Preprint of article published in *Geotechnical Engineering for Transportation Projects,* M.K. Yegian & E. Kavazanjian, Eds. Special Geotechnical Publication #126, ASCE, pgs 1767-1776, July 2004 (with publisher's permission to post)

RESPONSE OF CRACKS TO CONSTRUCTION VIBRATIONS AND ENVIRONMENTAL EFFECTS

Charles H. Dowding[1], M ASCE and Mickey L. Snider[2], M ASCE

ABSTRACT

This paper summarizes micro-inch response of cosmetic cracks in a typical slab-on-grade ranch style house to both construction equipment-induced vibration and environmental (weather) effects. This structure was instrumented, and its response studied as part of the development of an Autonomous Crack Measurement (ACM) system. ACM systems are intended to record -- with a single sensor -- micro-inch crack displacements from both long-term environmental changes and transient construction vibrations for comparison in an understandable fashion. Ground motions were measured with velocity transducers, and micro-inch crack displacements were measured with LVDT displacement sensors. Construction within 14 m (45 ft) of the house involved trackhoe excavation for a 10x12 ft. reinforced concrete box culvert , chain trencher excavation for an 8-inch water service line, and vibratory compaction of trench backfill and granular sub-grade. As with many other studies of this nature, it was found that the weather induced crack response far exceeded that produced by construction vibrations even when produced by vibratory rolling within 3 m (10 ft) of the structure.

INTRODUCTION

Autonomous Crack Measurement (ACM) combines two technologies not heretofore integrated: micrometer measurement of crack changes in crack width and digital seismographic technology. In addition autonomous operation can be combined with internet delivery to increase public access to data, which should lead to a greater

1 Professor, Department of Civil and Environmental Engineering, Northwestern University, Evanston, IL, 60208, c-dowding@northwestern.edu
2 Engineer, Wang Engineering, Naperville, Il 60148, msnider@wangeng.com

public appreciation of the relative effects of the silent forces affecting crack response. (Dowding and Siebert, 2000). More information, past articles, archived data and operational sites can be found on the ACM web page: www.iti.northwestern.edu/acm.

Rather than measuring only ground motion to compare with results from previous studies, direct measurement of changes in crack width can also be measured. This direct measurement is simple to understand and requires no reliance upon previous work by others. Most importantly, the same device, when placed across a crack can be employed to measure changes in crack width from both transient vibratory or long-term environmental effects such as temperature and humidity. Full time histories of vibratorally-induced changes in crack width can be recorded by the same sensor that measures the long-term effect of environmental changes.

Crack width is an index of the potential for crack extension: the greater the change in crack width, the greater the potential for extension. Miller (1995) demonstrated this basic principle by showing the correlation with crack length and crack mouth opening. He shows cracks extending only when the maximum crack width experienced is surpassed. Thus, if the crack width remains less than its maximum historic value, it will not extend. Crack measurements presented herein show that changes in crack width, or crack displacement, produced by seasonal frontal effects and daily temperature changes are cyclically so large that it is unlikely that crack extension would occur as the result of a vibratory event.

TEST STRUCTURE AND ADJACENT CONSTRUCTION

Location of the ranch house in Figure 1 on the right of way of road construction provided the opportunity to test the ACM approach for typical construction activity where soil transmission distances were as small as 8 ft (2.5 m). The one-story stucco covered ranch house was located immediately adjacent to the widening and reconstruction of West Ann Road in Las Vegas, Nevada. The interior walls are constructed of drywall over a wood-frame and the exterior is covered by southwestern-style stucco. The house is in generally good condition, with the majority of the cosmetic cracking on the exterior stucco.

Borings at 500 ft (150m) centers along Ann Road Soil revealed a variably deep, and at times thick, layer of caliche, a calcium-rich cemented soil formed by the evaporation of alluvial groundwater in desert climates. Above and between these random caliche deposits, the borings show thin layers of sandy gravel to silty clay fill over natural silty clay and sandy clay layers.

