IMPACTS OF CONSTRUCTION VIBRATIONS ON ROCK PINNACLES AND NATURAL BRIDGES, GENERAL HITCHCOCK HIGHWAY, TUCSON, AZ

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Abstract

In the Fall of 2003, the Central Federal Lands Highway Division (CFLHD), FHWA, investigated the potential for construction vibration damage to natural resources along the General Hitchcock Highway, northeast of Tucson, AZ. More specifically, the investigation focused on the vibration response of numerous rock pinnacles and a delicate natural bridge feature in close proximity to the existing roadway. These features range in height from a few meters to upwards of 20 m, possess various slenderness ratios, may comprise more than one distinct rock unit, and are subject to a wide range of mechanical/blast-induced vibrations associated with road reconstruction activities presently underway.

The potential for vibration damage was characterized via a three-part investigation, including **(1)** determination of the critical natural vibration parameters – natural frequency and damping – of the structure, **(2)** quantification of the vibration parameters of the various excavation, compaction, and haulage equipment used on the project, and **(3)** determination of the site-specific ground attenuation properties. In addition, amplification properties and the potential for airblast overpressure damage of the structures were evaluated at selected locations. Preliminary recommendations were provided regarding equipment operating distances and limitations on peak particle velocities, primarily based on experiences at other similar locations and established international guidelines for constructing in the vicinity of sensitive structures.

Introduction – Project Background

CFLHD is currently reconstructing an approximate 7.1 km segment of the General Hitchcock Highway, located within Coronado National Forest northeast of Tucson, AZ. This well-traveled forest highway provides scenic access from Tucson to the mountain retreats of Summerhaven and the Mt. Lemmon recreation and ski area, and is a favored tourist route for its broad valley vistas and interesting roadside geologic structures. It is the intent of the current construction project to provide for enhanced roadway safety through improved geometrics, and to also provide safe, convenient access to the many points of interest along the segment. Construction began in the Fall of 2003, and is scheduled to be completed late-2004, including roadway realignments, resurfacing, and the construction of numerous MSE walls, extensive rock cuts, and large side-slope fills.

Along the upper half of the segment, numerous rock pinnacles and a delicate natural bridge feature are located within 30 m of the existing roadway, ranging in height from 2-20 m. These features are comprised of granitic materials subject to varying stages of erosion and decomposition – but can generally be described as highly weathered rock units. In some cases, pinnacles are immediate to the roadway, and subject to considerable construction vibration exposure due to planned adjacent wall and embankment construction and the associated excavation, compaction, and material handling equipment. Vibration sources of greatest concern included a “Hoe Ram” – a track-mounted hydraulic chisel capable of exerting 10,000+ pounds of

force per impact; large vibratory compactors capable of exerting 20,000+ pounds of vibratory force; large haulage trucks carrying 40+ ton loads (very large by roadway construction standards); blasting (3-5 kg/hole, 10-80 holes/series); as well as other normal construction activities.

To characterize the constructability of the roadway without damaging these protected natural resources, CFLHD funded an investigation to define the natural vibration properties and construction vibration response of selected pinnacles and natural bridge features along the project segment. Altogether, twenty individual pinnacles and one large natural bridge structure were investigated for their vibration response parameters – natural frequency and vibration damping. The induced vibrations from the on-site hoe-ram, Hamm and Cat compactors, normal park traffic, and several test blasts were also documented and analyzed by spectra analyses to generally characterize these vibration sources. In addition, ground vibration attenuation functions were derived for three "type" locations in the construction area near pertinent pinnacles. Induced vibration attenuation functions were also derived for the Hamm compactor, hoe ram, and a test blast. Analysis of pinnacle response, equipment vibration, and ground attenuation were then combined to identify pinnacle features potentially at-risk from planned construction activities.

This report briefly describes the data acquisition plan implemented at the site, range of structure response, ground attenuation, and equipment vibration measured, and recommended course of action for protecting these highly valued natural resources.

Characterizing Pinnacle Vibration Parameters

Obtaining the natural frequencies of a structure requires installing portable, horizontal and vertical motion-sensing seismometers on the upper portion of the structure. Motion is then induced into the structure either mechanically or by body movement of a person on the structure (as was done during this study). When the induced motion is in close synchronization with the structure's suspected natural frequency, and the movement is abruptly stopped after one or two cycles, the structure will continue oscillating in its natural frequency with decreasing amplitude (damping). During the study, data are digitally recorded into a portable recording system, and later downloaded for transformation from the time-history domain into the amplitude-frequency domain via a fast Fourier transform (described in detail by Hudson, et. al., 1964, and King, et. al., 1969 and 1985). The peak spectrum (frequencies) derived from the test data are usually defined as the natural frequencies of the structure. Figure 1 illustrates the wiggle time-history traces of the movement at the top of a pinnacle after a person has stopped the induced motion. Trace (A) is motion in the horizontal plane perpendicular to the axis of the pinnacle; (B) is the documentation of vertical movement; and (C) is motion in the horizontal plane, 90^0 from the motion in (A). The horizontal components of the induced vibrations are the most important because these motions cause the principal damage to structures. The increase of amplitude shown in the (C) trace, going in and out of phase with the direction of the induced motion (A), indicates precession of oscillations within the pinnacle.

Percent damping is derived from the formula: $D = ½ \pi(-\ln(Xn-1/Xn)$; where X is a single, decreasing-cycle amplitude. The dashed line on wiggle trace (A), Figure 1, shows the damping slope or oscillation decay. Damping shows the ability of a structure to absorb and dissipate vibration energy. High (>10%) or Low (< 1%) damping is sometimes used as an indicator of structural stability.

