

# Interpretation of Microseismic Effects of Petroleum Production through Observed Response to Coal Mine Blasts

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**ABSTRACT:** This paper employs coal mine blast-induced ground motions to interpret microseismic phenomena that from time to time may be induced by petroleum resource development. Reservoir depletion, flooding, etc may produce microseismic ground motions that lead to concern on the part of those who feel the ground motion. These concerns can be addressed by comparison to other similar ground motions, such as the blast-induced motions described herein, and their effect on residential structures. These similar motions were found not to cause even cosmetic cracking of the weak wall covering of a residential structure. Furthermore ground motion-induced crack response was found to have an order of magnitude less effect than climatological changes associated with the passage of a weather front.

## 1. INTRODUCTION

The following caution from the web site "Induced Earthquake Bibliography: Oil and Gas Production Induced Earthquake References" is always important in any article such as this. "The very fact that someone has studied the possibility of induced seismicity at a given site or related to a given activity does not mean that activity or site has really induced seismicity. It certainly does not mean that the activity has "caused damaging earthquakes." Some human activities do induce microseismic events that cause damage in limited locations, but most induced micro-seismicity is not damaging.

This paper presents measured response of a structure to motions producing peak particle velocities of 10 to 19 mm/s at 5 to 21 Hz, which can be employed to interpret microseismic phenomena. These ground motions were produced by surface coal mining. They are compared to motions produced by two micro seismic phenomena, gas field depletion and hydraulic fracture. Ground motions produced by the gas field depletion were found to be similar to those produced by coal mine blasting. Since the ground motions were found to be similar, response of an instrumented test house to the coal mine blast-induced ground motions can then be assumed to be similar to that induced by the gas field depletion.

The paper begins with a description of the ground motions produced by gas field depletion and hydraulic fracturing. These ground motions are then compared to those produced by the coal mine blasting adjacent to the instrumented test house. Single degree of freedom response spectra, which account for both amplitude and frequency content, are found to be helpful in this comparison. Response of the test house and the instrumentation employed to monitor crack response are

then described. Crack responses to dynamic, ground motion- induced excitation are compared with those produced by long term climatological effects through use of micro-meter displacement transducers. The dynamic responses were found to be far less than those produced by the passage of a weather front.

## 2. GROUND MOTIONS PRODUCED BY OIL FIELD OPERATION AND HYDRALUIC FRACTURING

Van Eck et al's 2006 [1] description of the motions produced by general operation of the Roswinkel gas field in the Netherlands allows development of a response spectrum for the production induced ground motions. Data from monitoring between 1992 & 2003 showed that of ground motion with an expected return period of 1 year were associated with moment magnitude 2.25 events. Maximum horizontal acceleration at the epicenter was estimated from the moment magnitude,  $M_w$ , based upon a moment energy-distance relation developed by Van Eck for this field.

$$\begin{aligned}M_w &= 2.25 \text{ (Energy} = 0.03 \times 10^{18} \text{ ergs)} \\ \text{Max horiz. accel.} &= 0.05 \text{ g} \\ &\text{(at a hypocentral distance of 2 km)} \\ \text{Dominant frequency, } f &= 10 \text{ to } 15 \text{ Hz} \\ \text{Number of principal pulses} &= 1 \text{ to } 2 \\ \text{Max estimated velocity} &= \sim 0.78 \text{ cm/s} \\ &\text{(} = \text{ accel}/(2 \cdot \pi \cdot f)\end{aligned}$$

Two, 5% damped, pseudo velocity response spectra for ground motions that are bounded by parameters described above are shown in **Figure 1** ( thick lines ). They were produced by assuming that Van Eck's "1 to 2 principal pulse" motion could be idealized as a 1/2 cycle displacement and three half-sine acceleration pulses. This acceleration produces two (one positive and

one negative) velocity pulses [2] shown in the insert in **Figure 1** . Idealizations of all three motion descriptors begin and end with zero amplitude. Event energy is estimated from an equivalent moment chart [3] developed by Johnston [4] and is employed to describe general energy only.