Vibratory crack deformation in the test structure resulted from ground motion produced by backhoe excavation, trenching and vibratory compaction rolling. The trench for the 10’x12’ reinforced box storm culvert was excavated with a Hitachi 1200 EX Super trackhoe. Excavation of an 8” PVC sanitary line was accomplished with a Tesmec TRS-1175XL “chainsaw” trencher. Box culvert backfill materials were compacted with a Dynapac CC 522 single-drum vibratory roller, and roadway subgrade was compacted with an Ingersoll-Rand Pro-Pac Series SD-115F single-drum vibratory roller (Snider 2003).

Figure 1 Test House Showing Closeness of Construction and Sensor Across Crack 2

INSTRUMENTATION

Instrument locations are indicated on the photographs in Figure 1 and plan view in Figure 3. Excitation ground motions were measured by tri-axial (longitudinal, transverse, and vertical) velocity transducers installed in the ground approximately 2 ft (0.6 m) from the south (construction) face of the structure. As with previous studies, the longitudinal direction is defined as parallel to the long axis of the structure. (parallel to Ann Road). Changes in crack width were measured with Macro-sensor LVDT micro-inch displacement sensors shown in Figure 1. All of the crack sensors, as well as the geophones were wired to a Somat eDAQ data acquisition system. This eDAQ provides simultaneous recording of crack response whenever the excitation ground motion exceeds a predetermined trigger level. It also autonomously recorded crack displacement hourly to determine long-term response to environmental effects. The eDAQ was also connected telephonically by modem to allow remote control of the trigger algorithms. Inside and outside temperature and humidity were recorded hourly with independent Supco weather loggers. The data from these loggers was manually downloaded and correlated with the field measured crack data.

Details of the one of the two external stucco cracks and related sensors are also shown in Figure 1. Sensor 2 spans a vertical crack in the south stucco face of the house, which is parallel to Ann Road and closest to construction. It was so close to construction that the front stairs had to be removed to compact the subbase. The second sensor in the photographs is the null sensor. This sensor measures the non-crack response of the wall material and sensor itself to “null” out any long term drift or systematic response.

Dominant excitation frequencies influence structural response and are thus an important consideration. The trackhoe produced ground motions with dominant frequencies between 16 and 25 Hz. The factory prescribed operating frequencies for the Dynapac roller are 29 Hz (low frequency) and 40 Hz (high frequency) and those recorded during the tests were 28 Hz and 45 Hz. The larger Ingersoll-Rand vibratory roller employed during the actual testing for compacting within 8 ft of the structure has a frequency dial that adjusts between 18 to 32 Hz. Crack response was recorded at vibration at either 23 or 32 Hz. These dominant excitation frequencies were found to be constant out to the greatest distance measured for all data, 56 feet (17 m).

Vibratory crack and ground motion data were collected between July 2002 and March 2003. The trackhoe, trencher and two vibratory roller activities produced peak particle velocities (PPV) between 0.03 and 0.456 inches per second and maximum crack response up to 450 micro-inches (11 micro meters). Chain trenching produced the least vibration at the test house and will not be discussed in this article.

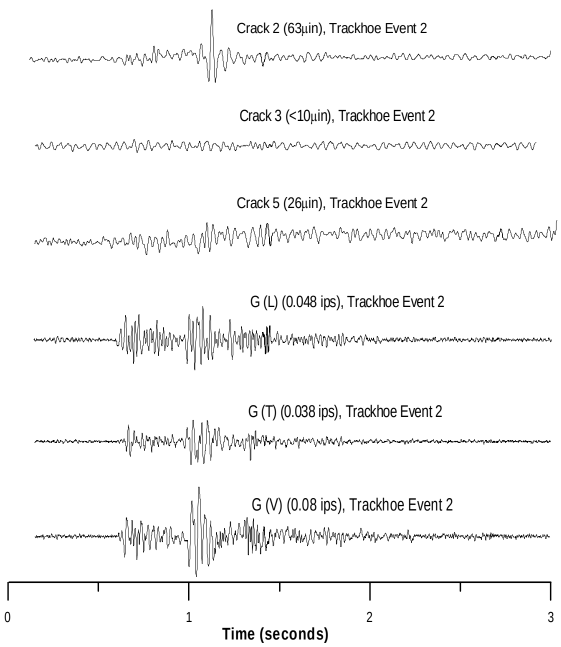

Figure 2 Time Histories of Crack Displacement and Ground Velocity for Trackhoe Excavation