The lower half of Figure 1 illustrates the resulting spectrum analysis graphs (Fourier analysis). The peaks of the spectrum analysis derived from the wiggle traces show the frequencies that have the most energy and are, in this case, the natural frequencies of the investigated pinnacle. Amplitudes are relative and non-scalable. The small vertical component, shown on Channel 2, comes from tilt and cross-feed of the horizontal seismometers.

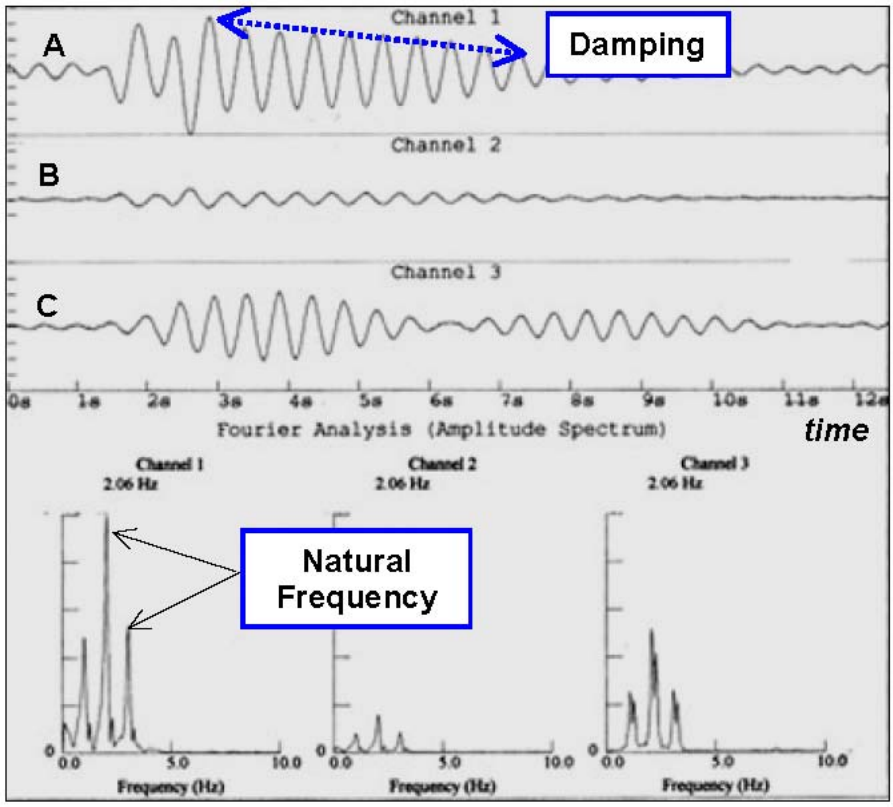

Figure 1. *Conceptual illustration of wiggle time-histories for three vibration measurement axes, damping characteristics of the natural oscillation of the pinnacle, and natural frequency identification from the Fourier frequency spectra.*

For comparison, Figure 2 shows the testing, data, and analysis of an actual pinnacle along the project segment. The person shown in the photograph gives a timed, single or double shift of his body, and then immediately stops to allow the pinnacle to freely move in its own natural frequency. The recorded wiggle traces are a magnified representation of the vertical and horizontal motion components. The horizontal wiggle trace perpendicular to the long dimension is then documented as the preferred frequency (swings) of that particular pinnacle. The Fourier transform of the pinnacle's desired swing or vibration frequency indicates the frequency for which the pinnacle is most sensitive, and which is considered to be at or very close to its natural frequency.

Many vibration grams indicate a lesser-amplitude, 2nd peak (and sometimes a 3rd peak) in which the structure may be sensitive. This secondary peak is often a harmonic of the primary peak amplitude; however, many times the prime natural frequency is <u>not</u> the peak amplitude but, rather, lower 2nd or 3rd peak amplitude. In some cases, the second period is neither a harmonic nor mode of the peak motion, but a second response of the structure due to the complexity of the rock column. In any case, the grams indicate the frequencies for which the pinnacles are most sensitive.

Table 1 lists the 1st and 2nd frequencies measured at the investigation sites, along with critical damping values (ranges, in some cases) for each structure. Figures 3, 4, and 5 further illustrate

the types of structures included in the investigation and the resultant frequency responses during structure excitation. All dimensions (scales) of amplitudes and particle motions are normalized for better visual inspection. Scaled amplitudes are shown in the attenuation studies (discussed later). Average induced motions of the pinnacles were approximately 0.5 to 2.0 cm.

