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Cover: Author Ken King, foreground, checks machine that registers ground transmission and attenuation of energy inputs typifying conditions at Chaco Culture National Historical Park. Story begins on page 3.

Seismic Research Protects Significant Ruins At Chaco Culture National Historical Park

By Ken King and Keith A. Yarborough

Boom! Crunch! Rumble! Thump!

These comic strip expletives are also apt expressions of energy inputs that can shake your house down – whether produced by real earthquakes or by human activities. Whatever the source, such perturbations are of great concern to cultural and natural resource managers throughout the National Park System. In the Southwest Region these energy inputs pose a major threat to the ruined remains of the magnificent Anazazi constructions which are preserved at Chaco Culture National Historical Park in northwestern New Mexico. These delicate treasures are the cultural remnants of the "City of Towns," which flourished in this arid area from the 10th through the 13th centuries, C.E.

This unique and significant part of the nation's cultural heritage is threatened by a number of activities in and around the park. Externally, coal strip mining is imminent to the north and northeast of the park, entailing extensive, continual blasting with large quantities of high explosives. Add to this a coal-hauling railroad, to be constructed only two miles north of the park, and then throw in oil and natural gas development, which surrounds the park. Internally, the park's road system loop, which carries visitors among the ruins, has been "upgraded" and paved. All of these activities go "boom," "crunch," "rumble," and "thump."

To protect the ruins from further damage, the Division of Natural Resources Management in the Southwest Region initiated an investigation by the USGS Seismic Risk Assessment Branch located at the Colorado School of Mines. This research quantified the two main factors of seismic damage to structures, in general: (1) energy input(s) causing vibrations and (2) responses of the receivers, the ruins at Chaco.

The objective of this work was to develop risk zone maps showing the zones around the ruins within which certain activities involving seismic perturbations and structural responses could be permitted and outside of which they must be precluded. The importance of the Chacoan ruin demands the safest, most conservative protection from **any** damage.

Energy inputs can be expressed in terms of ground shaking motions – as accelerations or as velocities. The safe upper limit of particle velocity in the ground

for industrial blasting, which will protect structures, is 50.8 mm/sec (2 in/sec.). This standard is used by many states and results in only minor cosmetic damage. A more conservative, safe level for dwellings is 2.0 to 3.8 mm/sec. European maximum allowable induced ground motion levels for residential sites are equally conservative:

- 1) 10 mm/sec. from commercial explosives in Czechoslovakia.
- 2) 10 mm/sec. at frequencies greater than 12 Hz and 12 mm/sec. at frequencies less than 12 Hz in Great Britain.
- 3) 4 mm/sec. or greater not permitted at German building sites.
- 4) 12 mm/sec. at 10 Hz and 6 mm/sec. at 5 Hz in Australia.
- 5) For historic buildings and sites in Germany, Great Britain, and Sweden: 2 mm/sec., 2.5 mm/sec., 2 mm/sec., respectively.

Note that **both** ground motions, representing energy inputs **and** frequencies of the ground motion, to which the fundamental or higher harmonic response frequencies of the structures may be "tuned," are important.

In considering energy inputs, one must ask: (1) What is the energy input of the source type, as to both frequencies of vibration and magnitude and (2) How does it attenuate (dissipate) while being transmitted through the ground (surface/sub-surface media) to the structure (receiver)?

This requires direct measurement of real ground motions and energy attenuations at the site(s) to determine if a damage problem will result. An attenuation equation was developed for each individual ruin. The fundamental frequency and higher harmonics must be determined, as well. The three energy source types which most threaten the Chacoan ruins were evaluated:

1. The Railroad and strip mining activity, exclusive of explosives;
2. The high explosives used in the strip mining; and
3. The energy inputs from traffic and road construction equipment (eg., motorized BOMAG compaction rollers, compaction "wackers," heavy trucks).

Surprisingly, the railroad and strip mining activity attenuates quickly, and is **not** a concern for ruins damage. However, the high explosives and road construction equipment are "heavy hitters." Figure 2 shows that the traffic and some of the construction equipment lie within and above the safe limits for historic structures and ruins.

