "peak-particle velocity… measured on the structure itself**. Therefore, we believe that the upper limit of ground velocity induced at the base of the structures should be 0.1 mm/sec in the 1.0-10.0 Hz frequency band." Via the following recommendations, "it is possible to limit the peak ground velocities to 0.1 mm/sec in the vicinity of the structures because of the small area involved. Normal automobile traffic should be kept a distance of 30 m from the base of the structures and heavy traffic and trenching equipment should be kept a distance of 65 m from the structures." Specific recommendations are made for buried explosives and vibration equipment in the frequency range of 1-10 Hz. A suggested zoning map using these criteria is provided for the vicinity of the ruins.
12. Battis, J.C. "Effects of Low Flying Aircraft on Archaeological Structures," Air Force Geophysics Laboratory, Hanscom AFB, Report No. AFGL-TR-88-0263, Environmental Research Papers, No. 1013, September 26, 1988.	Other Summary[i]: "Induced vibrations from aircraft overflights were measured at Long House, an Anasazi Indian site dating from approximately AD 1300. Aircraft overflights were performed by (various fighter and bomber) aircraft at altitudes ranging from 60 to over 300 meters (200 to over 1000 feet) above ground level. Seismometers on the Long House structure recorded the vibration response of the ruin. None of the overflights produced responses exceeding **established criteria for archaeological sites, taken to be a peak vector sum wall velocity of 1.3 mm/sec (.05 in/sec)**. A method for determining the admittance functions for archaeological sites using a shotgun firing as acoustic source was tested, but found not useful for large, massive walls. The study concludes that (1) low overflights can induce measurable vibrations in these ancient structures; (2) the motions result from the direct pressure loads on the structure; and (3) the overflight induced motions do not constitute an appreciable threat to the sites."

13. King, K.W., et al., "Vibration Investigation of the Museum Building at White Sands National Monument, New Mexico," USGS Open-File Report 88-544, 1988. http://pubs.usgs.gov/of/1988/0544/report.pdf	Author Introduction: "White Sands National Monument is located in south-central New Mexico near the White Sands" Missile Range and the Holloman Air Force Base (formerly Alamogordo Army Air Field). "This report presents the results of a study on the building response of the museum-administration building at the White Sands National Monument. The study evaluated the vibration response of the building, some sources of vibrations which are suspected to be the cause of cracking damage in the building's adobe material; this report suggests remedies to minimize future cracking as a consequence of induced vibrations." Author Discussion: The "**maximum velocity particle motion level of 2 mm/sec in the 1- to 20-Hz band**… accepted at the Chaco Culture National Historic National Park" is recommended "for the structures at White Sands National Monument. If this is adopted, then the normal take-off pattern used by the nearby airport would be acceptable, but the low-flying helicopters and low-flying, high-speed jet aircraft flying within a few thousand feet of the structures would not be acceptable. Also, additional road construction or heavy earth-tamping should not be nearer than approximately 200 feet of the main museum building. This vibration level is recommended only for historic, irreplaceable adobe-masonry structures or for those structures that may have irreplaceable mud-adobe artifacts within."
14. Sutherland, L.C., et al., "Evaluation of Potential Damage to Unconventional Structures by Sonic Booms." U.S. Air Force, Human Systems Division, Noise & Sonic Boom Impact Technology (NSBIT) Program, Wright-Patterson AFB, Report No. HSD-TR-90-021 (Wyle Laboratories Report No. 89-14), May 1990.	Other Summary[i]: "Supersonic operations of U.S. Air Force aircraft cause sonic booms which may be the source of damage to unconventional structures like those administered by the National Park Service. This problem is addressed in this report by (1) a literature survey of damage prediction and damage assessment techniques for such structures; (2) development of a statistical model for sonic boom overpressures with emphasis on supersonic operating areas employed for air combat maneuver training; (3) development of an analytical model to predict the probability of damage; (4) execution of a limited experimental program at White Sands Missile Range to evaluate response and potential damage of two unconventional structures in support of the prediction model; and finally (5) definition of algorithms for use in the Air Force ASAN computer program for evaluation of the probability of damage to unconventional structures from sonic booms." Author and Editor: **A summary of vibration criteria to avoid damage to prehistoric, historic, sensitive and conventional structures is provided in Table 4-7 (p. 4-41). Maximum recommended peak velocities for low frequency vibration at historic/ sensitive sites range from 0.004 in/sec to 0.3 in/sec at the ground. For archaeological sites (p. 4-47), two estimates of sonic boom-induced damage threshold stress are 3.2 psi (old adobe) and 3.9 psi (stone). "An average value for the failure stress of prehistoric stone walls of 3.5 psi is therefore used for analysis.** In the absence of any other data source, the standard deviation σ_L of the log of this damage stress is assumed to be 0.239 which is the same as the value obtained for the substantial set of measured failure data on adobe discussed earlier" in the report.

15. Sutherland, L.C., "Assessment of Potential Structural Damage from Low Altitude Subsonic Aircraft," Wyle Laboratories Report WR 89-16(R), submitted to Martin Marietta Energy Systems, Inc., Oak Ridge, TN, June 1990.	Other summary[i]: This report "presents an analysis of the potential damage effects from acoustic aerodynamic noise generated by low-flying, subsonic military aircraft on military training routes (MTRs), but it also applies to noise from civilian aircraft. Damage potential is estimated on the basis of statistical models… Principal findings indicate that a small but finite probability of damage to some structures can be expected for heavy traffic of bomber aircraft on low altitude MTR flights. Similar flights of heavy helicopters at altitudes down to 50 ft. may cause significant damage to structures located close to their flight tracks. Careful planning of low level flights for such heavy helicopters is indicated to avoid overflights over structures. MTR flight planning for light helicopters, fighter and cargo/transport aircraft must also consider routes to avoid structural damage, even though it is less than those for bombers and heavy helicopters." Author from section 5.4.1 (p. 5-10): "For historic sites, weakened (i.e., already cracked) Type B windows and plaster walls on wood frame buildings are the most susceptible to damage… Due to their lower assumed strength, damage potential for sensitive historic adobe buildings is substantially greater than for such structures (presumably occupied) in rural areas even though quite low... Prehistoric structures with intact roofs are estimated to have the highest damage risk... Prehistoric masonry structures without a roof have nearly a comparable damage potential. In general, these predicted values of the probability of damage, while low, indicate that such areas should be avoided for MTR routes for bomber aircraft wherever possible since the structures cannot be realistically repaired if damage does occur."
16. King, K.W., et al., "Induced Ground-Vibration Study at Pueblo Grande, Phoenix, Arizona," USGS Open-File Report 91-332, 1991. http://pubs.usgs.gov/of/1991/0332/report.pdf	Author Abstract and Editor: "This report addresses concerns about potential damage to the archeological structures at Pueblo Grande due to the induced ground shaking from the construction of the Hohokam Freeway, the construction of the expanded Pueblo Grande Museum and Cultural Park, and during future use of the park." The properties, including the Pueblo Grande Ruin and the Hohokam-Pima Irrigation Sites were separately designated as National Historic Landmarks (NHLs) in 1964 and combined into a single NHL in 2003. Author Discussion: The natural frequencies of the walls and the percent of critical damping are documented, as well as sensitivity to vertical motions induced by a hovering helicopter. "The maximum vibration levels documented during this study were well within the safe zone as designated for mine blasts near frame and brick homes (Siskind and others, 1980). However, the acceptable vibration level should be considerably less for irreplaceable historic structures, especially those of adobe and flat-roof construction. The general vibration standard is set for structures that can be repaired without risk of loss of historical significance. Because of the irreplaceability of the structures, the historic contents, and the absence of knowledge of the cumulative effect of low to medium level of vibrations (1-20 mm/s at 1-40 Hz) on adobe construction, a conservative level of induced vibrations should be established. **A maximum particle velocity vibration level of 2 mm/sec**… established at Hovenweep, Chaco Culture National Historic Park and Mesa Verde National Park… affords a safe upper level of induced motion without overly restricting normal cultural and industrial activities."