VIBRATION FROM TRACKHOE EXCAVATION

Figure 2 compares time histories of excitation ground motions and the associated crack response produced by the trackhoe excavation of a 12 foot wide trench at a distance of 46 ft (14 m) . Displacement time histories of cracks 2, 3, and 5 are shown at the top, and the longitudinal, transverse, and vertical ground velocity time histories are shown on the bottom. Cracks 2 and 5 are exterior and 3 is in the the interior. This particular event produced the highest trackhoe-induced PPV , 0.08 ips (2mm/s) in the vertical direction. Crack 2, the external south wall crack nearest the excavation, experienced the greatest displacement of 63 micro-inches zero-to-peak (1.6 micro meters) while Crack 5 experienced 26 micro-inches zero-to-peak. Internal Crack 3 showed little or no discernable response, even after filtering of general instrument and electrical noise is performed. Attenuation relationships (Aimone, 2002) show that this PPV matches that expected.

VIBRATORY COMPACTION

Figure 3 compares time correlated time histories of crack responses (top) with particle velocity excitation of one pass during vibratory compaction of stone sub-grade in front of the house. The sub-grade was compacted with the Ingersall-Rand (IR) Pro-Pack series SD115 soil compactor. The top two time histories are crack displacement time histories, and the bottom three show the corresponding excitation ground velocities. This event produced a PPV of 0.46 ips (12 mm/s) , and resulted from compaction within 8 ft (2.5m) of the south wall. As can be seen, crack displacements varied greatly, with Crack 2 responding the most at 450 μ in.