C

time

Natural Frequency

B

A

Damping

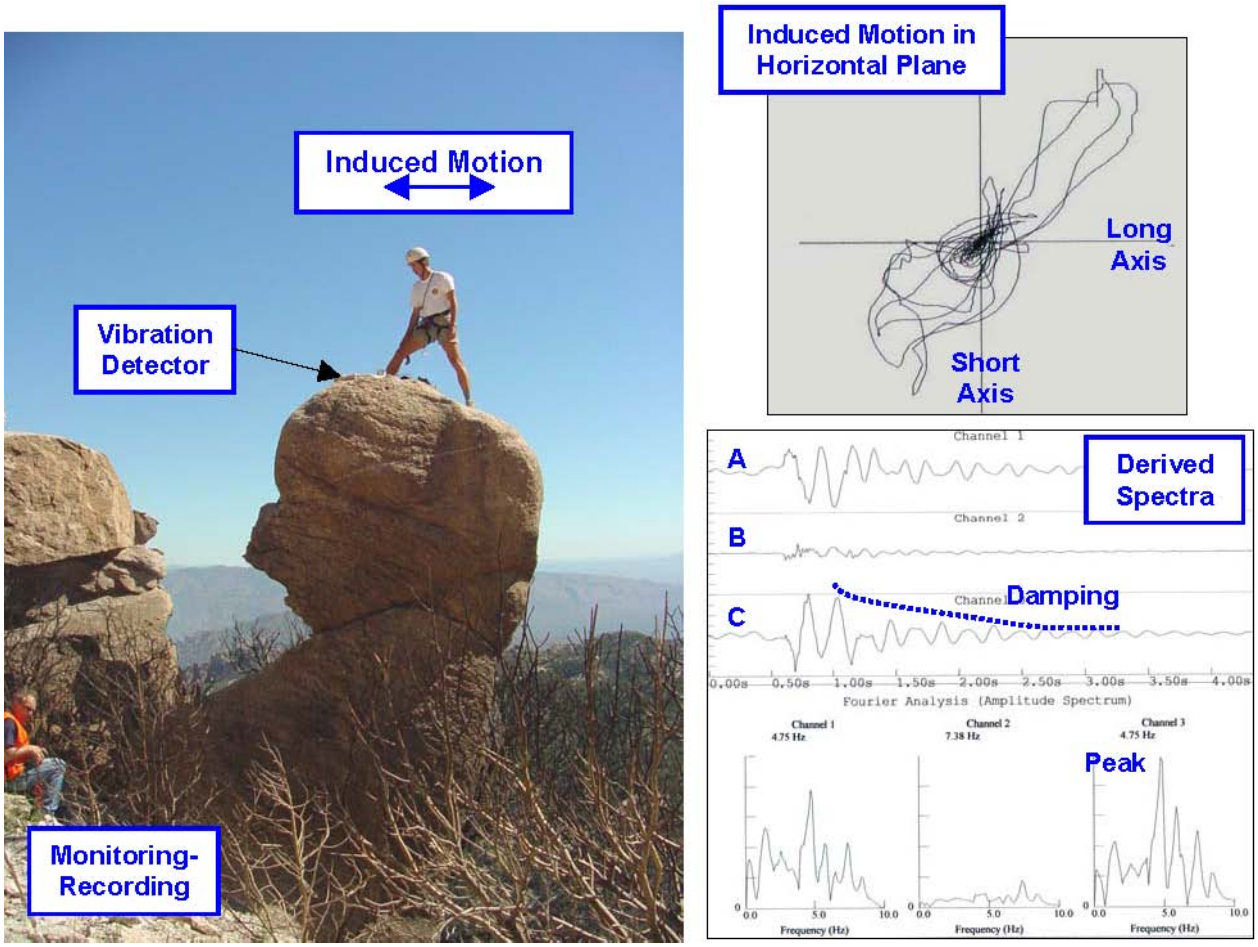

Figure 2. *Note decaying swinging of the pinnacle in the above plots, representing a moderate-to-low damping decay of 1.1% critical. This indicates the pinnacle is flexible, taking longer to dissipate the induced energy than pinnacles with higher critical damping values. Also note the irregular horizontal motion shown on the top diagram, indicating uneven resistance to induced motion of the pinnacle.*

Table 1. *Natural frequencies and critical damping measured at selected pinnacles along the General Hitchcock Highway.*

Pinnacle Station	~ Height, m	1st frequency, Hz	2nd frequency, Hz	**Damping, % Critical**
22 + 700 (Hitchcock Rock)	14.0	1.8	2.7	1.4
23 + 390	5.5	10.0	0.5	1.8
23 + 990	8.5	6.0	11.8	2.2
24 + 015	4.6	8.5	15.8	3.4
24 + 020	4.9	9.0	17.4	1.6
24 + 033	3.4	15.3	19.3	4.7
24 + 055 (General Bird Rock)	14.9	6.0	8.5	2.0
24 + 320 (Duck Bill Rock)	20.7	2.5	3.4	1.8
24 + 350	7.3	5.0	2.4	2.3
24 + 420	7.3	3.4	6.8	2.2
24 + 550	7.3	5.4	6.7	--
24 + 700 (Natural Bridge)	15.9	1.5	7.0	0.89*
24 + 748 (Natural Bridge)	10.7	4.3	8.6	2.8
25 + 165	6.1	4.8	6.2-9.1	0.9-1.4*

	25 + 170	8.5	4.9	6.4	1.8			
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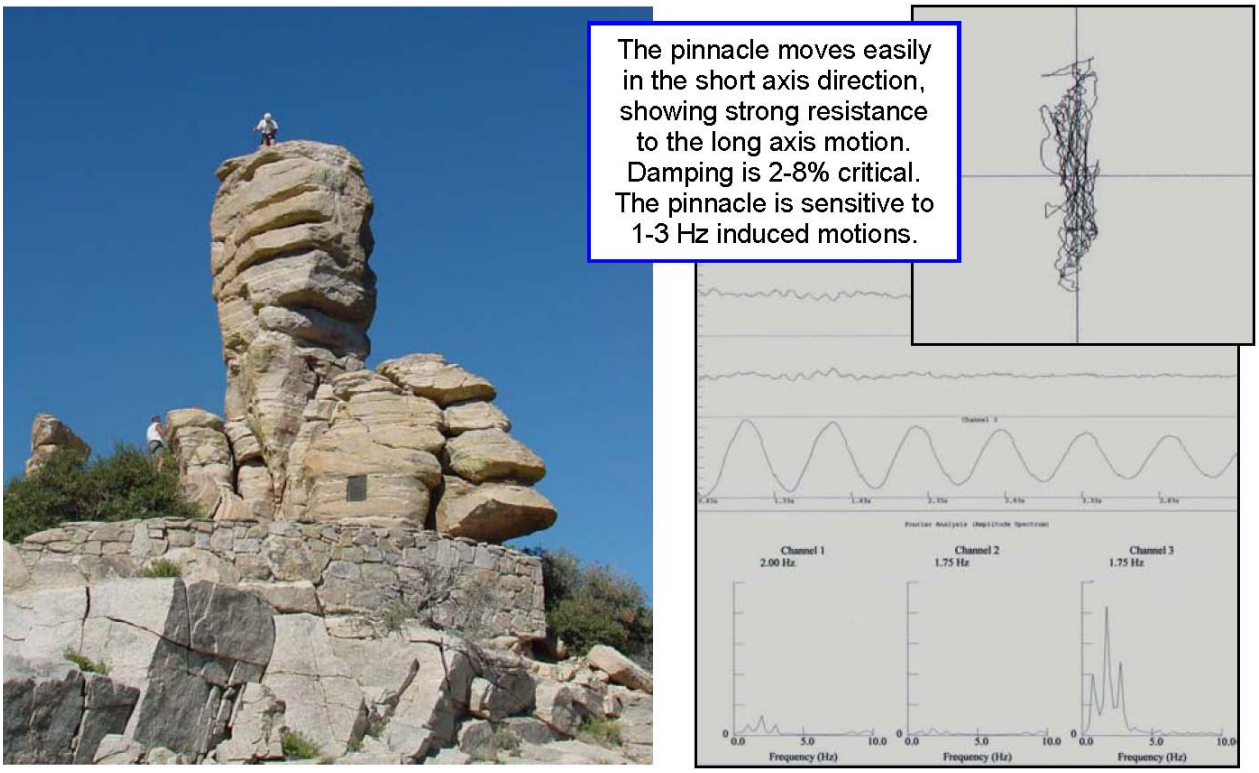