17. King, K.W., et al., "Bonito Vibration Tests: Chaco Culture Historical Park," USGS Open-File Report 91-444, 1991. http://pubs.usgs.gov/of/1991/0444/report.pdf	Author Introduction: "Chaco Culture National Historic Park is a national park unit developed to protect and display unique Anasazi stone and adobe structures… Some of the most complex and best preserved (of the over 2,000 known park) archeological sites are large stone pueblo and kiva complexes located in the upper confines of Chaco Canyon near the Bonito bridge… The main objective of the vibration project was to document the vibrations that were induced into the archeological structures located near the Bonito bridge by the drilling operations and by the extraction of the bore-hole casings." Author Conclusions: "No construction or trucking activities documented during this study period produced vibrations to the archeological structures which were above the specified maximum 2 mm/sec peak-particle motion level in the 1 to 20 Hz band-width. The attenuation study analysis show that motions induced from a vehicle hitting a bump are much greater than motions induced by normal drive-by a 3/4-ton pick-up truck... Analysis of the data indicates that rotary drilling of the piling holes can be a vibration-safe method to install pilings near sensitive archeological or historic structures in Chaco Canyon… Comparing the data derived from this project with the past experience of vibrations induced from drilling (King and others, 1986), it is likely that a similar drilling operation in sand or gravel could be accomplished at approximately 100 meters from a sensitive archeological site without inducing motions above **2 mm/sec peak-particle velocity limit in the 2-15 Hz bandwidth**… The vibration study of Casa Rinconada indicated that vibrations induced by personnel or native activities such as dancing on the kiva floor are at higher frequencies than the natural frequencies of the structures and are not a vibration threat to the complex... However, the vigas which form the lintels are sensitive to vertical load factors which would limit the personnel use; that is, personnel or equipment should not be allowed on the walls with the exception of the kiva floor bench. It would also be prudent to not allow mechanical equipment on or near the walls-lintels without previous vibration testing."
18. Hanson, C.E., King, K.W., et al., "Aircraft Noise Effects on Cultural Resources: Review of Technical Literature," NPOA Report No. 91-3 (HMMH Report No. 290940.04-1), September 1991.	Author Introduction and Editor: This report is an excellent overall reference for aircraft noise effects on cultural resources. It presents a comprehensive "review of the existing scientific literature (up to 1991) concerning aircraft noise-induced damage to structures, with a focus on historical structures and cultural resources." It describes short term and long term effects. It includes published prediction models which "enable the estimation of probabilities of damage from aircraft operations and the specification of mitigation measures.... Summaries of the best available methods for the evaluation of damage to historical and cultural resources are provided," as well as a few specific mitigation measures. **Vibration criteria are summarized in Table 2.3; a ranking and probability of aircraft noise induced structural damage is included in Table 4.1.** Two associated work products, a report on recommendations and rationale for further research and an annotated bibliography of reviewed literature, are contained in separate documents. **Maximum ground motion velocity criteria of 2 mm/sec (0.08 in/sec), 2.5 mm/sec (0.1 in/sec) and 2 mm/sec (0.08 in/sec)** are cited as adopted by various governments for historic buildings and sites.

19. King, K.W. and Carver, D.L., "Induced Ground-Vibration Study, Allegheny Portage Railroad Skew Arch Bridge," USGS Preliminary Report, 1991.	Author Introduction: The Allegheny Portage Railroad National Historic Site was established "to protect and display the remains of a unique transportation system developed in 1840… One of the unique historic structures within the park is a stone arch bridge… which used no mortar and has an under-arch not at a right angle (skewed) to the length of the bridge… The National Park Service requested documentation and evaluation of the vibration environment of the unique and irreplaceable bridge," in part because it is believed that site-specific empirical data will result in better resolution and accuracy than structural models when identifying the vibration parameters of a specific structure. Author Objective and Discussion: The report documents "the vibrations induced into the Skew Arch Bridge historic structure by the traffic on the adjacent 4 lane highway and the susceptibility of the bridge to those vibrations… No traffic or trucking activities documented during the study produced vibrations to the bridge above the specified **maximum 2 mm/sec peak-particle motion level in the 1 to 20 Hz bandwidth**. The largest peak-particle velocity of shaking measured on the bridge was approximately 1.0 mm/sec, induced by the motion of two trucks." **A peak-particle velocity limit of 5 mm/sec is suggested as an acceptable upper level for induced vibrations at the bridge**, and other recommendations related to highway road surface smoothness, construction, and traffic are made.
20. King, K.W. and Carver, D.L., "Vibration Tests—Mesa Verde," Technical letter, February 26, 1992.	Editor: The letter provides preliminary recommendations based on induced vibrations at Mesa Verde and at the Balcony House, in particular. A sensitivity analysis for cliff and surface structures indicates they are most sensitive to frequencies in the 8 to 20 Hz range. Vibration levels due to generators, road construction/repair equipment, and snow removal equipment are summarized. **A peak particle velocity limit of 2mm/sec in the 5 to 20 Hz frequency range is recommended** for helicopters and traffic, and minimum distances for helicopters are recommended. Suggested controls for number of busses, pavement smoothness, vibrating paving equipment, snow plows, and helicopter use are provided.
21. King, K.W., et al., "Vibration Analysis Study for the Lincoln Memorial: Preservation and Restoration of the Lincoln Memorial," 100% Report, Harman-Cox Architects, December 12, 1994 (contains March 1992 Technical letter by King and Carver and January 26, 1994 Phase I Documentation of Induced Vibrations by King and King)	Author Summary: "This study examines two sources of ground vibration at the Lincoln Memorial: ambient (or baseline) vibration and induced vibration." After analysis of the data, guidelines were recommended, "not only for the scheduled restoration of the raised terrace, but also for future construction and maintenance activities at the memorial." **A peak particle velocity of 5 mm/sec was recommended as an acceptable upper level for induced vibrations at the monuments.** It was recommended that additional testing be performed during construction in order to monitor the initial and maximum levels of induced vibration. "The maximum motions induced in the memorial during this study were found to be from air traffic, both military and civilian," although "not enough information could be gathered to definitively determine the effect on the memorial." The report recommended "further study be undertaken in this area to develop guidelines for air traffic in the vicinity of the Lincoln Memorial." In addition, the report recommended further study on monument rotation and cracks via a long term monitoring system (detailed in a separate Hartman-Cox report, December 15, 1994).