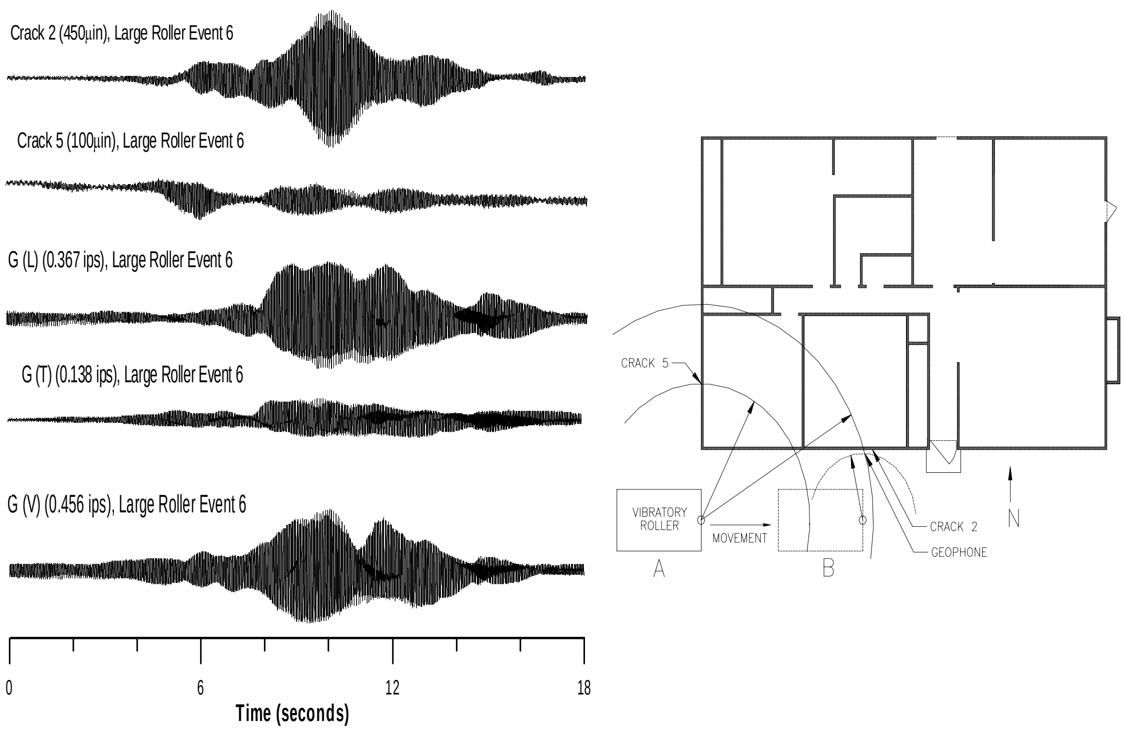

Figure 3 Time Histories of Crack Displacement and Ground (Particle) Velocity Produced by Vibratory Roller Compaction within 3 m of the House

CRACK RESPONSE TO ENVIRONMENTAL EFFECTS

Weather conditions varied daily with indoor temperatures and humidity ranging between 62° and 86° F, and 14% to 35% respectively, and outdoor temperatures and humidity ranging between 27° to 124° F, and 2% to 86% respectively. Observations began in July and ended in March. Thus they spanned summer, fall and winter weather and incorporate large seasonal weather changes as well as daily and frontal weather effects.

Figure 4 compares the time variation of long-term response of outside cracks 2 & 5 with long-term outside temperature and humidity weather indicators for each crack. Space prohibits display of a similar figure for the inside cracks. See Sinder (2003) for more details of other responses. Large daily changes in temperature as well as those produced by the passage of weather fronts, particularly outdoors, are characteristic of Nevada's desert climate. These weather phenomena correlate well with both large, sharp daily changes and the more slowly changing frontal and seasonal response of