Figure 3. *Induced vibration measurements at Station 22+700 – General Hitchcock Rock.*

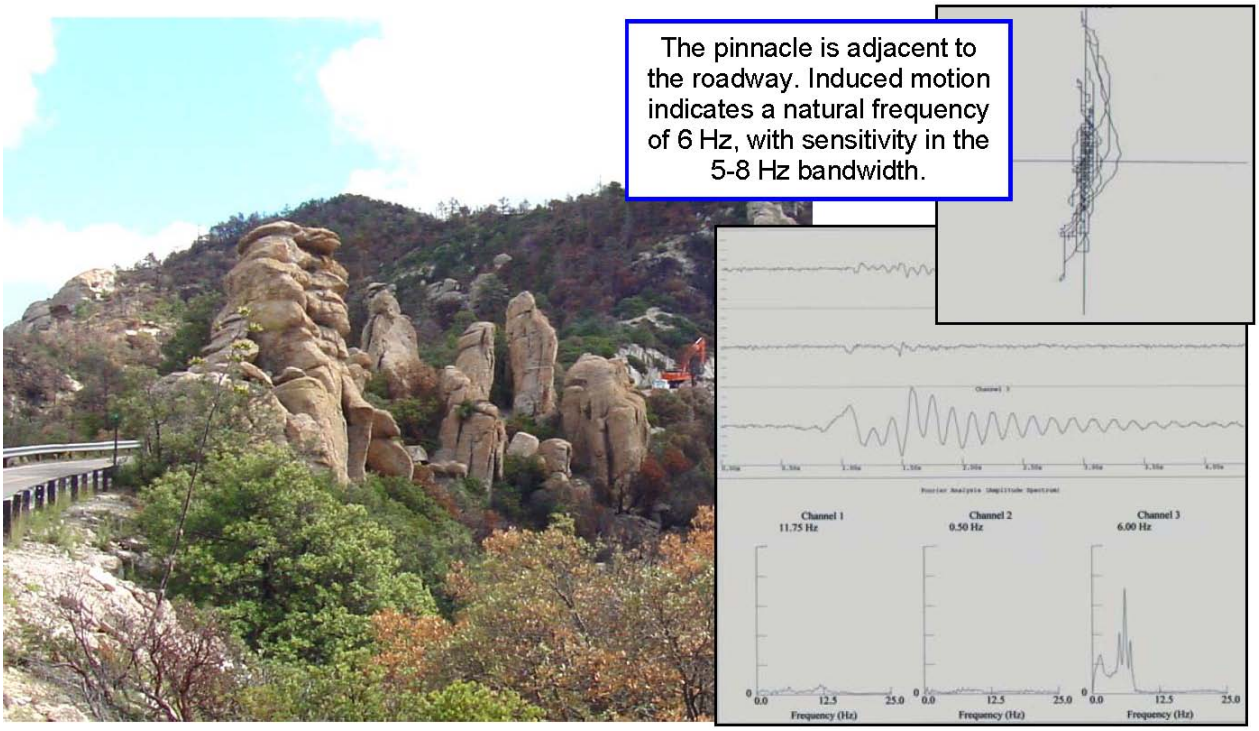


Figure 4. *Induced vibration measurements at Station 23+990. Note: Hoe ram working the background.*

The pinnacle moves easily in the short axis direction, showing strong resistance to the long axis motion. Damping is 2-8% critical. The pinnacle is sensitive to 1-3 Hz induced motions.

The pinnacle is adjacent to the roadway. Induced motion indicates a natural frequency of 6 Hz, with sensitivity in the 5-8 Hz bandwidth.

