Ground Motions from and House Response to Underground Aggregate Mining

By
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Abstract

A unique judicial opportunity allowed measurement of the response of three cracks in residential structure to blasting for underground aggregate mining. Instrumented cracks were located in the interior basement CMU mortar and upstairs dry wall as well as exterior brick work. The dynamic environment was unusual. Even though the blasting occurred some 490 m (1600 ft) away, excitation frequencies were unusually high and there were no apparent surface waves. In addition there was no air overpressure wave to produce secondary crack response. As is typical, long term environmental effects produced greater crack response than did the blast induced ground motions.

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Introduction

This article compares crack response to climatological and occupant effects with those induced by subsurface mining of aggregate. The vibration environment associated with subsurface mining of aggregate has become of increasing interest because many urban quarries have gone underground or are considering doing so. Three cracks were instrumented in conjunction with a study by a court appointed expert to determine future blasting controls (Revey, 2005). The cracks, which were observed for over four months, were located in the interior basement concrete masonry mortar, upstairs dry wall as well as exterior brick work. The dynamic environment was unusual. Even though the blasting occurred some 490 m (1600 ft) away, excitation frequencies were unusually high (35 to 50 Hz) and there were no apparent surface waves. In addition there was no air overpressure wave to produce secondary crack response. As is typical, long term environmental effects produced greater crack response than did the blast induced ground motions. Occupant induced crack responses were also large for the crack near occupant activities. The article begins with a description of house, cracks, sensing system and blasting environment. Then crack responses to changes in temperature and humidity are presented, which are compared to blast and occupant induced responses.

Project Setting

The house shown in Figure 1 was instrumented in conjunction with a study by a court appointed expert to determine future blasting controls for a underground aggregate quarry near Franklin, KY (Revey, 2005). Measured crack response was instrumental in allowing the court to set guidelines that were reasonable and founded on measured response. In addition measurements allowed a greater understanding of the uniqueness of the blasting environment associated with nearby underground aggregate mining.