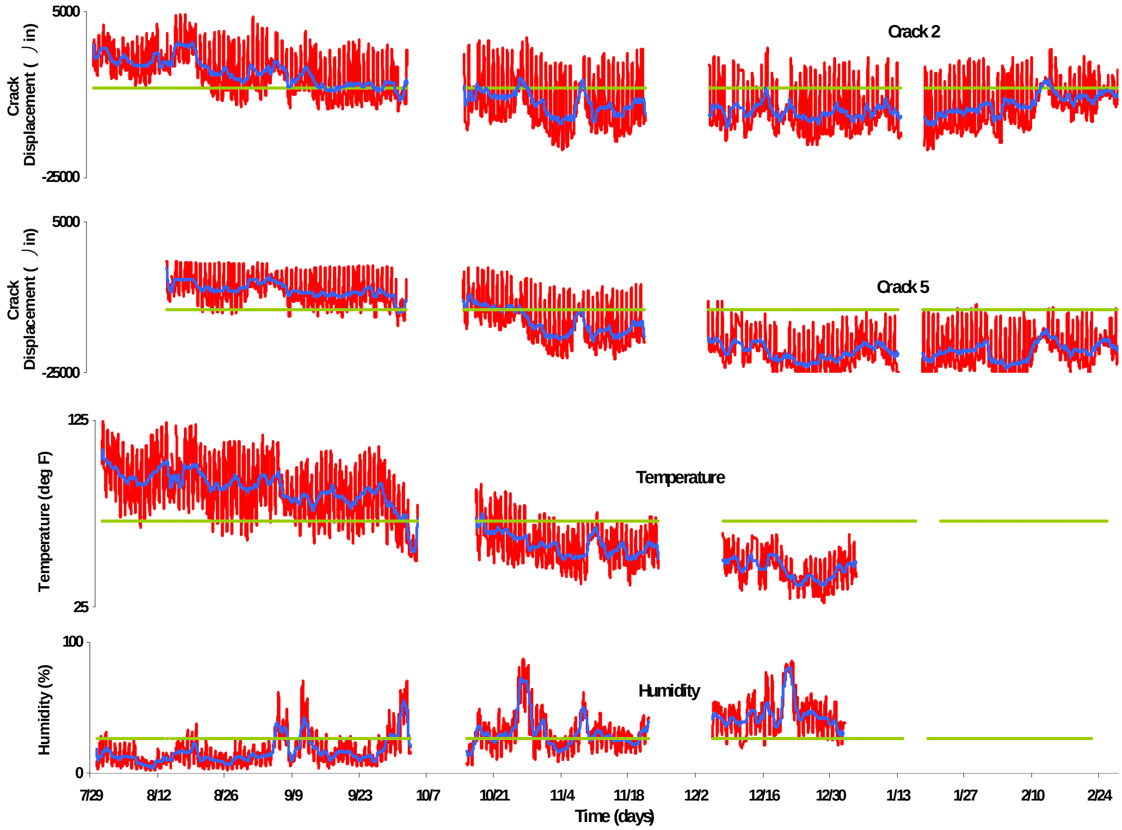

Figure 4 Long Term μ in Crack Displacement, Temperature and Humidity vs Time, Showing Effects of Changes in Seasonal, Frontal, Rainfall, and Daily Weather Changes

the cracks. The interior of the house is air-conditioned, which controls temperature and humidity, which thus reduces weather fluctuations and crack displacements relative to those outside.

Several notable weather events occurred during the collection of the long-term data. Most importantly these measurements spanned the fall months with steadily dropping average temperatures. As would be expected average crack displacement also declined, which indicates that the cracks tended to close. Significant increases in humidity and declinations in temperature, such as those seen around the 11th of September, 27th of October and 21st of December during rainfalls of 0.27, 0.17, and 0.06 in. (7, 4 & 1.5 mm) respectively. During these rain storms the 24-hour rolling humidity average steadily increased and crack 2 responded the most.

Average and maximum responses of three cracks can be seen in Figure 5 for each weather descriptor: frontal (24 hour rolling average minus overall average) , daily

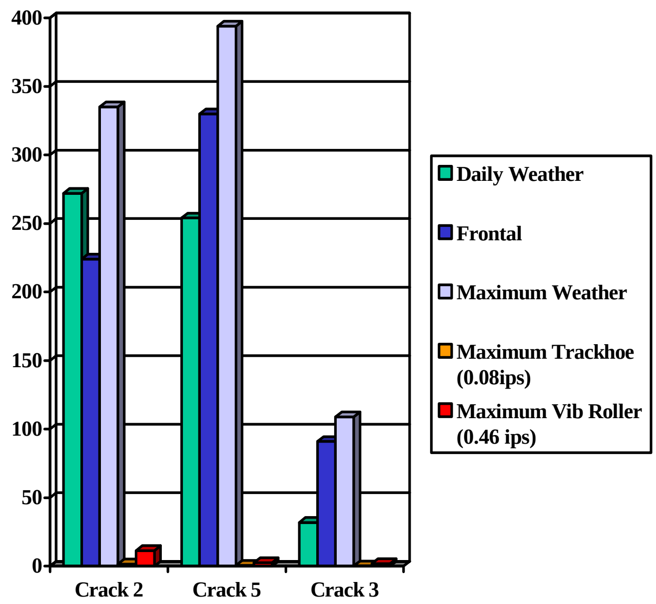

Figure 5 Comparison of Crack Displacements from Maximum Weather (Tall Bars) and Construction Vibration Effects (Short Bars) for Cracks 2, 3 & 5

(daily maximum/minimum minus the 24 hour rolling average), and seasonal/maximum (maximum minus the overall average) . These descriptions follow previous approaches (Siebert and Dowding , 2000, Louis, 2001,and McKenna, 2002). The disparity in magnitude between internal and external crack displacement is expected, as the interior of the house is temperature and humidity controlled and out of the influence of direct sunlight. Within any 24 hour period external walls containing cracks are subjected to changes in temperature as large as 50 degrees F and humidity changes of as much as 40 percent.