22. King, K.W. and King, E., “Documentation of Vibrations at Taos Pueblo-North and Taos Church, Phase I,” Report for Taos Pueblo, February 3, 1994.	Editor: Due to concern with potentially damaging vibration sources, the Pueblo requested a vibration study and reports. This report contains a description of those frequencies at which the Pueblo will be most sensitive, as well as preliminary recommendations. Some initial vibration measurements were made. The natural frequencies of the structures were documented, along with observable amount of damping. Author Discussion: “The data also suggests that the buildings are/have absorbed a considerable amount of vibration frequencies and should be protected in the future.” For example, a lack of damping for the natural swing (frequency) of the church “may indicate some internal damage from vibrations.” It is speculated that heavy vehicle traffic adjacent to the church may be “the reason for some of the damage to the church; and, it is not likely to stop unless the traffic is rerouted or the building is structurally reconfigured.”
23. King, K.W. and King E., “Vibration Investigation of Archaeological Structures, Aztec Ruins National Monument, New Mexico,” Report for National Park Service, August 27, 1994.	Author Introduction: “This report shows the methods and results of a vibration study of the risks concerning the more fragile archaeological structures at Aztec Ruins National Monument. The study was made to discern what vibration frequencies are the more pertinent structures sensitive to, how far some of the sources of vibrations should be kept from the structures, and how much vibratory energy is induced to the structures from normal daily activities.” **The maximum vibration limit recommended for the fragile, ancient, wall paintings is 2 mm/sec peak particle velocity.** A suggestive vibration "zoning" of the structures is included, as “a guide for safe future use of vibration sources near the ruins and for the future protection of the ruins.”
24. King, K.W. and King, E., “Vibration Investigation of Mission San Miguel Arcangel, San Miguel, California,” Report for Mission San Miguel, August 30, 1994.	Author Summary: The Mission San Miguel NHS contains “some of the finest historic frescoes and early religious paintings,” and there is concern that they may be at risk from induced vibrations. **The vibration limit for the fragile, interior painted walls of the church was recommended not to “exceed 2.0 mm/sec in the frequency bandwidth of 2.5 to 11 Hz. The church wall vibration amplification factors indicate that the ground shaking amplitudes on the ground near the church should not exceed 0.87 to 1.1 mm/sec to assure no further risk to the painted walls**… The vibrations from the vehicle traffic on the adjacent highways were not found to be in tune with the church's walls and are not a threat to the structures.” However, some of the railroad traffic on the tracks adjacent to the Mission was found to be “inducing vibrations… in tune with the natural vibrations of the church. The amplified induced vibrations from the rail traffic were at the threshold of damage to the frescoes; therefore, the tuned, induced, vibrations are accelerating the deterioration of the frescoes.” Since moving either the railroad or the Mission “is not probable or realistic,” it is recommended that “the rails and ballast of the railroad tracks within 400 feet be kept in very good repair. No water should be allowed near the church's sub-foundation,” and induced vibrations from other sources such as earth compacters, pile drivers, explosives, and trucks “should be controlled according to the suggested vibration zonation (plot) in this report.”

25. King, K.W. and King, E., "Vibration Investigation of Jean Lafitte National Historical Park, New Orleans and Thibodeaux, Louisiana," Report, June 1995.	Author Introduction: As part of construction of a new foundation system to rehabilitate a 1850-1920 period New Orleans French Quarter building (419 Decatur St.) and keep the structure stabilized for the Jean Lafitte National Historical Park general headquarters and public use, the pile driving method generally used in the lower Louisiana area is not deemed satisfactory by the National Park Service due to the effects of induced vibrations to the building and to adjacent structures. In order to establish the value of a new no-vibration-intrusive method for foundation installation, the National Park Service established operational criteria including documentation of the induced vibrations. The vibration documentation project also included the vibration level baseline tests, vibration risk investigations at the Percy-Lobdell Building and Chalmette National Cemetery tower, and recommendations for those structures. Author Summary: The building at 419 Decatur Street was found to be "very robust. **The recommended allowable vibration limit could be raised from the usual 2 mm/sec limit for historic and archaeological structures to approximately 5 mm/sec.**" Traffic, bob-cat vehicles, and rotary type drills were found to be a low vibration risk, while chipping hammers were found to be a higher risk, requiring extreme care in their applications. Large cracks at the end wall of the Percy-Lobdell Building are believed due to foundation instability, while the tower at Chalmette is at very low risk from any known sources of vibrations.
26. King, K.W. and King, E., "Vibration Investigation of Bear Gulch Visitor Center, Pinnacles National Monument, California," Report for National Park Service, Pinnacles National Monument, December 27, 1995.	Author Introduction: "This report shows the methods and results of a vibration study of the Bear Gulch visitor center at Pinnacles National Monument… a stone veneer frame structure which was constructed by the CCC in 1936... The study/ report shows the vibration frequencies that are potentially damaging to the structure," reports the baseline level of natural vibrations in the area, "and establishes the level of vibratory energy that is being induced into the structure from public activities and Park operations." Author Summary: **A 5 mm/sec peak-particle velocity is recommended as a good current maximum level for allowable vibrations** at the visitor center, and recommendations are made for possible stabilization and preservation of the structure. The recommendations include restrictions on heavy vehicle traffic, continuously running generators and diesels, small cement mixers, and operating helicopters. A vibration survey is recommended in 1-2 years if stabilization is not accomplished.