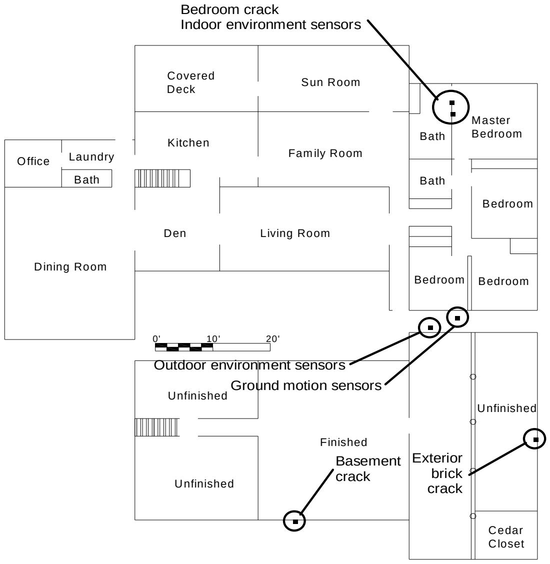
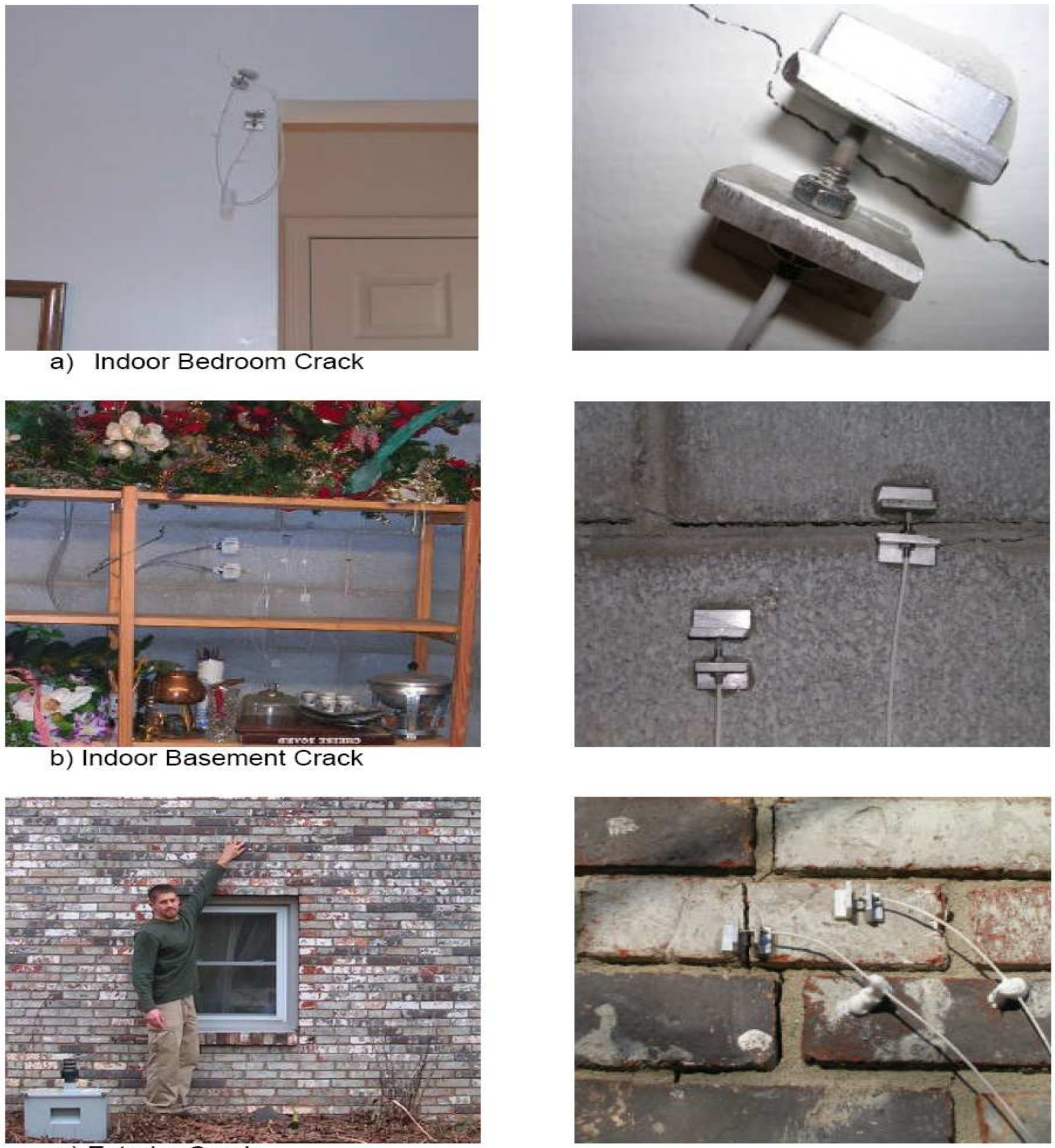


Figure 1: Photograph of single story house with walkout basement (above) and plan views of basement and first floor showing location of 3 crack sensors, geophones and environment sensors.



a) Indoor Bedroom Crack

b) Indoor Basement Crack

c) Exterior Crack

Figure 2: Orientation and detailed photographs of cracks and sensors for cracks in interior bedroom drywall, basement CMU mortar and exterior brickwork

The house was fitted with Kaman eddy current crack sensors over cracks in three different materials. The crack monitoring system is composed of the crack sensors, a Somat eDAQ data logger or acquisition system and a cable modem for high speed communication. This system is employed with all Northwestern University Infrastructure

Technology Institute (ITI) systems (Waldron, 2006). Description of the Autonomous Crack Monitoring (ACM) systems and all supporting theses, articles, and demonstration sites can be found on the ITI web site (ITI, 2006). Geophones were buried outside of the house as shown in Figure 1 to trigger the system. No air overpressure measurements were made with this system. A separate seismograph, which was also located at the house confirmed the absence of mine blast generated air over pressures.