Weather-induced crack displacement for all cracks as defined by the three weather descriptors was at least a factor of ten larger than any vibration-induced displacement, and often much more. The weather induced responses of cracks 2, 3 & 5 are compared to those produced by vibration in Figure 8. Despite the vibration of the structure at a PPV of 0.46 ips (12 mm/s) by roller compaction, the weather induced crack displacement still dominates.

STICK-SLIP NATURE OF CRACK RESPONSE

Cracks do not open and close in a continuously smooth fashion, but rather intermittently over time in a stick-slip fashion. Figure 6 (a) shows five seconds of external Crack 5 data recorded at a rate of 10 samples per second (10 Hz), at approximately 8:30 AM on a day when no construction activity significant enough to trigger vibratory response took place in the vicinity of the house. This stick-slip phenomenon may influence the interpretation of vibratory response if it occurs during a stick-slip event. As shown by the vibratory response in Figure 6 (b), there may be the appearance of what might be mistakenly interpreted as "permanent" crack displacement in a recorded time history. However, this jump would have occurred without the vibratory excitation as shown in the upper three time histories of crack displacement. The upper time histories portray increasingly narrow time windows that eventually show the stick slip jump in the change in crack width over a 5 second

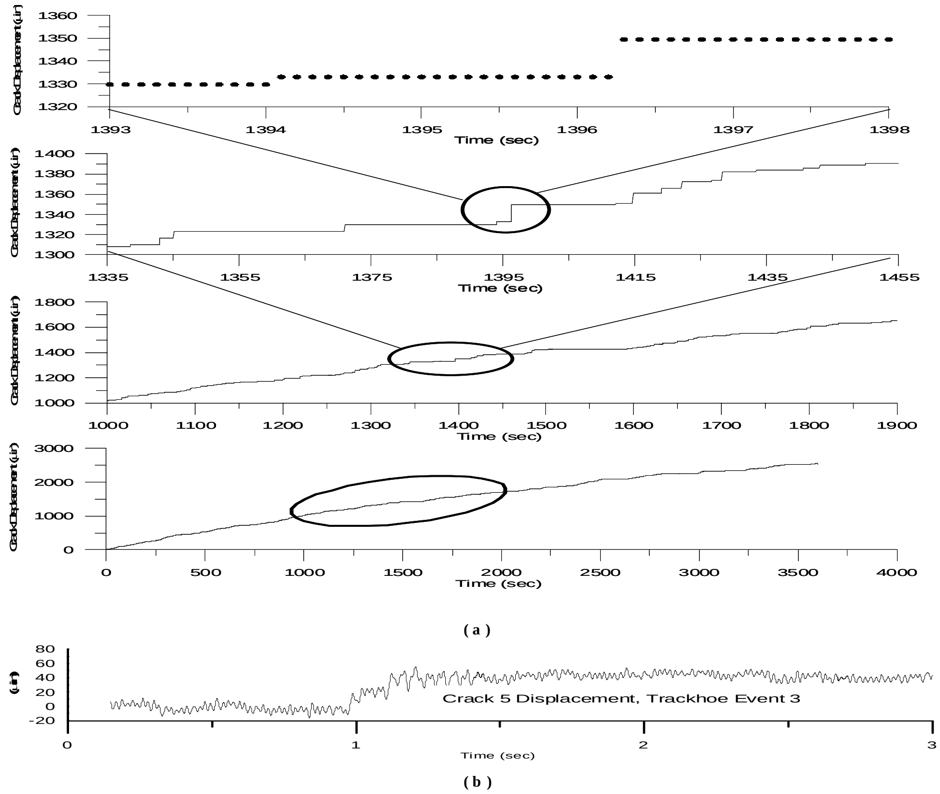

Figure 6 Stick-Slip Behavior of Crack Displacement and Potential Misinterpretation of Effect of Vibratory Crack Response

time span. More importantly, the continuing opening of the crack shown by the 4000 second long measurement, completely overwhelms the stick-slip and possible misinterpreted vibratory offset.