27. King, K.W. and King, E., "Vibration Investigation of Taos Pueblo, Taos, New Mexico," Report for Taos Council, January 8, 1996.	Author Discussion: Taos Pueblo contains one-of-a-kind, irreplaceable historic-archaeological structures. The report "presents the methods and results of the vibration study, including natural vibration frequencies, baseline vibration levels, and vibration from public activities and tribal operations. Recommendations are made for possible stabilization and preservation of the structures. Author Recommendations: **Vibration levels at the Pueblo structures are recommended not to exceed 2 mm/sec in the 8-22 Hz range.** The Pueblo buildings are sensitive to 8, 14, 16, and 22 Hz vibrations, and the church is at risk from heavy traffic. Recommendations include keeping the road by the church very smooth and prohibiting any vibration source of 8, 14, 16, or 22 Hz within 100 feet of the Pueblo. General tourist traffic should be at least 50 feet from the Pueblo helicopters, and no helicopter traffic should be allowed within 1000 feet of the Pueblo. Busses, heavy vehicles, and RVs with running generators should be restricted to parking areas outside of the plaza. A long term vibration monitoring programs is advised.
28. King, K.W. and King, E., "Hough Site Vibration Investigation," Report, April, 29, 1996.	Author Summary: "As requested by NPS… a vibration risk investigation was made at the Hough Site. The investigation included the potential vibrations induced from Highway 180, public use of the area, and adjacent parking facilities. The intent of the investigation was to determine if any additional cautions beyond those that the USFS-NPS are now employing may be necessary for the future development of the site for public display, determine if the presented display plan will increase the vibration risk to the ruins, and discern if a more detailed future vibration investigation is warranted." Natural frequencies and damping rates for the structures were measured and ground-borne vibration attenuation functions were determined. **Recommendations were made to ensure vibration values would not exceed 2 mm/sec amplitude**.
29. King, K.W. and King, E., "Pipe Springs National Monument Vibration Investigation," Report, May-June, 1996.	Author Introduction: "Pipe Springs National Monument consists of a Mormon built fort, a bunkhouse, a blacksmith shop-harness room and a National Park visitor center." The study was conducted; a) to identify the vibration frequencies (at which) the structures are most sensitive; b) to document minimum distances for certain vibration sources; and c) to quantify induced vibration from traffic and daily activities. Recommendations are "presented for safe future use of vibration sources near the structures and for the future protection of the structures." Author Recommendations: **A 5 mm/sec peak-particle velocity is recommended as a "maximum level for allowable maintenance" and "short-term vibration at the structures." A 2 mm/sec peak-peak velocity is recommended as a "maximum level for public or industrial development," with continuous operation and longer-term vibration.** It is recommended that heavy vehicles be restricted "from a zone of 200 feet from the structures." Light vehicles and small cement mixers "should be restricted to a distance of 20 feet from the structural walls… Operating helicopters should be no closer than 300 feet to any historic structure in the Monument." A full vibration survey is recommended for any new highway construction within 300 yards or within 600 yards if any pile driving or explosives are used.

30. King, K.W. "Investigation of Helicopter Induced Vibrations at Balcony House, Mesa Verde," Unpublished Report, 1996.	Author Introduction: "During the fall of 1991, a vibration study was conducted at Mesa Verde (National Park) on the Balcony House, Cedar Tree structure, and the resource building. The study determined the natural frequencies of the structures (and) induced vibrations to the structures from vehicle traffic, foot traffic, and low flying helicopters. The helicopter tests… indicated that a viga type roof can amplify" the induced vibrations, "sufficient to cause stress cracks at the viga-wall connections (King, 1991). An unexpected observation made during the roof tests indicated that a very low hovering helicopter off to the side of the building may induce (thickness noise) and some very high amplitude vibrations of more concern than overhead flights… Further evaluations were conducted by testing the explicit effects attributable to helicopter induced vibrations." A series of 34 vibration tests were scheduled at the Balcony House. "This short report presents an abbreviated version of those tests and results." Author Note and Summary: **The vibration limit for one-of-a-kind, irreplaceable structures is recommended as 2 mm/sec.** Relatively light helicopters can produce vibration amplitudes at high risk to structures, and duration of hovering time is a risk factor. Specific recommendations, including minimum horizontal and vertical distances ranging from 100-300 feet, along with time durations, are made for light helicopters in the 2,400 lb. range. Horizontal hovering in the plane of sensitive sites is generally discouraged, due to thickness noise that can generate high amplitude vibration of concern.
31. King, K.W., "Preliminary Overview of the Vibration-Structural Characteristics at Tumacacori NHP," 1997.	Author Introduction: "A cursory but thorough vibration inspection was made of the Tumacacori church and adjoining building during April, 1997." The study determined at "which frequencies the pertinent structures are most sensitive," and "vibrations induced by the cultural and industrial activities… were documented on the ground near the church." Author Summary: The church was found to be very robust, with the larger, high walls amplifying the ground vibrations by a factor of 3 to 7. "However, considering the adobe-type construction and the historic worth of the interior of the church, **the recommended allowable vibration limit should not exceed the usual 2 mm/sec limit for historic and archaeological structures.** The vibration base line for this area is 0.01 to 0.03 mm/sec." All but two of the walls tested were stable; however, the part of the structure with the highest vibration risk was found to be the west wall at the SW comer. It was recommended that this wall be pinned to the main west wall as soon as possible, to prevent further deterioration.

32. King, K.W. and King, E., "Tonto National Monument Vibration Investigation," Report for Tonto National Monument, National Park Service, June 1998.	Author Introduction: "The Tonto National Monument is a 1,120 acre reserve which contains several fragile, one-of-a-kind, Salado cliff dwellings. This study was conducted to establish the vibration sensitivity of pertinent structures at the Tonto National Monument, determine the vibration scaling functions for the area, and develop a vibration parameter which is protective to the archaeological structures." Natural frequencies of the structures, as well as ground attenuation functions, were measured. Author Summary and Recommendations: "The irreplaceable, one-of-a-kind, archeological cave dwellings are built within slightly friable rock and are sensitive in the 3 to 14 Hz range and amplify the ground vibrations by a factor of 1.7 to 3. The ambient vibration background for the area is 0.004 -0.006 mm/sec… The motions induced by traffic at the visitor center and induced by public visitation are no vibration risk to the structures," but "the structures can be damaged by induced vibrations from some construction equipment," and a person leaning on the walls could induce a large motion and damage the wall when pushing off from the wall. "**A 5 mm/sec peak-particle velocity would be a good maximum level for allowable vibrations at the less pertinent structures and most of the archaeological structures. The walls that exceed 60 inches in height should not be subjected to vibrations that exceed 2 mm/sec**… Aircraft and "especially helicopters should not pass within 200 feet of the cliff dwellings. Helicopters can hover for observation but beyond the safe 200 foot distance."
33. King, K.W. and King, E., "Vibration Investigation of the Visitor Center-Quarry Site, Dinosaur National Monument," Report for National Park Service, Dinosaur National Monument, October 16, 1998.	Author Discussion and Editor: The quarry visitor center at Dinosaur National Monument was a unique Mission 66 historic "building built to allow observation of a unique geologic feature." Before it had to be demolished, the building was "being damaged by differential compaction," as a large part of the structure was "built on expansive soils." This project defined those vibrations to which the structure was most sensitive and that might accelerate the damaging process. While buildings with steel I and H beams are normally very flexible and robust, the quarry visitor center was under severe stress and was acting as separate substructures. The damping values indicated that the building was not in immediate risk of vibratory damage; however if the differential displacement were to increase and the building were subjected to vibrations in the 4 to 9 Hz range, the damage would greatly accelerate.