Sasaki's 1998 [5] description of motions produced by hydraulic fracturing in a geothermal field in Japan allow an estimate of the order of magnitude of near surface motions from such activities. Particle velocities resulting from pressure injections at depth of ~ 1.8 km to increase fracturing in the Hijiori, Japan geothermal site were measured with geophones buried at depths of 50 to 150 m. These motions can be described as follows:

Mw = -1.2 (Energy = 0.00000001x10<sup>18</sup> ergs)  
 Dominant frequency, f = 28 Hz  
 Number of principal pulses = several  
 Max measured velocity = 0.000075 cm/s  
 (hypocentral distance of ~ 2.2 km)

Surface ground motions produced by hydraulic fracture at a depth of 1.8 km are of such small amplitude that they are inconsequential for a consideration of structural response. For instance they are smaller than ground motions produced by trees waving in the wind. While these estimates are for this case only, they do indicate the general intensity of peak particle velocities associated with well pressure induced hydraulic fracture at depth.

At depth with a 200 m standoff, motions are 40 to 630 times those at distances of 2000 m or 40 to 630 \*0.000075 cm/s = 0.003 to .05 cm/ or 0.03 to 0.5 mm/s.

### 3. LARGE SURFACE COAL MINE BLAST INDUCED GROUND MOTIONS

The instrumented test house was located adjacent to a surface coal mine in central Indiana, which involved large-scale cast blasting. This adjacent surface mining produced unusually high amplitude, low frequency ground motions. A typical blast, 600 to 360 meters (2000 to 1200 ft) away from the house involved 54, 30 m (100 ft) deep holes arranged in six rows (in a direction radial to the house). Each hole was loaded with 306 kg (675 lbs) of explosive with four decks and thus ~76 kg of explosive per delay. Such a shot would produce ground motions with a peak particle velocity of 0.14 ips to 0.75 ips (3.5 mm/s to 19 mm/s) [6]. **Table 1** summarizes three of the most intense of a number of low frequency, high amplitude ground motions at the test house. As seen in the table, these large and distant surface coal mine blasts produced ground motions both in the 5 to 7 and the 10 to 25 Hz frequency range.

Five percent damped , pseudo velocity response spectra of coal mine blast-induced ground motions described in **Table 1** (thinner lines) are compared to those from the Roswinkle gas field in **Figure 1**. Roswinkle motions have a return period of one year. Spectral bounds from blast- induced ground motions equal and exceed those of

Table 1: Summary of excitation and response of test house

Date	Time	Frequency (Hz)			Peak Velocity (mm/s)							Amplification		Crack Response (µm)		
		L	T	V	L	T	V	H1	H2	H3	H4	Wall	Struct	C7	C9	C10
1-Jan	9:03	21	21	25	19.3	10.4	10.9	72.3	18.2	16	17.9			3		
23-Feb	14:47	28	9	36	10.4	6.6	8.1	25.3	15.4	10.3	8.3	4.23	2.78	1.8	0.7	1.8
2-Apr	14:40	6	9	5	10.2	5.1	7.0	23.6	11.6	24.2	24.9	3.56	2.84	6.4	0.4	3.4

Motions at depth produced by hydraulic fracturing will be larger than those at the surface. Magnitudes of peak particle velocity (PPV) at depth can be estimated from Sasaki's surface measurements with a power law attenuation relation such as

$$PPV = k(R/E^{1/2})^{-a} \quad (1)$$

Where -1.5 < a < -2.8, R = distance, E = energy (in this case, moment magnitude). For events with the same energy traveling through the same material, the ratio of

$$PPV_{near}/PPV_{far} = (R_{near}/R_{far})^{-a} \quad (2)$$

the production-induced ground motions at natural frequencies of residential super structures (5 to 10 Hz) and their walls & floors (10 to 20).