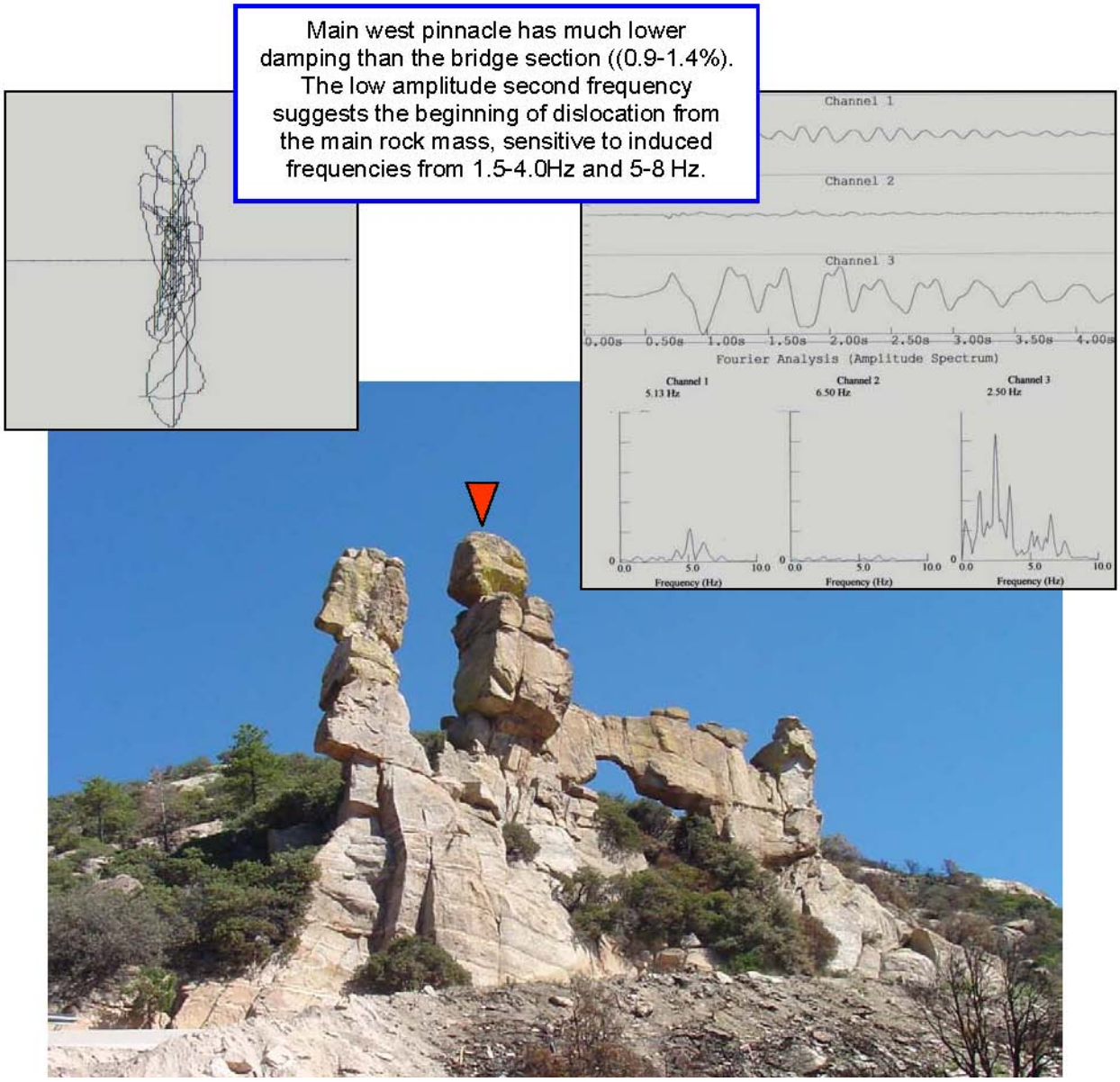


Figure 5. *Induced vibration measurements at Station 24+722 – Natural Bridge. This structure sits immediate to the existing roadway, with planned retaining walls and large compacted fills in close proximity to the base.*

Induced Vibrations from Construction Operations

Certain types of construction equipment and blasting methods may induce vibrations of sufficient frequency and amplitude to pose a vibration risk to natural features. To determine if this may be the case along the current General Hitchcock Highway project, induced motions from normal construction operations were documented and analyzed to determine the vibration response of the aforementioned pinnacles and natural bridge features. Figure 6 shows several of the different vibration sources considered on the project.

Main west pinnacle has much lower damping than the bridge section ((0.9-1.4%). The low amplitude second frequency suggests the beginning of dislocation from the main rock mass, sensitive to induced frequencies from 1.5-4.0Hz and 5-8 Hz.

Figure 6. *Types of excavation, earth moving, and compacting operations that may pose significant vibration risk to natural rock pinnacles and bridge structures.*

Motorized, vibratory compactors induced a variable, yet controlled vibratory drive into the ground. Operating specifications for these compactors typically result in vibration frequency ranges well above that of the oscillation frequency of most natural features; however, as noted in the field tests, and has been documented in the past, vibratory drives may also induce harmonics as large as the primary induced frequency. Figure 7 illustrates the high-amplitude frequency harmonics produced by one of the compactors employed on the project.

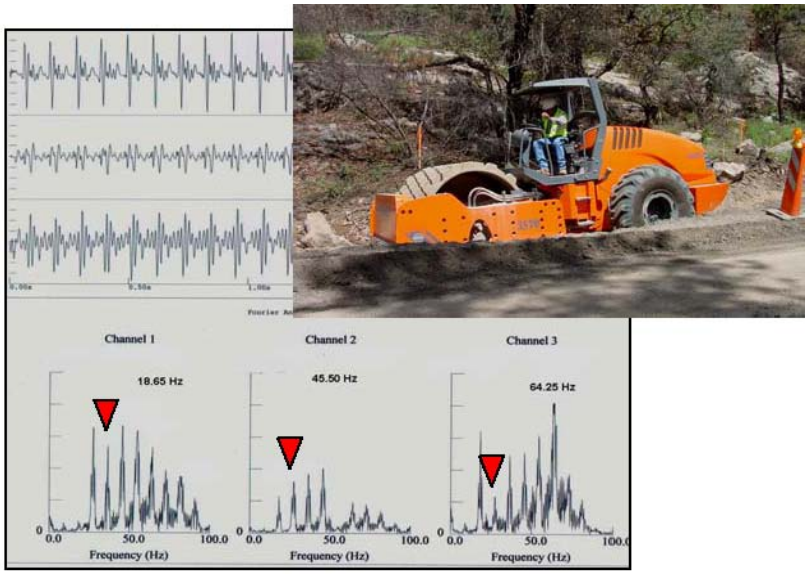


Figure 7. *Typical compactor frequency spread showing specified vibratory frequency (denoted by arrows; ~1,600-1,800 vpm or 25-30 Hz) and associated harmonics (often at greater amplitude).*