COMPARISONS PPV AND MEASURED CRACK DISPLACEMNTS

Since measurement of crack displacement is a new approach to assessing the effect of construction vibrations, it is important to understand how the traditional controls of ground and structural motions correlate to crack displacement. To investigate the correlation, maximum measured response of Cracks 2, 3, and 5 produced by trackhoe, trencher and vibratory roller construction vibrations were compared to traditional ground motion controls of 1) peak particle velocity, 2) ground displacements via integrated velocity, and 3) computed structure/wall displacement through single degree of freedom response (Snider, 2003). Unfortunately space limitations prevent the complete discussion of these various traditional measures of the effects of ground motions, and only the comparison of with the PPV is presented.

Comparison of PPV and crack displacement presented in Figure 7 show that crack displacement is correlated with PPV. While correlation exists for both trackhoe and vibratory compaction excitation, it is the strongest for vibratory compaction. Four of the compaction events included in Figure 7, involved passage of the roller within 10 feet of the house, an atypically small stand-off distance. These events made it

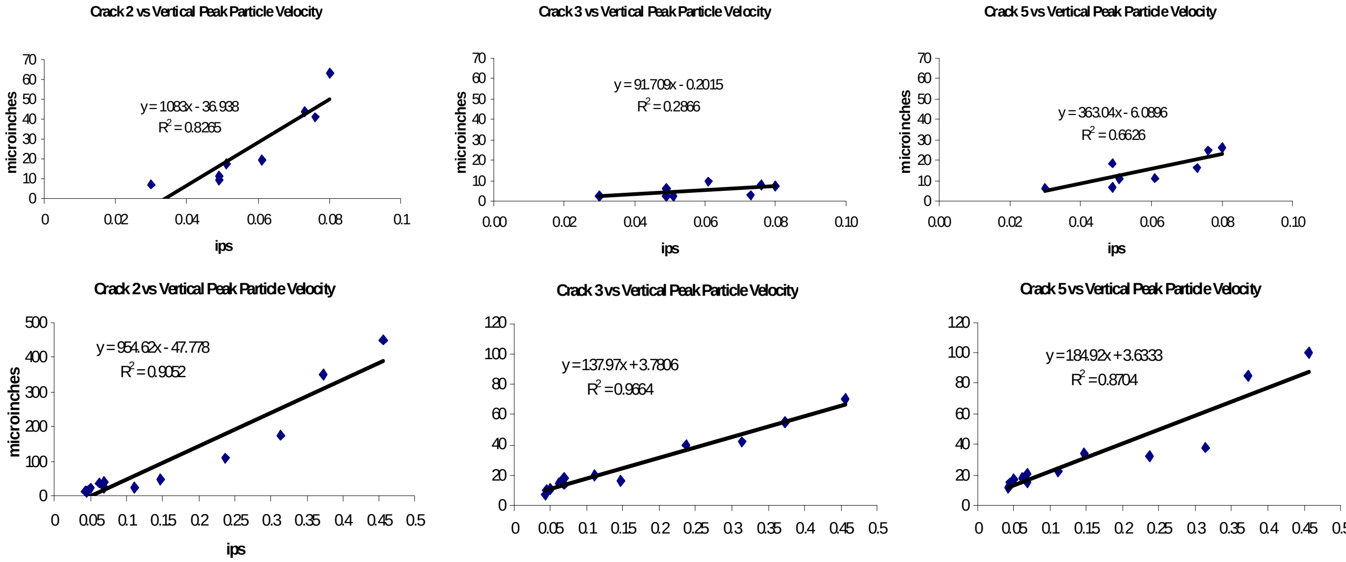

Figure 7 Correlation of Crack Displacement in micro inches (y axis) with Peak Particle Velocity (ips) (1 ips = 25 mm/s) (x axis) for Cracks 2, 3 & 5 for Trackhoe (top row) and Vibratory Roller Excitation (bottom row)

possible to examine and correlate excitation PPV and crack response for a broad and complete range of peak particle velocities, much like traditional blasting studies.