34. King, K.W. and King, E., "Casa Grande National Monument Vibration Investigation," Report for National Park Service, December 1998.	Author Introduction: "The Casa Grande National Monument is a unique site which contains a one-of-a-kind Hohokam multi-story building and an innovative engineered steel structure to protect that building. The two structures, one built approximately 650 years ago (the Great House) and one built approximately 60 years ago (the steel roof shelter) are a combination which allows protection and open observation of the archaeological building. The Hohokum building has (been) and currently is being damaged. The National Park Service is investigating the degree, the rate, and the type of damage; and methods of stabilizing the building. The purpose of this project is to define those vibrations (to which) the structure is most sensitive" and to integrate vibration data into a comprehensive computer model of the structure. Author Conclusion: While the original Great House construction of a multi-story, mud-adobe building, inter-supported with vigas and roof/floor beams, was likely very robust to vibrations, removal of the beams and collapse of pertinent building sections have compromised its structural integrity, and it is now sensitive to moderate earthquakes. **While several NPS vibration studies have established a general vibration limit of 2.0 mm/sec for the sensitive natural frequencies of a historic building or archaeological structure, the physical inspection and natural frequency data from the Great House suggest an induced vibration limit of 8 mm/sec, between the NPS limit of 2.0 mm/sec and the Bureau of Mines limit of 12.5 mm/sec for an average one or two story frame house.**
35. King, K.W., "Vibration Assessment, 3-D Seismic Surveys: Beaumont, Jack Gore Baygall, Neches Bottom, and Lance Rosier Units, Big Thicket National Preserve," 1998-2001.	Editor: Vibration risk analyses were performed based on information provided by developers proposing to use explosive charges for 3D seismic surveys. NPS concerns included breaches in aquicludes (aquifer boundaries), contamination of surrounding plant life, the possibility of side "blow outs", and the formation of unsightly surface craters. Specific recommendations were made for shot hole arrays of various depths: for example, the backfill material, need for expansive plugs, and the setback distances from sags, trenches, tree pulls and drainage channels. Shallow holes generally had more requirements and greater setbacks.
36. King, K.W., "Vibration Study - Pueblo del Arroyo and Pueblo Kin Kletso," Report, April 2001.	Author Introduction: A vibration risk and stability investigation was conducted at Chaco Culture National Historical Park in April, 2001. "The objective of the project was to establish the vibration limits of construction equipment near the archaeological structures at Pueblo del Arroyo and Pueblo Kin Kletso." In order to accomplish this, several construction equipment sources were documented, ground attenuation functions were determined, vibration parameters of pueblo walls were analyzed, and induced vibration from those equipment sources was recorded. Author Discussion: "**Previous studies have strongly suggested a 2mm/sec maximum amplitude limit… (for) induced vibration at the one-of-a-kind, irreplaceable structures in Chaco Canyon.** This is in line with the maximum allowable vibration limits by other nations such as Germany, Britain and Sweden." Specific setback distances ranging from 5 to 200 feet are recommended for ATVs, generators, bobcats, tractors, cement mixers, front end loaders, pickup trucks, soil compactors, vibratory rollers and the dumping of fill soil and large rocks. **In particular, the walls on the NE corner of Pueblo del Arroyo, the SW corner of Pueblo Kin Kletso, and the North-center area of Kin Kletso are sensitive and "should not be exposed to any vibrations exceeding 2 mm/sec until future stabilization is accomplished."**

37. King, K.W., "Chiricahua Pinnacle Vibration Investigation," Preliminary Report for Chiricahua National Monument, August 2001.	Author Introduction: This study was initiated "to aid the protection of one-of-a-kind rock pinnacles (at) the Chiricahua National Monument… a 12,000 acre national preserve to protect the geologic and historic features of an eroded caldera area." The project investigated "the induced motions from standard construction equipment and helicopter operations," and recommended limits for their use. A vibration sensitivity analysis was conducted, known vibration sources were documented, and ground attenuation functions were developed. Minimum source distances were recommended to reduce vibration damage risks. Author Recommendations: "The pinnacles act and respond similar to cantilevered structures… The general accepted level of induced vibrations could be as high as 2.5 cm/sec in the 1-20 Hz bandwidth… **However, as these are one-of-a-kind and are totally irreplaceable… a 1.0 cm/sec limit would be more prudent" as a maximum recommended value.** "The data shows that climbers, wind, and helicopters can be a risk to some of the pinnacles." Limits are suggested for helicopters, vibratory rollers, and blasting.
38. King, K.W. and King, E., "Livingston Depot Vibration Assessment," Report for Livingston Depot Center, Fall 2001.	Author Introduction and Editor: The Livingston Depot is a historic structure designed to draw and welcome tourists traveling to Yellowstone National Park via the Northern Pacific Railroad. It originally served as the headquarters for the Northern Pacific's Central Division. While rail traffic still passes by the structure, the Depot no longer functions as a train station. It now contains a museum providing historic exhibits and cultural programs for the benefit of local residents and visitors from around the world. This project was initiated "to aid the protection of these one-of-a-kind historic structures," by identifying "those areas of the structures that may indicate instability" and could require protective rehabilitation. A vibration sensitivity (natural frequency) analysis was conducted, vibration source levels were documented, and ground attenuation functions were developed, in order to identify minimum distances for reducing vibration damage risk. Author Discussion: "The general vibration limits recommended by the Bureau of Mines for masonry structures is 12 mm/sec in the bandwidth of 2-20 Hz… Germany, Britain and Sweden have lowered the allowable vibration levels to approximately 2-5 mm/sec for sensitive laboratory equipment, museum displays, and historic structures. The National Park Service… has adopted the 2 mm/sec limit for mud and stone Anasazi, one-of-a-kind, structures." **It is contradictory; while "the normal vibration limit for an operating railroad station would be 12-25 mm/sec, the normal limits for a museum containing delicate displays and stacked glass shelving would be between 2 and 5 mm/sec in the bandwidth of 2-20 Hz."**