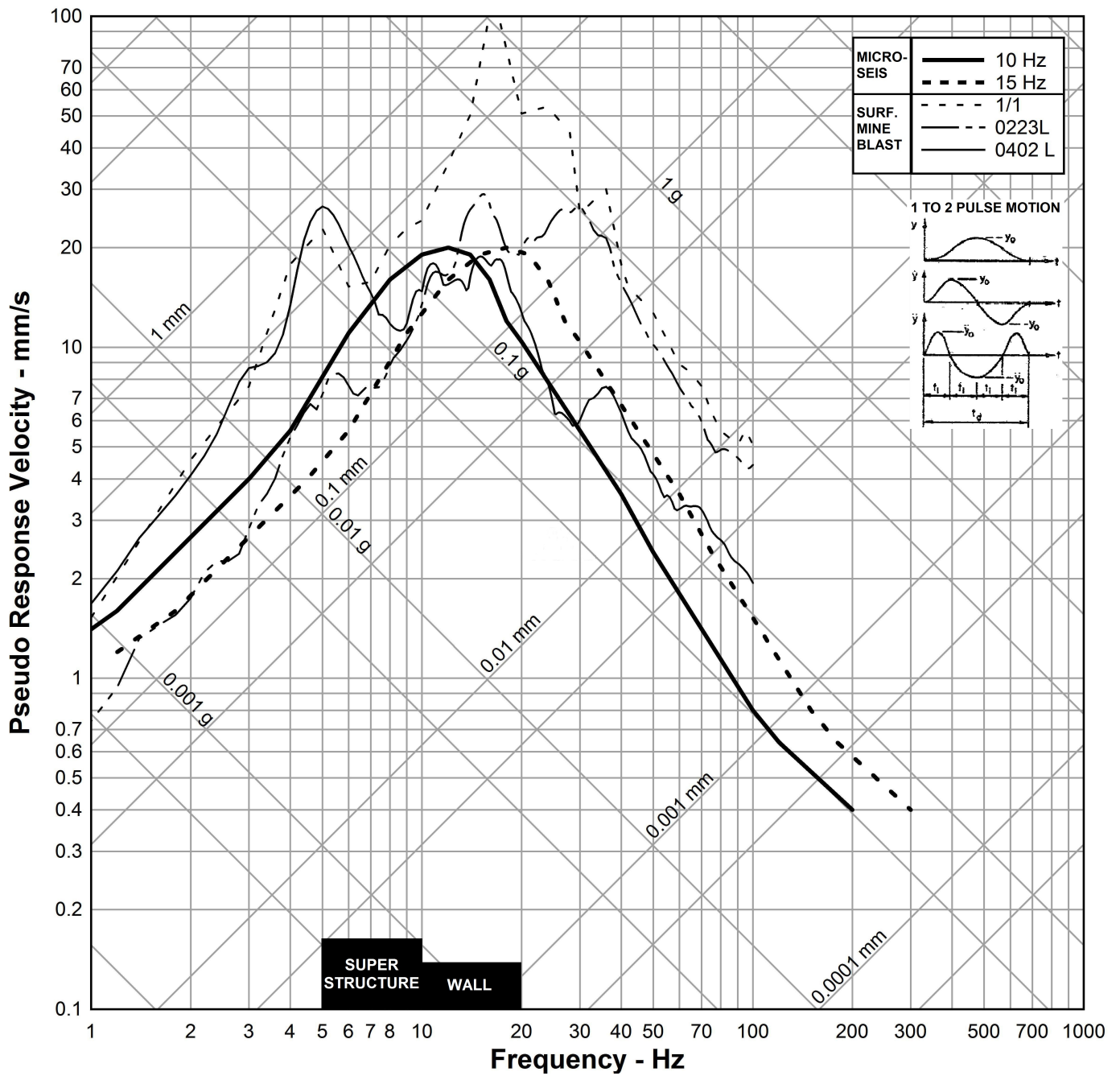


Figure 1: Comparison of pseudo velocity response spectra (damping = 5%) of ground motions from micro seismic events induced by long term reservoir depletion [1] with spectra from ground motions produced by large scale blasting for surface coal mining [7]

Because of similar response spectra, observations of crack response to blast-induced motions in this paper can be employed to describe expected crack response to production-induced motions. If two ground motions produce the same pseudo velocity (y axis of response spectrum) at the natural frequency of a structure or its components (x axis), they will produce the same structural response and thus have the same potential to cause cracking in the structure. Ground motions that produce smaller pseudo velocities at these natural frequencies have lower potential to induce cracking. Thus expectations regarding crack response to production-induced microseismic events can be described by comparing response spectra of those motions to those generated from the blast-induced motions. Therefore the documented crack response to the blast-induced ground motions in the following sections is key to the usefulness of this comparison.

#### 4. TEST HOUSE AND INSTRUMENTATION

The test house and locations of velocity and crack response instruments are shown in **Figures 2 and 3**. The walls, interior and exterior, of the test house are constructed with a standard wood stud frame and were covered with gypsum drywall board on the interior and aluminum siding and a 1/2 brick wall on the exterior. The house was founded on multiple level basements, beneath the middle and right [8].