Differing times of maximum response to close in vibratory rolling in Figure 3 illustrate the local nature of excitation with unusually close construction. While the peak displacement of Crack 2 occurs at roughly the same time as the peak ground motions, the peak response of Crack 5 occurs four to five seconds before the peak ground motions at the velocity transducer. The insert on the right shows that if the roller is moving west to east (as it was during this event), then when the peak motions occur at the wall containing Crack 5, they will be significantly attenuated by the time they reach the velocity transducer some 30 feet (9 m) away. In blast cases the origin of the perturbation is sufficiently distant that the radius of curvature of the excitation front is sufficiently large that the ground motion wave front arrives simultaneously everywhere on the responding structure. Thus all portions of the structure will respond relatively simultaneously (Dowding and Snider, 2003) .

CONCLUSIONS

Measurements of excitation ground motions generated by adjacent construction vibrations and response of cracks in a typical ranch house led to the following conclusions:

- Trackhoe, trencher, and vibratory roller construction in the vicinity of the structure (<50 ft) did not create significant (>0.5 ips) ground motions.

- Long-term environmental and weather-induced crack displacement was over 30 times greater than the crack displacement caused by the largest measured construction-induced ground motion (0.435 ips).
- Cracks in Las Vegas site structure appear to displace in a stick-slip fashion, rather than smoothly over time. Further examination of this phenomenon is needed.
- One hour of typical weather-induced Crack 2 displacement was twice as large as that produced by the largest vibratory event (0.435 ips) occurring during the same time period.
- Localized in time, component responses may have been accentuated by the small radii of curvature of the excitation vibrations.
- Cracks reacted to changes in humidity with different sensitivities, which may be the result of differences in construction as well as differences in inside and outside temperature and humidity\

ACKNOWEDGEMENTS

Successful completion of this project required the contributions many individuals and organizations. Dr. Catherine Aimone-Martin of the New Mexico Institute of Mining and Technology performed the attenuation study. Kleinfelder Inc. Las Vegas (Darren Pleiman and Marco Furlan) provided the local logistical. Walt Vanderpool's inspiration initiated this study. Gary Johnson of the Clark County RTC provided oversight. The long-term financial support of the Infrastructure Technology Institute (ITI) at Northwestern University, which is funded by a block grant from the U.S. Department of Transportation, was essential for demonstration projects of new instrumentation such as this. Finally special mention is necessary for the help of the instrumentation crew at ITI and in particular for Daniel Marron and David Kosnik who, when necessary, dropped everything to help.

REFERENCES

Aimone-Martin, C. (2002). Ann Road Expansion Project Attenuation of Ground Velocity Measurements, Report, Aimone-Martin Associates LLC, Socorro, NM.

Dowding, C. H. (1996) Construction Vibrations, Prentice Hall Inc., Englewood Cliffs, NJ, 620 pp.

Dowding, C.H. & Siebert, D (2000)"Control of Construction Vibrations with an Autonomous Crack Comparometer", Explosives and Blasting Technique, R. Holmberg, Ed. , A.A. Balkema, pp 103-110, September 2000.

Louis, M (2001) "Field Authentication of Autonomous Crack Comparometer," M.S. Thesis, Department of Civil and Environmental Engineering, Northwestern University, Evanston, IL, USA.

McKenna, L (2002) "Comparison of Measured Crack Response in Diverse Structures to Dynamic Events and Weather Phenomina," M.S. Thesis, Department of Civil and Environmental Engineering, Northwestern University, Evanston, IL, USA.

Miller, R. (1989), Analysis of the Fracture Process in Mortar Using Laser Holographic Interferometry, PhD Thesis, Department of Civil and Environmental Engineering, Northwestern University, Evanston, IL, USA

Somat TCE eDAQ version 3.5.1 (2001). Somat Corporation, Champaign, IL.

Snider, M (2003) "Autonomous Crack Measurement of Construction Vibrations" M.S. Thesis, Department of Civil Engineering, Northwestern University, Evanston, IL, USA.