39. King, K.W. and King, E., "Vibration Investigation of Kozlowski Trading Post," Report for Pecos National Historic Park, National Park Service, November 17-19, 2001.	Author Scope: "The purpose of this project is to evaluate the condition of the historic structure known as Kozlowski's (Trading Post) and to develop recommendations for preserving the historic fabric of the structure," located at Pecos National Historic Park. The vibration parameters (natural period and damping) were established, the rate of attenuation around the structure was found, vibration levels from construction equipment were documented, and minimum distances were recommended. Author Recommendations: **"Due to the robustness and condition of the (existing) station," 5-8 mm/sec was recommended as an upper limit of induced vibrations. "If and when the station is rehabilitated to its semi-original (state of) construction, then the upper limit of induced vibrations should be lowered to 2 mm/sec."** Minimum distances of 100 and 200 feet were recommended for heavy construction equipment and blasting. In addition, it was recommended that the adjacent highway be kept smooth and moved further away, if possible.
40. Hendricks, R. Transportation Related Earthborne Vibrations (Caltrans Experiences). California Department of Transportation, Division of Environmental Analysis, Technical Advisory, Vibration TAV-02-01-R9601, February 20, 2002.	Author Introduction: "This document is a revision of technical advisory TAV-96-01-R9201 with the same title, prepared by the same author, dated June 13, 1996... The advisory covers general vibration principles, vibrations caused by construction and operation of transportation facilities, criteria used by the California Department of Transportation (Caltrans), impacts, vibration study approaches, possible mitigation, and screening procedures to identify potential vibration problems in the field." Caltrans Criteria: Table 2 (p. 11) contains a range of criteria for continuous vibration, along with potential damage risk to buildings. **A peak particle velocity of 2 mm/sec is listed as the "recommended upper level of the vibration to which ruins and ancient monuments should be subjected." 5 mm/sec is the "threshold at which there is a risk of 'architectural' damage to normal dwelling – houses" and special types of finishes. At 10-15 mm/sec, vibration "would cause 'architectural' and possibly minor structural damage."**

41. King, K.W. and King, E., "Vibration Investigation of Glorieta Battlefield National Historic Landmark- Pigeon Ranch Structure," Report, August 2002.	Author Introduction: "The purpose of this work is to evaluate the vibration risk that an increase in logging truck traffic may impose on the Pigeon Ranch," the Glorieta Battlefield National Historic Landmark structure, "and to document the vibrations being induced by present day, normal traffic... The structure is an important western United States' wagon trail and civil war edifice… that figured prominently during the era of the Santa Fe Trail and the Battle of Glorieta Pass… The structure was tested for its natural frequencies (those vibrations that the structure is most sensitive) and the amount of induced vibrations from traffic on the adjacent road. Vibration attenuation factors were derived for future planning." Author Analysis and Recommendations: **"Vibration studies at Hovenweep, Casa Grande, Mesa Verde, etc. as well as studies made in Great Britain, Sweden, and Germany have strongly suggest that an upper vibration limit for one-of-a-kind, historic, adobe-stone structure should be 2 mm/sec. However, this limit is for original fabric, one-of-a-kind, historic or archaeological structures. Modern masonry-adobe structures (unreinforced) could have a higher limit; more near 6 mm/sec** (which is lower than the recommended 12 mm/sec limit for reinforced masonry structures by the Bureau of Mines)." Recommendations for this structure include periodic installation of temporary buttresses to detune the walls, when heavy logging trucks may pass by the structure, and relocation of the road, if possible.
42. King, K.W. and King, E., "Historic Structure Vibration Investigation, Highway 16 and Maverick Road-Big Bend National Park," Report, December 2002.	Author Project Description and Recommendations: As part of a DOT project to "repave Big Bend National Park highway 16 from Old Castolon to Santa Elena Canyon," this study was done "to discern the vibration risk to historic structures located along highway 16. Historic structures that are located near the Old Maverick road were also checked… Twelve historic structures were inspected," including four identified by NPS and the author "for more thorough testing." Natural frequencies and damping rates were identified for key structures, as well as the vibration attenuation rate around the structures. Recommendations included temporary detuning of sensitive walls, temporary rehabilitation at the Rock House, relocation of the road away from the structure at Tomas Hernandez, and use of non-vibratory compactors (rollers).
43. Lacave, C., et al. "Prevention of speleothem rupture during nearby construction," Environmental Geology, Vol. 43, Issue 8, April 2003, pp. 892-900.	Author Abstract: A new highway with a tunnel was planned to be built over a decorated part of the Milandre cave, in the Swiss Jura, with a rich speleothem population. "In order to prevent damage in the cave, a study was conducted in the framework of an impact study. One of the goals was to evaluate the risk of speleothem rupture caused by explosive shots that will be used to excavate the tunnel portal. To this end, the speleothems' vulnerability to ground shaking was compared with the observed accelerations induced by experimental explosions. This procedure allowed (the investigators) to determine maximum acceptable explosive charges."

44. King, K.W. and King, E., "Pueblo del Arroyo – Refraction Tests and Wall Damping Study," Report, June 2003.	Author Summary: "A vibration investigation (was conducted) at Pueblo del Arroyo from June 2, 2003 through June 8, 2003. The objective was… to see if a pattern of vibration parameters (specifically, damping) exists... (to) better understand the evolving foundation/wall problems at the complex… and to (see) what extent geophysical refraction methods may help understand the potential underlying problems at the complex." Accordingly, vibration parameters were documented, and short high-resolution refraction lines (traverses) were performed. Author Discussion: None of the pueblo walls had measured "damping values… out of the norm expected for walls… No tall or average height walls had damping values… indicating abnormal stiffness." White no immediate high risk walls were identified, "the walls of rooms 27, 141, and 102 are at moderate risk." Although the refraction lines "resolution was not sufficient to identify specific buried walls, voids etc.," it did illuminate the water table with "probable wet sand at 48-52 foot depth" and "bedrock at approximate 85-foot depth consistent across the complex."
45. King, K.W. and King, E., "Vibration Study - Fort Bowie National Historic Site," Report, July 2003.	Author Introduction: A vibration risk and stability investigation was conducted at Fort Bowie National Historic Site in May, 2003. The vibration sensitivity of the structures was identified via assessment of natural frequencies and damping rates. The vibration attenuation rate of the ground around the structures was measured, as well as vibration due to typical quarry blasts. Author Discussion-Recommendations: **"The standard recommended vibration limit for homes is 12-15 mm/sec in the 1-15 Hz bandwidth (limits established by the old Bureau of Mines); but the general recommendation for irreplaceable, one-of-a-kind Anasazi-Hohokam type structures is 2 mm/sec. The Ft. Bowie structure type and sensitivities place them somewhere between these two limits," resulting in a recommended "conservative allowable maximum vibration limit… of 4-6 mm/sec peak amplitudes in the 1-20 Hz bandwidth."** Recommended minimum distances for blasting, vibra-rollers, compactors, generators, cement mixers, heavy trucks, light trucks, ATVs, and helicopters are also provided.
46. King, K.W., "Construction Vibration Studies for Pinnacles and a Natural Bridge, General Hitchcock Highway—Project AZ PFD 39-1 (7)," Report, September 2003.	Author Project Description: This investigation was conducted "to characterize the natural vibration properties and potential construction vibration response of selected pinnacles and natural bridge features located along the General Hitchcock Highway construction project" in September 2003. Twenty pinnacles were tested for vibration sensitivity. Vibration attenuation functions were derived for three ground types in the construction area. "Induced vibration functions were also derived for the Hamm compactor, hoe ram system, and a test blast." Author Summary: Only two of the pinnacles examined had a low damping characteristic potentially signifying a tendency toward instability, although only one of those pinnacles was believed to be potentially impacted by vibration from the Hamm compactor. Blast size during the test period was not well documented, leading to the conclusion "explosive series larger or closer to the pinnacles than the September 10^{th} construction blast are a potential vibration risk to certain pinnacles."