A hoe-ram is also planned for extensive use on the project, primarily for rock excavation in several designated "no-blast" zones. This piece of equipment consists of a large track vehicle with extensible arm (excavator) tipped with a hydraulic chisel. The chisel impacts the rock to split, break and remove rock faces and large boulders, and was originally considered a potentially serious vibration threat to nearby pinnacles. However, as shown in Figure 8, the operating frequency range for high amplitude impacts is well above the natural frequency range for most of the structures along the roadway.

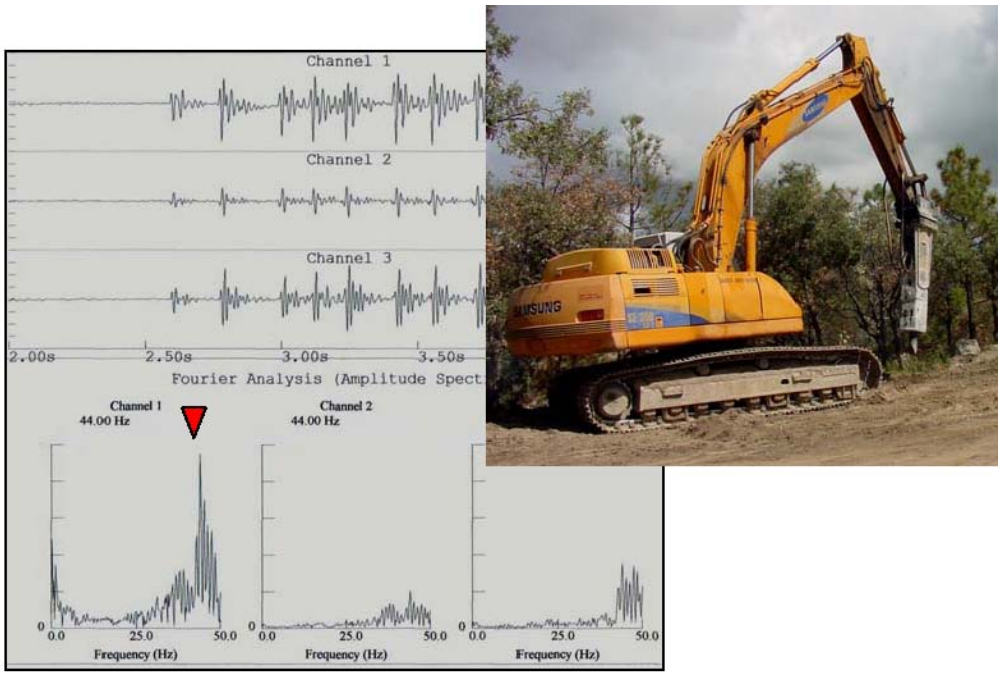


Figure 8. *Typical high-amplitude operating frequency range for the hoe ram (~45 Hz).*

Additional frequency and amplitude data is provided in Table 2, including information related to blasting, daily traffic, scrapers, and the large haul trucks previously described. Additional equipment data is presented for comparison from a past study at Chaco Canyon, NM (King, 2001).

Table 2. *Measured vibration parameters for selected sources. [All amplitudes/frequencies are at the peak amplitude normalized to a 15-m distance and assuming an attenuation of decomposed granite.]*

Vibration Source	**Frequency, Hz**	Amplitude, mm/sec
Hamm Vibratory Compactor	7.2 – 18.7 – 45.5 – 64.3	**3.2**
CAT Vibratory Compactor	16.8 – 35.9 – 48.6	**2.1**
Hoe Ram	18.3 – 45.8	**0.5**
Scraper	46.8	**0.1 – 0.2**
Haul Truck	28.3 – 47.1	**0.1**
Auto Traffic	18.0 – 37.8	**0.1**
Blasting – 5.5 kg charge	31.5 – 41.5	**18.3**
Blasting – Multi-hole	15.5	**NA**
Saki Vibra Roller[1]	18	**5.2**
RT Bomag Roller[1]	14	**3.8**
Manned Whacker[1]	34	**0.2**
Slide Compactor[1]	**38**	**0.1**

[1] Values obtained during a previous project at Chaco Canyon, April, 2001.

Vibration amplification was also investigated, particularly as it related to heavy haul-truck traffic. It was determined that amplification only occurred at or very near to the natural frequency of the structure. In some cases, amplification of nearly three times the attenuated amplitude at the base was observed – though haul-truck vibration amplitudes were so low to begin with (generally < 1 mm/sec) that they were not considered a significant risk.