More than a dozen dynamic crack deformation, velocity, and air-blast transducers were continuously monitored by computer to record structural velocity response as well as vibration and environmentally induced wall and crack deformation [8]. As shown in **Figure 2**, crack and wall deformation gauges, C6, C7, C9 and C10, were concentrated in the first floor living room. Ground motions (L, T, and V) particle velocities and air blast overpressure were measured outside at the northwest corner nearest the mining. Out of plane, or horizontal, wall motions (H1 and H2) were recorded at mid height and mid span of exterior (H1) and at interior (H2) first-story walls and at an upper corner of the second story (H3 and H4). Thus H1 & H2 measure wall response, while H3 & H4 measure superstructure response

Context (top) and details (bottom) of the instrument installation are shown in **Figure 3**. The living room walls contain the instrumented dry wall joints as shown in the drawing by dashed lines and center photograph by the white plaster coating over the paper taped joints. Horizontal and vertical un-cracked dry wall joints are C9 and C10. Un-cracked locations near the centers of the drywall sheets are C2 and C6. Drywall joint crack, C7, shown in the bottom right most photograph, is at the doorway (adjacent to C6) between the

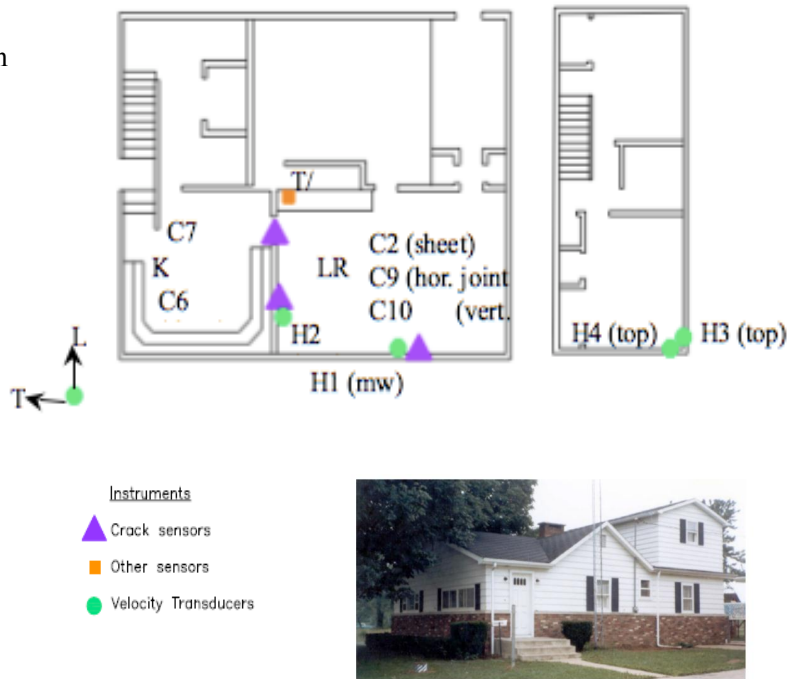
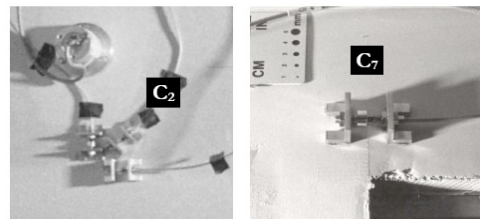
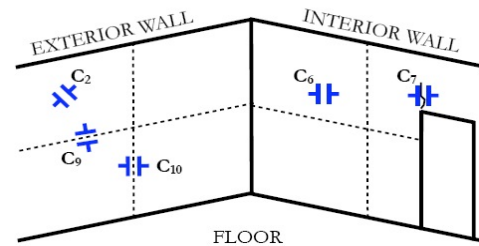


Figure 2: Photograph of test house and plan view showing instrument locations



**Figure 3:** Context and details of instrumentation: top - illustration of crack gauges spanning joints and cracks; mid - photograph of the instrumented room; bottom - details of velocity transducers and crack gauges

living room and the kitchen. This crack is not fully extended, and did not extend during the observation period. Out-of-plane, mid-wall motions were measured with Geospace HS1 LT velocity transducers with a flat response between 3 and 250 Hz shown in the bottom left photograph. Ground motions were measured with same velocity transducers.