47. King, K.W. and King, E., "El Morro National Monument Preliminary Vibration Study," Report, September 2003.	Author Introduction: "This project was initiated to aid the protection of one-of-a-kind rock inscriptions," including carvings "from prehistoric Anasazi era through the Spanish occupations of 16-1700s to the emigrant trains of the 1800s and cattle drives and travelers of the late 1800s and early 1900s." This project investigated the induced motions from highway traffic and public foot traffic. Author Discussion and Recommendations: The rock columns were tested for natural frequencies, vibration sources were documented, and the attenuation functions for ground-borne vibration were determined. "The natural frequencies of the rock columns (0.3-1.5 Hz) are far below those induced by the traffic on the adjacent highway (9.0-17.0 Hz)." It was recommended that the adjacent highway be checked periodically for smoothness, and any vibration from quarry blasts be documented. It was also recommended that no new roadways, rock moving, drilling, blasting, or other heavy construction be allowed within 300 feet of the inscriptions or ruins without a new vibration study.
48. King, K.W., "Historic Wall Vibration Study at Carlsbad National Park, Walnut Canyon Entrance Road—DOT-New Mexico PRA cave 10(1)," Report, December 2003.	Author Project Description: (The study, analysis and results are very similar to a parallel effort in Saguaro National Park) As part of reworking and repaving of a portion of the Walnut Canyon entrance road of Carlsbad Caverns National Park, a number of historic rock retaining walls were tested "to characterize the natural vibration properties and potential construction vibration risks to these historic walls." Induced vibrations were documented and vibration attenuation functions were determined. Author Discussion: **Vibration limits were derived from past experience, including NPS acceptance of "a 2mm/sec vibration limit at several Hohokam and Anasazi structures, (which) is in agreement with the British, Swedish, and German standards at or near historic structures. The Bureau of Mines published that 25 mm/sec is a good limit for average homes," but since the walls "are historic and normal risks should be avoided," it is believed that the induced vibration limit for the walls should be "less than for a masonry home." In this case, "an approximate 10-15 mm/sec limit (is recommended) in the 30-40 Hz bandwidth."** It is recommended "that the motorized, vibratory compactors should not operate with the vibrator turned on within 20-30 feet from the walls." Although smaller, slide compactors can be allowed, large compactors should turn off their vibrators and use the roller's weight only within 30 feet of the walls.

49. King, K.W., “Historic Wall Vibration Study at Saguaro National Park, Cactus Forest Drive—Highway Project AZ PRA SAGU (500),” Report, December 2003.	Author Project Description: (The study, analysis and results are very similar to a parallel effort in Carlsbad National Park) As part of reworking and repaving of a portion of the Cactus Forest Drive in Saguaro National Park, a number of historic rock retaining walls were tested “to characterize the natural vibration properties and potential construction vibration risks to these historic walls.” Induced vibrations were documented and vibration attenuation functions were determined. Author Discussion: **Vibration limits were derived from past experience, including NPS acceptance of “a 2mm/sec vibration limit at several Hohokam and Anasazi structures, (which) is in agreement with the British, Swedish, and German standards at or near historic structures. The Bureau of Mines published that 25 mm/sec is a good limit for average homes,” but since the walls “are historic and normal risks should be avoided,” it is believed that the induced vibration limit for the walls should be “less than for a masonry home.” In this case, “an approximate 10-15 mm/sec limit (is recommended) in the 30-40 Hz bandwidth.”** It was found that the vibration attenuation function is low and vibration energy does not diminish quickly with distance. It is recommended “that the motorized, vibratory compactors should not be allowed within 30-40 feet of the historic walls.” Although “smaller slide compactors or low-range compaction are a low risk to the walls,” the large construction compactors should turn off their vibrators and use the roller’s weight only within 30 feet of the walls.
50. King, K.W., “Big Bend National Park Historic Structure Vibration Project Phase 2, Vibration Risk Mitigation and Documentation—Highway 16,” Report, August-November 2005.	Author Project Description: As part of the DOT project to repave Big Bend National Park highway 16 from Old Castolon to Santa Elena Canyon, this phase 2 study was done to re-check the vibration parameters of pertinent historic structures located along highway 16, to install protective buttresses, to document vibration from new sources, and set recommended setback distances for certain construction equipment. “The six historic structures were re-tested for natural frequencies and vibration damping” rate. Three construction equipment vibration sources were tested for amplitude and frequency. Author Discussion: Re-testing of structural vibration parameters did not find significant differences, with the exception of La Coyota major walls, which were found to be unstable and at high risk of failure. Road work did not produce vibration in excess of the 2 mm/sec limit. Shoring of the walls reduced motion amplification, increased frequency of sensitivity, and increased damping. Footnote: **“The conservative vibration limits (2 mm/sec) are based on one-of-a-kind, irreplaceable, state-national historically important structures. The structures are usually constructed of masonry, mud, or adobe with little or very poor support to divert the induced structural load to a foundation or the ground, do not have interlocking corners and few if any buttress; the ‘normal’ limit (5 mm/sec) is similarly based on more robust masonry-adobe structures which have roof-wall support system, may have wall buttress, locking corners etc. The "normal" value is approximately half again lower than the limit for a sensitive wood frame structure with a truss or rafter system (12.5 mm/sec) (recommendation based on experience by author K. King)”**