Three points about energy inputs are important:

1. Energy does **not** attenuate the same for the various frequencies of transmission through the ground. Each attenuates differently.
2. Both the response frequency periods **and** the magnitude of energy inputs as expressed by ground motions must be measured empirically, especially to obtain the higher harmonics.
3. The response frequencies of vibration in the structures will tell whether damage will occur.

Therefore, the different modes of wall vibrations, as well as the fundamental period and higher harmonics and wall damping were measured by placing a seismometer at the top and bottom of selected test walls



Seismometer mounted on a typical Chaco wall is employed to determine the wall's vibrational response to energy inputs.



Propping and bracing of a wall at Casa Chiquita after the wall's response to energy inputs. Ken King checks the new readings.

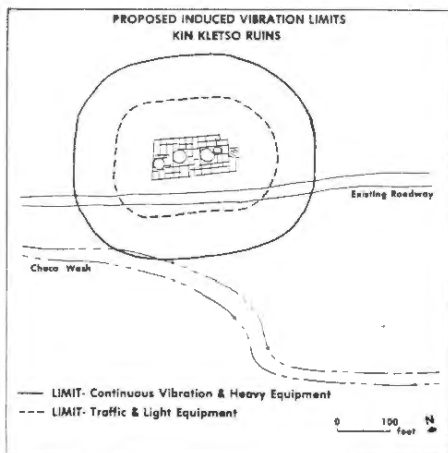


Figure 1 – Recommended minimum distances for road building equipment and traffic.

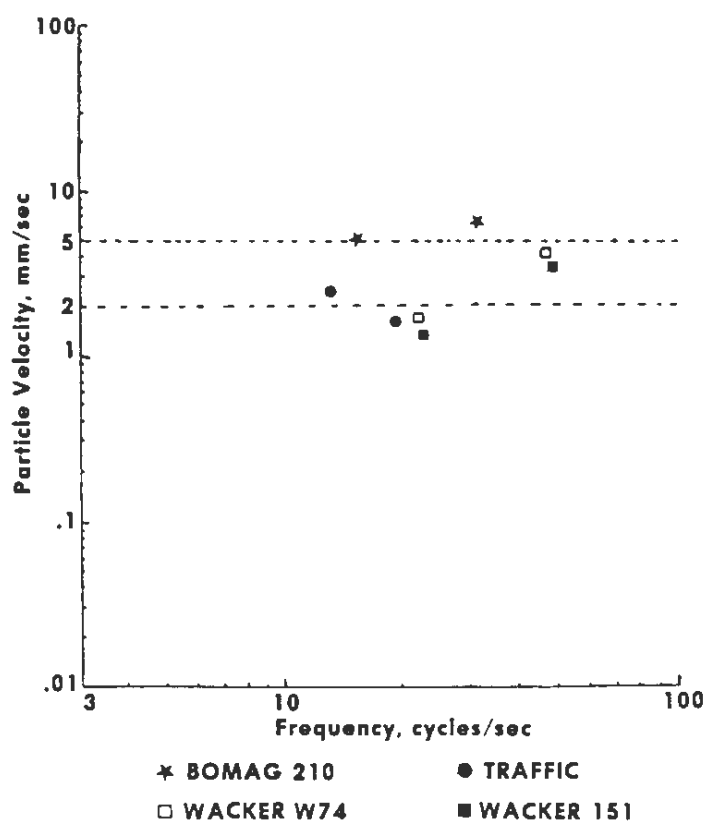


Figure 2 – Peak horizontal ground velocities at a distance of 10 m from four different types of road building equipment.