Attenuation Study

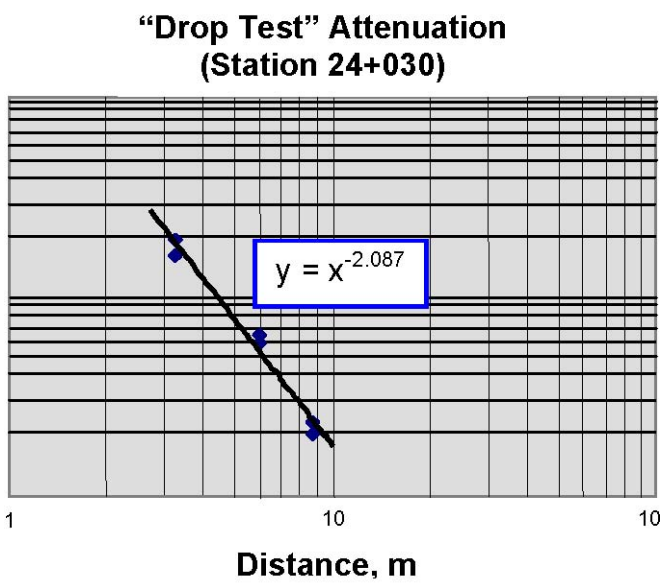
Induced vibration amplitudes at a pinnacle are dependent not only on the natural structure response and source function, but also the characteristics of the transmission path between source and structure. Vibration attenuation is the amount of energy lost between the source of vibration and the area or pinnacle of concern. Different frequencies will attenuate at different rates: however, this study was only concerned with those frequencies with which the pinnacles are most sensitive, i.e., 1-20 Hz (Table 1).

The attenuation function for a given groundmass can be derived by measuring the frequency and amplitude from vibrations induced by a weight dropped at different distances along a survey line, and by further measuring signal decay for different construction sources at different distances. The peak amplitudes are

then plotted on log-log graphs (vibrations decay by a power function). The data fit a general power law function of $A = CD^{-b}$, where A is the peak particle velocity amplitude, C is a constant, D is the distance from source, and -b is the attenuation exponent (slope). A least squares program is used to calculate the best-fit line on an amplitude/distance plot. The slope of the plotted line is the attenuation function. Attenuation tests by weight drop were made at three locations. Attenuation tests were also made from one of the test explosions, the Hamm compactor, and the hoe ram.

The vibration function (-b) for granite is approximately -1.6, whereas soils can be as high as -2.5. The material along the General Hitchcock Highway construction project is comprised of granitic materials at varying stages of decomposition; therefore, the attenuation should be higher (steeper slope) than intact, unweathered granite – as seen in the following results (illustrated in Figures 9 and 10):

- The drop tests indicate an attenuation function of -2.1 to -1.9,
- The Hamm compactor indicated an attenuation function of -1.8,
- The hoe ram data gave an attenuation of -2.0, and
- The test blast gave an attenuation of -1.9.



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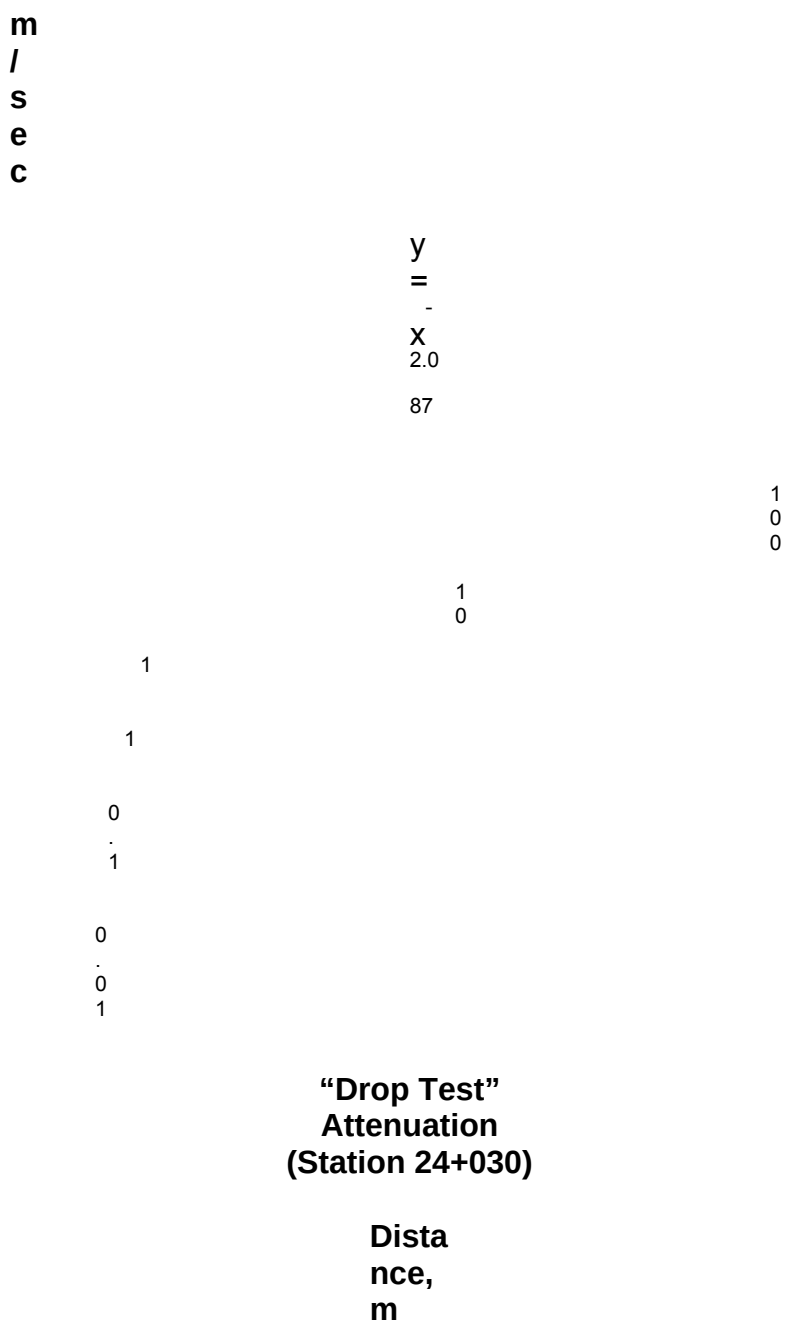

Figure 9. *Impact attenuation test on weathered granite using an 18 kg weight dropped 1.5 m. Vibration detectors were set at ranges of 3, 6, and 9 m. Two drops were made at each station.*

Attenuation functions varied from -1.91 to -2.13.