Figure 2 shows the 3 crack sensors mounted in place. As in standard installations each crack sensor is accompanied with by a “null” sensor to measure wall and sensor material response. As is typical the null sensor response confirmed that the sensors were recording the crack response (Waldron, 2006). As has been the case with similar installations (Dowding and McKenna, 2005), the crack sensor is mounted on a bracket that is glued or epoxied on one side of the crack while the target is affixed to the other. Long-term crack response is obtain by sampling the crack every hour, while dynamic response is obtained by sampling at 1000 samples per second for 3 or more seconds. Temperature and humidity were measured both inside near the bedroom crack and outside near the geophone. In all 13 channels of information were recorded by the eDAQ system and transmitted daily for posting on a web site for analysis.

Blasting Environment

As shown by the plan view and cross section in Figure 3, the house was located some 480 to 500 m (1550 to 1650 ft) away and 120 m (385 ft) above the mine during the study. The rock mined was limestone and the thickness of the residual soil overburden varied from location to location. Limestone was removed with conventional room and pillar mining methods. Rock was fragmented with blasts that consisted of 20 to 50, 64 mm diameter holes, charged with of Ammonium Nitrate Fuel Oil, each primed with a booster. Typical designs employed initiation sequences with 25 ms delays between adjacent holes and 84 ms delays between rows. Each delay involved detonation of some 23 kg (50 lbs) of ANFO.

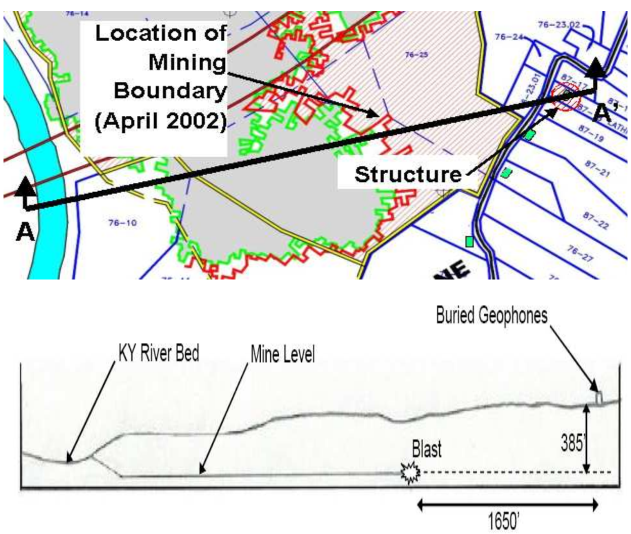


Figure 3: Plan and elevation views of mine and house

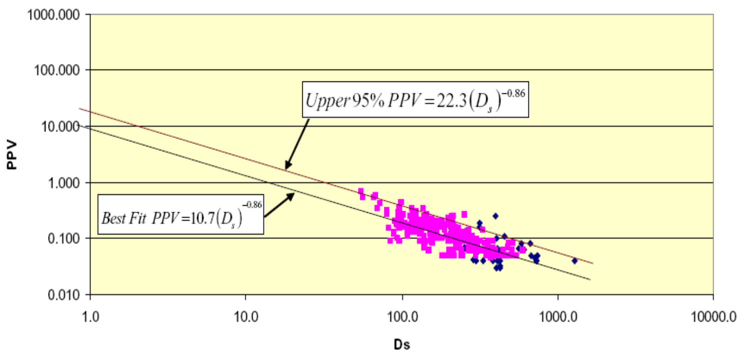


Figure 4: Attenuation of Peak Particle Velocity (PPV) with square root scaled distance

The resulting attenuation relation at the ground surface is shown in Figure 4. When plotted in log-log scale, the exponential relationship between scaled distance and PPV generally follows a straight line with a negative slope (***m***) and Y-intercept (***K***). Values of K typically vary between 960 and 26, as defined by Oriard (1972). Curve slopes generally range from -1.6 to - 1.2. For this site, the 95% confidence curve has a ***K*** value of 22.3 and a slope (***m***) of -0.86. The slope of the PPV curve for the this site is shallower than normal but does compare to other sites where energy arriving as body waves from an underground source is not influenced by surface waves (Revey, 2005). The 95% confidence line shows that if a blast at the site had a maximum charge-per-delay of 23 kg (50 lb), there is 95% probability that PPV in the ground near a home 600 m (2,000 ft) away would not exceed 0.12 in/s [$22.3 \times (2{,}000 / 50^{1/2})^{-0.86}$].