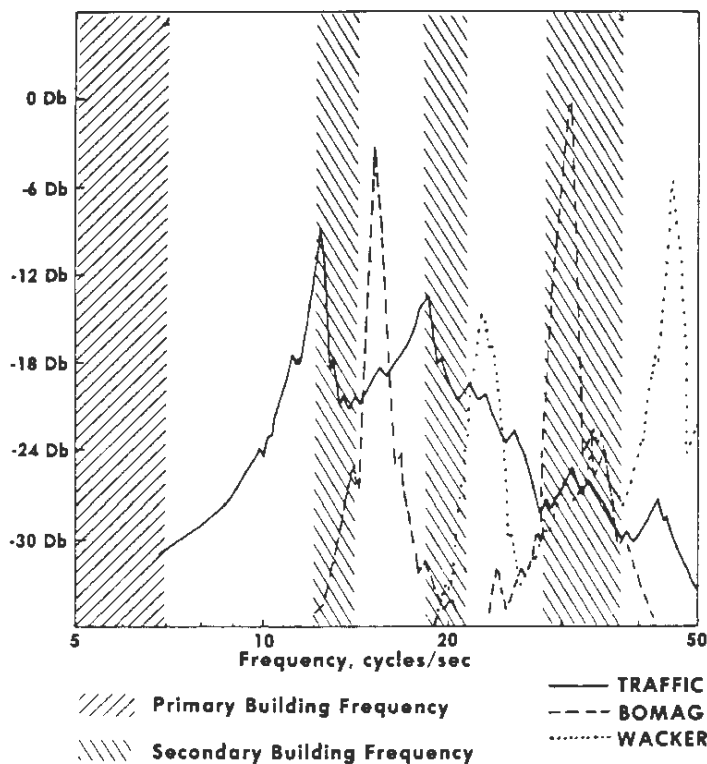


Figure 3 – Spectra of average induced horizontal ground motion from traffic and road building equipment at 10 m and the primary and secondary natural frequencies of the walls.

at Chaco to observe how they shake, as a function of wall height, for a standard energy input. The three modes of wall vibration observed were:

1. longitudinal: a side-to-side motion;
2. torsional: a rippling down the wall's height and length;
3. diaphragming: a successively reversing bulging.

The results showed that the **stable** ancient ruin walls behave just as any structure, in general. Unexpectedly, they respond very much like contemporary steel framework buildings. However, a few walls were found which did not respond in this predictable fashion. These were deemed to be unstable, due to crumbling doorways, lack of interties with cross-walls, poor rubble fill inside the dressed wall surfaces, etc. Short walls can be just as vulnerable to damage from energy inputs as tall walls, depending on their frequencies and modes of vibration.

The predictability which was found permits measurements of a few representative walls to provide height vs. fundamental frequency of vibration determinations. Also determined were the important engineering parameters of natural frequencies and rates of damping or amplification at certain "tuning" frequencies, due to internal wall stiffness. Both the frequencies and the damping analysis involve transforming an energy vs. time plot by Fourier spectral and transfer function techniques. It was noted that excessive or insufficient damping can produce damage, depending on the wall's height, modes of vibration, and frequencies of vibration in "tune" with the frequencies of ground motion induced by energy inputs.

When the frequencies of the energy input vibrations resulting from various sources such as traffic, road construction equipment, high explosive blasting, etc., are superimposed upon the fundamental and higher frequencies of wall response vibrations, as shown in Figure 3, it was possible to predict which walls would

be damaged by some of these various activities. The fundamental frequencies of the walls are not "tuned" to the frequencies of the ground motions; i.e., they do not have the same natural frequencies as the vibrations produced by traffic or road building equipment. However, many of the other higher harmonics of vi-

bration in the walls are in "tune" with the frequencies of the induced ground motions. Figure 4 shows the situation for Kin Kletso ruin. The transfer function analysis showed that the walls at Kin Kletso can magnify the induced ground motion at their base to their top by three to eight times. Furthermore, it was possi-