51. King, K.W. and King, E., "Case History On Vibration Risk Investigations," #1-Final Draft, 2005.	Author Text: "The most important principal to discern the vibration risk to a structure is the structure's raison d'être or underlying use. Is the structure a modern structure built within the recent UBC limits or is it a historic-archaeological one-of-a kind, irreplaceable, state or national heritage structure? The two structures do not reasonable fit within the same vibration risk limits. The older structure will not have homogeneous construction, flexible joints, and proper roof-wall, window-door support and many internal structural strains not evident by visual inspection. A strict numerical vibration limit will in many cases be either too restrictive to construction near the average structure or too generous for the "irreplaceable" structure. However one must note; many older wooden frame structures from the 17 and 1800s are very robust especially those built around mining operations or heavy incumbent weather. Some of these structures are classified as "historic" but should be classified with the more modern frame buildings for vibration risks analysis. **Proper judgment can only be made by field inspections of the structures.** The engineering parameters most important to all structures that may be at vibration risk are the structures' natural vibration frequency(s) and the damping rate at those frequencies… Knowledge of these two parameters and the "underlying use" described above is necessary before a risk value or a reasonable vibration limit can be integrated into an operation that may induce such motions. The source(s) of vibrations also must be investigated. If the source is inducing frequencies which are similar to the natural frequencies of a structure, the structure will "resonate" or amplify those vibrations. This amplification greatly increases the structure's vibration risk... The distance/attenuation of the source from the structure is an important consideration as are the soils beneath the structure." Assessment of these factors is shown using a variety of case studies and example field projects, each with different conditions.
52. Hanson, C.E., et al. Transit Noise and Vibration Impact Assessment. U.S. Department of Transportation Federal Transit Administration Report No. FTA-VA-90-1003-06 (May 2006). http://www.fta.dot.gov/documents/FTA_Noise_and_Vibration_Manual.pdf	Author Abstract: "This report is the second edition of a guidance manual originally issued in 1995 which presents procedures for predicting and assessing noise and vibration impacts of proposed mass transit projects. All types of bus and rail projects are covered. Procedures for assessing noise and vibration impacts are provided for different stages of project development, from early planning before mode and alignment have been selected through preliminary engineering and final design. Both for noise and vibration, there are three levels of analysis described… This updated guidance contains noise and vibration impact criteria that are used to assess the magnitude of predicted impacts. A range of mitigation measures are described for dealing with adverse noise and vibration impacts." **Table 12-3 contains a range of construction vibration damage criteria ranging from 0.5 in/sec for reinforced concrete to 0.12 in/sec for fragile, old buildings that are extremely susceptible to vibration damage.** "This guidance will be of interest not only to technical specialists who conduct the analyses but also to transit agency staff, federal agency reviewers, and members of the general public who may be affected by the projects."

53. Tillar, B.J. "Noise and Vibration Survey For Stinson Municipal Airport / Mission San Juan," Prepared for City of San Antonio ESD by Raba-Kistner Consultants, Inc., Project No. ASF08-089-00 and -01, July 10, 2008.	Author Cover Letter: "The purpose of the noise and vibration assessment was to evaluate the impact of noise and vibration from various transportation sources including aircraft overflights, train, and roadway vehicles on the Mission San Juan Capistrano site in San Antonio, Texas. The assessment consisted of the direct measurement of ambient noise and vibration levels at a location near the Mission San Juan structure. The results of the vibration assessment show that the maximum monitored vibration level along the vertical axis was 0.04 inches per second… Based on the recorded vibration data and impact threshold levels (0.08 in/sec recommended upper level of vibration to which ruins should be subjected), no vibration impacts to the San Juan Mission structure are expected as a result of aircraft overflights, nearby freight train traffic, or from other sources located near the Mission site."
54. National Cooperative Highway Research Program (NCHRP) 25-25/Task 72: Current Practices to Address Construction Vibration and Potential Effects to Historic Buildings Adjacent to Transportation Projects. Report prepared by: Wilson, Ihrig & Associates, ICF International, and Simpson, Gumpertz & Heger, September 2012.	Author Introduction: This is "a comprehensive compilation of current and successful practices that address construction vibration impacts on historic buildings adjacent to roadway construction projects. The goal of this compilation is to help historic preservation resource agencies and organizations, departments of transportation (DOTs), and the public understand the technical aspects of vibration impact studies." A literature search was conducted "to identify the current state of the art for assessing the fragility of historic structures and their susceptibility to damage, for monitoring vibration transmission from construction projects, and for mitigating potentially damaging vibration." State DOTs and other agencies were surveyed "to understand how they currently address this issue and to identify several case studies." This report summarizes those efforts "and provides a detailed discussion of seven informative case studies." A summary of vibration criteria from the literature search is provided in Table 1, p. 9 (part 1), with **recommended vibration limits ranging from 0.08 in/sec (2 mm/sec) for ruins and ancient monuments to 0.5 in/sec (12.7 mm/sec) for historic buildings in good state of maintenance.** "A recommended guideline approach for addressing construction vibration effects on historic buildings has also been provided."
55. Andrews, J., et al. Transportation and Construction Vibration Guidance Manual. California Department of Transportation (Caltrans), Division of Environmental Analysis, Report No. CT-HWANP-RT-13-069.25.3, September 2013.	Author Introduction: "This manual provides practical guidance to Caltrans engineers, planners, and consultants who must address vibration issues associated with the construction, operation, and maintenance of California Department of Transportation (Caltrans) projects… The guidance and procedures provided in this manual should be treated as screening tools for assessing the potential for adverse effects related to human perception and structural damage. General information on the potential effects of vibration on vibration-sensitive research and advanced technology facilities is also provided, but a discussion of detailed assessment methods in this area is beyond the scope of this manual." Table 2 (p. 11) contains a range of criteria for continuous vibration, along with potential damage risk to buildings. **A peak particle velocity of 2 mm/sec is listed as the recommended upper amplitude of vibration to which ruins and ancient monuments should be subjected. 5 mm/sec is the threshold for risk of "architectural" damage to normal buildings and special types of finishes. At 10-15 mm/sec, "architectural" and possibly minor structural damage is expected**.

[i] Hanson, C.E. and N. Peterson. Aircraft Noise Effects on Cultural Resources: Annotated Bibliography. HMMH Report No. 290940.04-3 (additional work product #2 for NPOA Report No. 91-3). Prepared by : Harris Miller Miller & Hanson Inc. Prepared for: National Park Service, U.S. Department of the Interior, NPS-DSC Contract No. CX-2000-0-0025, Work Order No. 4, May 1993.