Crack Response to Blast Events

Table 1: Comparison of ground motions (PPV) and crack response (µ in) (40 µ in = 1 µ m) for high and typical ground motions

Shot Date	GROUND MOTION				CRACK DISPLACEMENT		
	Longitudinal PPV	Transverse PPV	Vertical PPV	FFT Frequency (Longitudinal)	Exterior Crack	Basement Crack	Bedroom Crack
	(in/sec)	(in/sec)	(in/sec)	(Hz)	(µin.)	(µin.)	(µin.)
01/20/05	0.15	0.08	0.14	35	444	379	104
03/07/05	0.17	0.13	0.06	45	348	687	82
03/16/05	0.05	0.05	0.04	45	244	163	71
05/17/05	0.05	0.04	0.04	58	147	142	36

Table 1 summarizes the range of ground motions experienced at the instrumented structure from the above described underground blasts at a square root scaled distance of some 230 ft/lb$^{1/2}$. As described above the ground motion environment was constrained to PPV's less than 5 mm/s (0.2 ips) early in the project and below 2.5 mm/s (0.1 ips) at the end. There was no air over pressure pulse as it was apparently muffled by the mine configuration, so no air over pressures are reported.

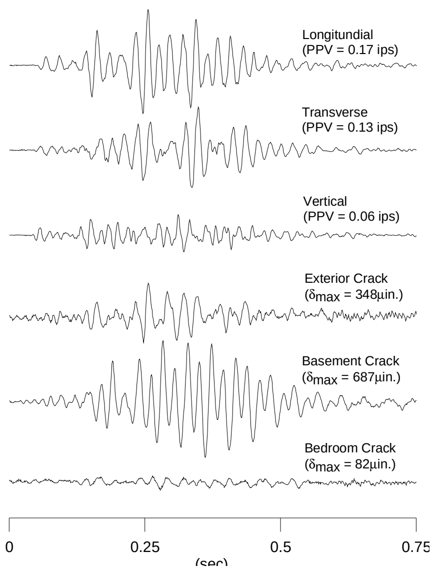


Figure 5: Comparison of time histories of ground motions and crack response

Typical time histories shown on Figure 5 show no late, low frequency crack response for several reasons. First the lack of any mine blast induced air over pressure. Secondly, there is no surface wave. This absence of surface wave excitation is unusual, so early on in the project, the normal observation period for dynamic response of 3 seconds was extended to 20 seconds to ensure that there was no delayed surface wave response. Even such an unusual extension of the observation period failed to reveal any surface wave. Because of the apparent lack of different wave types there is only one dominant frequency, and it was unusually high for such stand off distances. The dominant frequencies as calculated by response spectrum analysis are on the order of 35 to 60 Hz (Waldron, 2006). The ground motions are short, on the order of 0.4 seconds

Crack Response to Changes in Temperature and Humidity

Long term response of the three cracks is illustrated by the compound graphs in Figure 6. A complex combination of indoor & outdoor temperature-humidity and home heating affects the interior cracks (left two graphs). However, it appears that the temperature has the greatest affect on the exterior brick crack (rightmost graph). Bedroom and basement cracks recover from the winter effects at the end of the home heating season. Horizontal bars on the left graph show that when the weather is warm enough to open the windows, the average interior humidity increases. Arrows in the middle graph show that it is during this period that the bedroom crack begins to responds to weekly weather fronts as does the basement but to a lesser degree. Finally on the left, circles show response of the exterior brick to extreme changes in temperature.