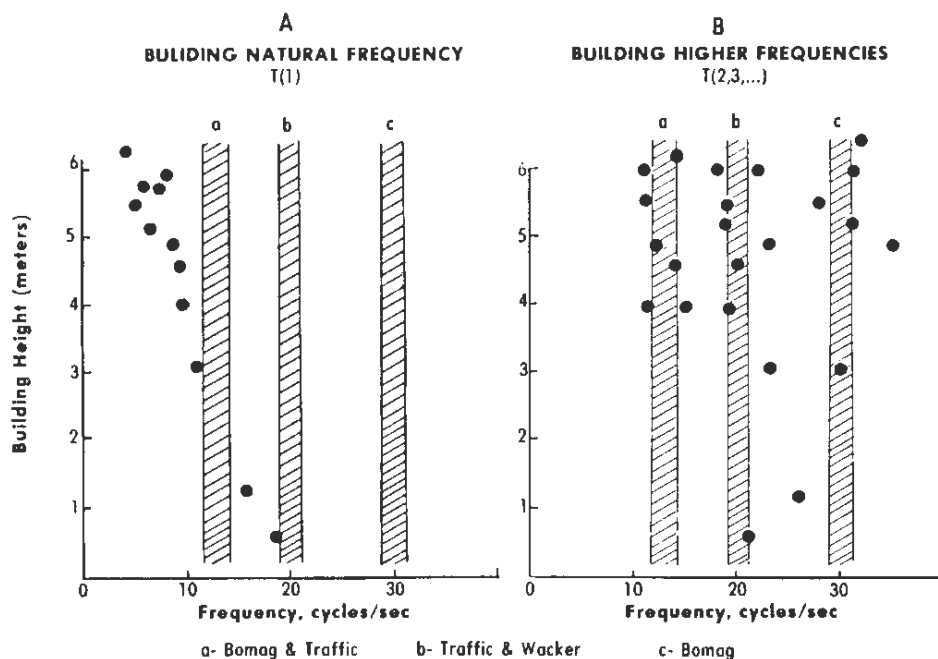


Figure 4 – (A) Comparison of frequency of induced ground motion with fundamental (first) frequency of vibration of the buildings (solid circles). (B) Comparison of frequency of induced ground motion with higher frequencies of vibration of the buildings (solid circles).

ble to predict the respective distances from the source of energy inputs of various magnitudes to the receiver walls to provide adequate protection. For certain traffic types, and wall response characteristics, some distances as small as 10 meters put some of the ruins' walls in jeopardy from the road construction. Figures 2-4 show the data.

A synthesis of all of these findings produced the risk zone maps for the canyon's most imperilled major ruins. Figure 1 shows proposed vibration limits for the protection of Kin Kletso from traffic, and light and heavy construction equipment. Similar maps drawn to expanded scales, delineate the risk zones for the ruins from the high explosive blasting by the coal strip mining operations. These zones differentiated among three magnitudes of explosives used: 1000 lbs., 5000 lbs., and 10,000 lbs., and show the respective distances that such blasts must be kept away from the ruins to prevent any damage.

Mitigation procedures to protect the ruins are of two main means:

1. Reduce the magnitude of energy input(s) at the source, and/or
2. Change the vibrational characteristics of the receiver (fundamental period and higher harmonics).

Accordingly, certain of the ruins' walls were braced and supported during the road construction. This was done to alter their frequencies of response vibration – i.e., to “detune” them with respect to the ground motion vibrational frequencies – and **not** to support them. However, this has to be done carefully so that the **altered** response frequencies of the bracing and of the wall are not “tuned” to some other input source. This would be an “out of the frying pan, into the fire” change. For example, the back wall of Pueblo Bonito has been braced for many years. The large main brace has a natural frequency of 13.8 Hz, and a damping value of 6.8 percent. The wall itself has a natural frequency of 2.8 Hz, so the two are decoupled as well as being detuned with respect to the various energy source inputs.

Kin Kletso was built partly on a large rock which conducts more energy. Therefore, because heavily loaded trucks carrying fill material passed very close to this ruin, the roadway was built up with cushioning sand, smoothed, and paved. Furthermore, the drivers were admonished **not** to accelerate or to decelerate in the vicinity of this ruin.

This type of research can produce findings that managers of all historic and prehistoric structures will find valuable in protecting these cultural resources from a wide variety of energy sources. Had this research not been ongoing at Chaco fortuitously at the same time as the road construction, Kin Kletso and Casa Chiquita, along with portions of Pueblo Bonito and Pueblo del Arroyo, would have been reduced to heaps of building stones.

The bottom line for “Boom! Crunch! Rumble! Thump!” is Beware!

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Reference:

Seismic and Vibration Hazard Investigations of Chaco Culture National Historical Park,” King, K.W., St. Algermissen and P.J. McDermott, USGS/Denver, Colorado, Open-File Report 85-529, 58 pages.