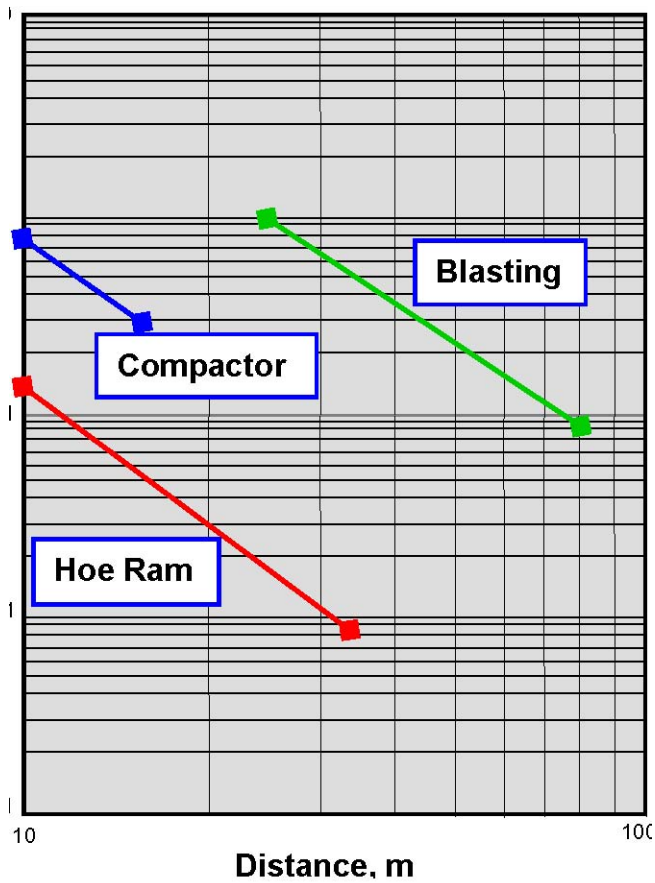

Figure 10. *Attenuation relationships measured for hoe ram, compactor, and light charge blasting (5.5 kg).*

Summary

The field studies indicate that the natural oscillating frequency of the pinnacles and natural bridge structures along the General Hitchcock Highway project ranges from 1.5 to 15 Hz. This bandwidth is generally below the frequency range of induced motions from traffic and most vibratory construction equipment. However, field tests have also shown that equipment operating specifications do not always account for harmonics that may be associated with the prime vibration. These additional high-amplitude vibrations may have frequencies much lower then those specified, falling within the natural frequency range for the smaller pinnacles – elevating the risk for natural structure damage.

Based on the low damping characteristics measured, the study identified only two pinnacles showing a potential tendency toward instability: a relatively small pinnacle at Station 25+165, and the eastern most Natural Bridge pinnacle at Station 24 + 700. Both pinnacles have natural frequencies generally below the higher amplitude vibrations induced by the compactors; however, the smaller pinnacle at 25 + 165 may be impacted by lower mode vibrations associated with compactor harmonics. This pinnacle also has a relatively low ability to absorb vibration energy, an erratic horizontal motion, a rather complex natural frequency (suggesting separate column responses), and a natural horizontal joint plane range from 10^0 - 20^0. The natural jointing allows gravity to increase the destabilization of the column.

The 24+700 pinnacle on the eastern Natural Bridge abutment is somewhat unique, as it tends to vibrate as two separate columns: a smaller component located on top of a much taller column. In some ways, this composite column may provide an advantage as the low natural frequency of the lower column portion (1.5Hz) is a natural filter for the upper portion (8-9 Hz). This natural filtering serves to decrease the risk to vibrations induced by construction equipment.

100

10

100

10

1

0.1

0.01

Ampl. mm/

s
e
c

Distance, m

Compactor

Blasting

Hoe Ram

Acoustic overpressures from blasting may not create significant impacts as the side profile of most of the pinnacles along the project segment are less than 9 m wide and are not flat – two primary factors for impacts to occur [2-5 Hz acoustical frequencies at ~400 m/sec would require over 13 m of semi-flat surface to create significant impacts]. The natural irregularity of the pinnacles has a tendency to dispersively reflect the energy or reflect to a focal point away from the column. In truth, only very limited data was acquired on air overpressures during this investigation, so additional investigation is warranted, particularly regarding production-scale blasts.

In general, the investigation has shown that, with but minor exception, the pinnacles evaluated are robust and not overly susceptible to construction vibration damage. The appropriate vibration amplitude limit for these structures is somewhat arbitrary, but is worth discussing. The National Park Service has accepted a 2 mm/sec vibration limit for several Hohokam and Anasazi historic structures. This limit is in agreement with well-published British, Swedish, and German standards for vibrations in close proximity of historic structures. The now defunct U.S. Bureau of Mines established 25-75 mm/sec as a safe limit for the average modern home (blasting standard). It is probable that the induced vibration limit for sensitive natural rock pinnacles (those exhibiting low damping and/or irregular horizontal motion) is somewhere in between these established limits for vibrations approximating the natural frequency of the structure. That is, induced frequencies falling within the range of the structure's natural frequency should be kept to maximum amplitudes ranging from 5-15 mm/sec – always bearing in mind the potential for amplification within the structure.

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