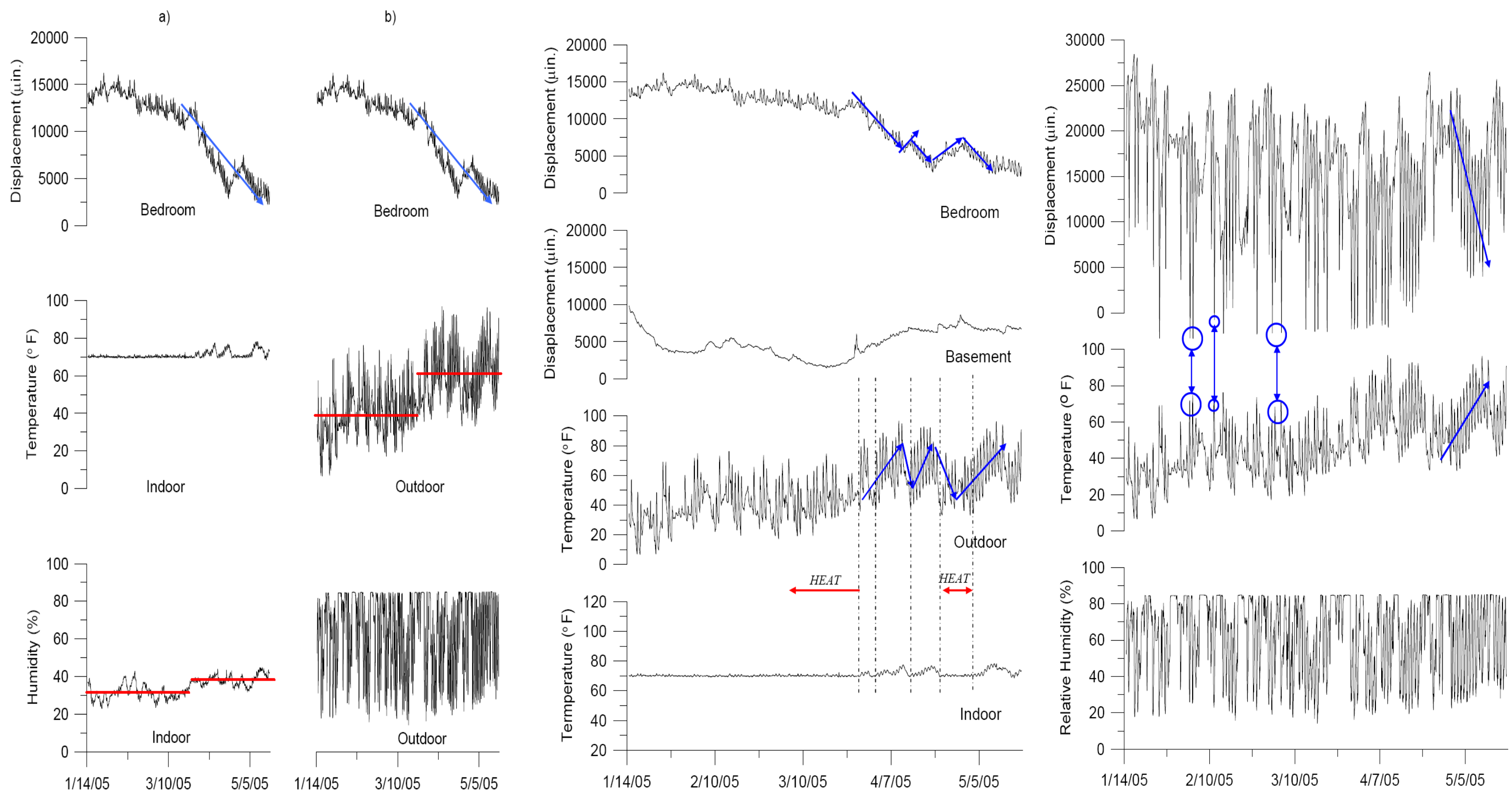


Figure 6: Four month time histories of crack response and changes in temperature and humidity showing crack responses to long term changes in climate and home heating habits.