Micro-meter deformation gauges, which measure distance between the sensor and target, allow recording of both static and dynamic deformation because of their long-term stability. Thus long-term phenomena such as change in crack width in response to daily, weekly (or weather-front related), and seasonal changes in temperature and humidity as well as foundation response to changes in the water table can be sensed by the same gauge that records the dynamic response to vibrations. A close-up view of gauge C7 is shown in the bottom right of **Figure 3**. This inductance deformation gauge measures the proximity of the aluminum target to the magnetic field induced by the sensor. These industrial-grade sensors, manufactured by Kaman, have a resolution of 0.0001 mm (0.004 mil or 0.000004 in.), and in the configuration shown can sense strains as small as 7 micro in/in ( $\mu\text{mm}/\text{mm}$ .) between bases spaced 15 mm (0.6 in) apart.

In addition to the extensive instrumentation, the house was thoroughly inspected for cracking before and after each blast in so far as possible. The house was divided into inspection grids, which were visually inspected by the same person in the same fashion in each instance over a period of some 6 months. No new cracks or extensions, not even cosmetic, were observed through 04 April when observation of crack response ceased. The 25 year old project report [6] has been scanned for archival purposes and is available for public inspection at [www.iti.northwestern.edu/acm](http://www.iti.northwestern.edu/acm).

## 5. TIME HISTORIES AND RESPONSE SPECTRA OF COAL MINE BLASTING GROUND MOTION

**Figure 4** presents time histories of ground motion (L,V,T in upper third), wall (H1 & H2) and superstructure (H3 & H4) velocity response in the middle third, and crack C7 and the most active wall board joint (C10) in the lower third. These excitation and response motions are those associated with the shots on 23 Feb and 2 April with low dominant frequencies of horizontal ground motion and greatest super structure response (H3 & H4). Peak particle velocities were 10 mm/s in the longitudinal direction. Time of the peak values are encircled in the figures. These time histories show that the higher frequency components are most effective in exciting the higher natural frequency walls (H1 & H2) and the lower frequency ground motions are

most influential in exciting the super structure (H3, H4). As shown in Table 1, the dynamic crack responses are proportional to the peak particle velocity. The vertical drywall joint (C10) responds the most and is more responsive than the horizontal joint (C9). However, its response is still smaller than that of the cracked joint (C7).

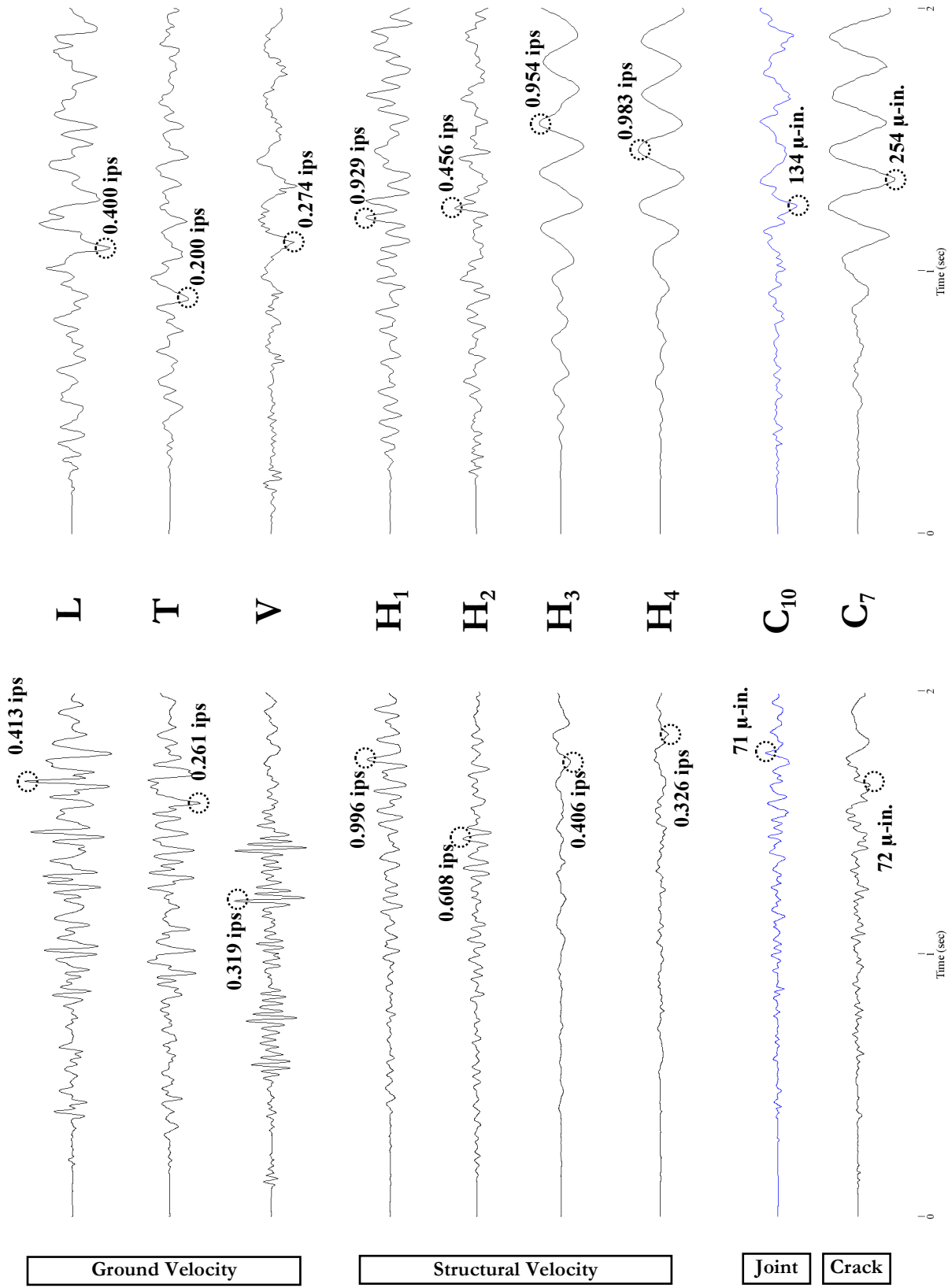
## 5. COMPARISON OF CLIMATOLOGICAL AND VIBRATORY RESPONSES

**Figure 5** compares four months of responses of the 2 un-cracked (C9,C10) and one cracked (C7) drywall joints, and 2 un-cracked drywall sheets (C2,C6) to temperature and humidity-induced, climatological effects. Variation in temperature and humidity inside and out is presented on the bottom. Joint, crack and sheet responses are plotted to the same scale at the top for comparison. Responses to other longer term environmental effects such as changes in the ground water table and frost heave at this structure are described in Dowding [8]. These responses are also compared to those of some 20 other structures and more than 30 cracks in Dowding [9].

Responses of the center of drywall sheets (C2,C6) are small, and response of positions such as these are regularly used as the null response. The null response describes the response of the sensor metal and un-cracked mounting material to changes in temperature and humidity. Comparison to the crack response (C7) shows that dry wall sheet response is so small as to be inconsequential compared to the crack response. It is also small compared to the response of the paper tape joints.

Responses to long-term climatological effects of the un-cracked, literally paper-thin, plaster covered (and thus weak) drywall joints (C9, C10) at the test house are less than 1/10th that of the cracked drywall joint (C7). Significant changes in exterior humidity, marked with circles, seem to drive the largest long-term crack response. It is reasonable for changes in humidity to produce crack and joint response because of the response to changes in humidity of wooden wall frames to which the sheets are attached.

These long-term measurements, spanning some four months, show that un-cracked weaknesses in wall covering are less responsive to long term, climatological effects than other cracked locations. The same is true for vibratory response as shown next.



**Figure 4** - Time histories of ground motion, structural response, and cracked (C7) and uncracked drywall joint response (C10). Low frequency excitation show joint response follows the motion of the upper story. 2/23/87 on the left and 4/2/87 on the right. (1 ips = 25.4 mm/s, 1 μ-in = 0.025 μm)