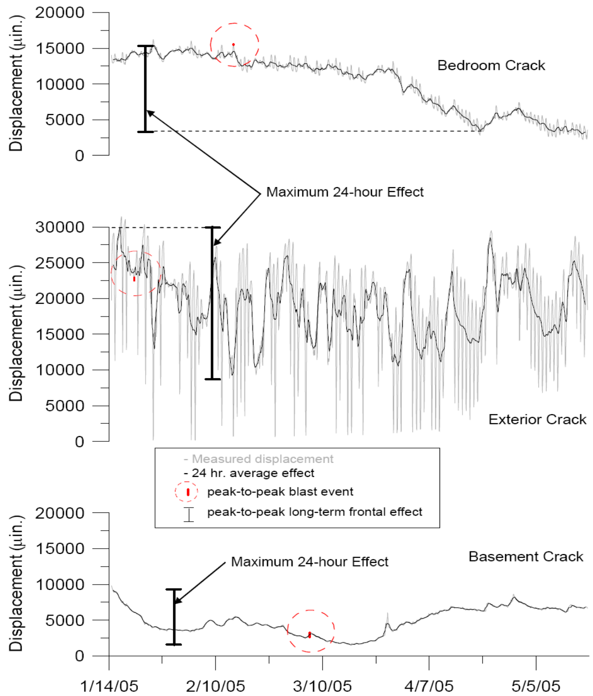


Figure 7: Comparison of large climatological crack response with small vibratory response

Dynamic crack responses are compared to the long-term in Figure 7. The dotted circles describe the area within which the peak to peak crack response occurs; however, at a scale which permits comparative display of the long-term response, the dynamic response is so small as to be almost invisible. The thicker lines in long-term time histories in Figure 7 are 24 hour rolling averages, which are the averages of the crack response 12 hours before and after the plotted point. This line displays the effect of the more slowly varying weather fronts. There is so little temperature response of the crack in the basement (bottom graph) that the hourly and 24 rolling average curves are the same. The vertical bars show the maximum change in crack width during the 4 months of observation as described by the 24 hour rolling average.

Table 2 compares this darker – 24 hour line – with the maximum peak to peak vibration induced crack response. As has been true in the other case histories (Dowding and McKenna, 2005), the environmental effects greatly exceed the blast induced effects.

Table 2: Comparison of the darker, 24 hour average, climatological crack responses with responses to typical and maximum ground motions

	Temperature Change (degF)		Humidity Change (%RH)		Bedroom Crack	Exterior Crack	Basement Crack
Environmental Effects (peak-to-peak)	*int.*	*ext.*	*int.*	*ext.*			
Max measured long-term response	10	90	22	71	14,000	31,254	8,346
Max 24-hour average response	8	59	19	51	12,335	20,542	7,595
Vibration Effects (peak to peak)							
Typical ground motion (PPV = 0.08 ips)	-	-	-	-	66	207	235
Max ground motion (PPV = 0.17 ips)	-	-	-	-	114	444	687

Comparison with a Surface Quarry Operation

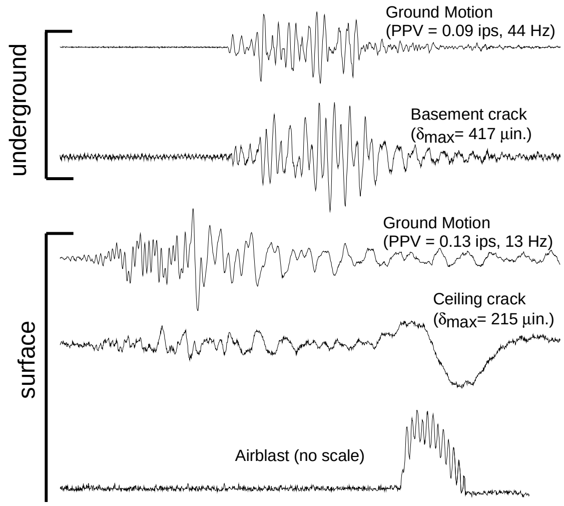
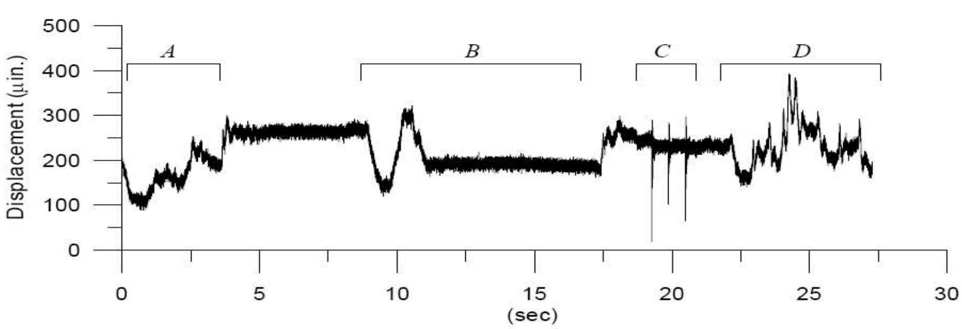


Figure 8: Comparison of Underground and Aboveground Quarry Blasting Environments

Crack response in Figure 8 of a similarly constructed house near a surface limestone quarry reveals several differences. Both homes are approximately 460 m (1500 ft) from the blasting. The wave train produced by the surface quarry is longer because of the later arriving surface waves. The dominant frequency is lower 13 Hz for the surface quarry vs. 44Hz for the subsurface quarry. Finally there is a late arriving air over pressure and the induced response of a crack in the ceiling.



Event	Description	A	C
A	Ending lean on far doorjamb		
B	Leaning on near doorjamb		
C	Pounding on wall		
D	Walking through doorway		

Figure 9: Deliberate occupant excitation for comparison w/ long term observation

Occupant Induced Crack Response

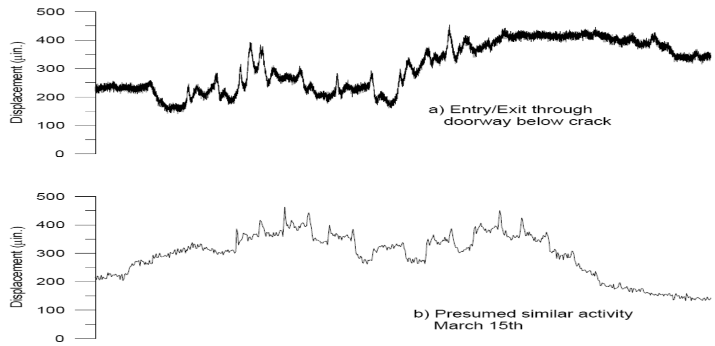


Figure 10: Comparison of Deliberate Doorway Activity with That Measured During Continuous Measurement

Figure 9 above shows the effects of deliberate occupant activity near the bedroom crack, which is located at the corner above the doorway between the bedroom and the bathroom. Leaning on the door jamb causes some 3.8 μ m (150 μ in) of peak to peak crack response and walking through the door way produces even greater response. A study of all possible crack responses was conducted by sensing continuously over periods of one to three days for each of the cracks. During this continuous observation of the bedroom crack, a number of unusual responses were observed during periods of the day when there would be passage through the instrumented doorway (Waldron, 2006). Figure 10 shows compares one of those responses to the response recorded while the person in Figure 9 was walking through the doorway. The two wave forms are quite similar in both magnitude, length of response and high frequency details.

Conclusions

- Vibratory environment associated with subsurface aggregate mining differs from that associated typical surface mining in this geology.
- Crack response to both long term climatological and vibration effects varies by location and material
- Crack response induced by long term climatological effects and home heating is greater than that induced by subsurface aggregate mining.

Acknowledgements

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