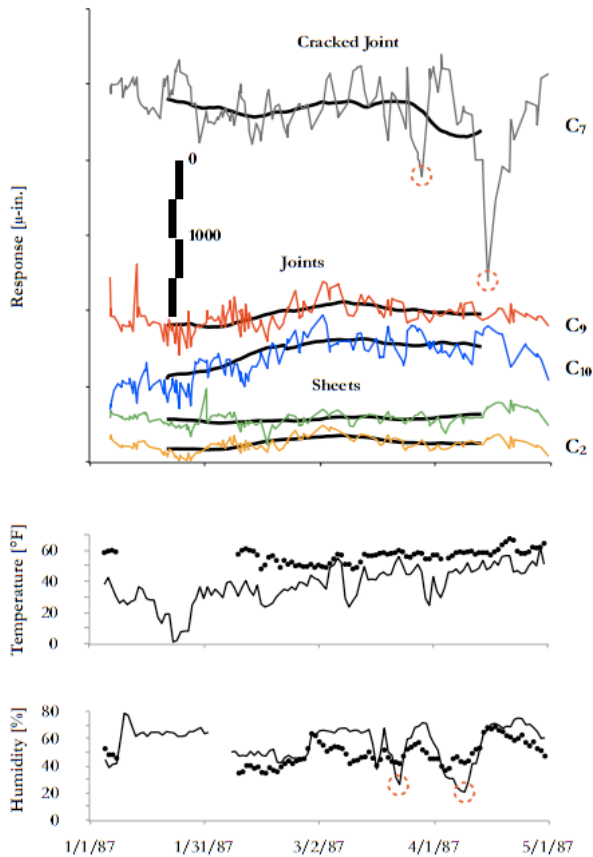


Figure 5: Crack and Drywall Joint Responses Compared with Time Variation of Temperature and Humidity. Indoor Temp and Humidity (dots) are less variable than Out of Doors (solid line). Crack (C7) is highly responsive to large, sustained drop in humidity at the end of April.

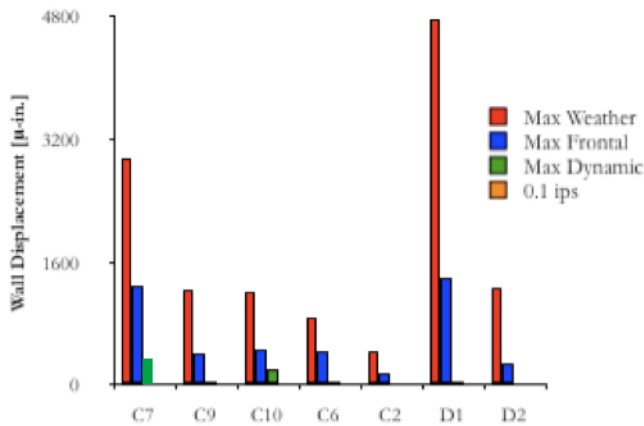


Figure 6 - Bar chart comparison of crack/joint/sheet response induced by weather and dynamic motion

Even for high PPV (10 to 19 mm/s) and a mix of low (4 to 8 Hz) and higher frequency (9 to 28) excitation motions, climatological response is greater than vibratory response for un-cracked wall weakness (dry wall joints) and cracks as shown by the bar chart comparisons in **Figure 6**. The ratio of vibratory response to climatological effects is small even for low frequency excitation events. This ratio is approximately 0.1 for typical weather and typical blast events and even smaller for extreme low humidity events such that in April as described in Dowding [8 & 10]. Cracked joints are seen to respond more than un-cracked joints to both vibratory and climatological drivers. Large response of cracks is not unexpected. The cracking of wall covering provided by the drywall and its weakest element, the paper-thin joints, can often be a function of the structural deformation beneath “the wall cover.” Deformation of the underlying structural interface or element is unlikely to be affected significantly by a thin covering.

## 6. DISCUSSION

Ground motions from micro seismic events associated with some human activity, industrial facility or resource recovery are a result of unique circumstances and as such should be considered to be source specific. In addition to source specificity, evaluation of resulting ground motions should be based upon considerations of amplitude, dominant frequency, and number of significant pulses of the ground motion. Such considerations are included in time histories of the ground motion which allow the calculation of pseudo velocity response spectra as compared in this paper.

As shown in this paper, residential structures are naturally resistant to ground motions that exceed 10 mm/s. Not even cosmetic cracks are produced by ground motions described in this paper. Other studies by the US Bureau of Mines [9] that addressed response of weak wall coverings of residential structures to blast vibrations should not be overlooked when assessing the importance of activity induced micro seismic events.

Typical changes in humidity and temperature produce far more crack response than typical vibrations. This observation sheds light on the absence of observations of cracking at particle velocities below 12 mm/s [10]. At some time in the past climatologically induced distortion has already opened cracks further than at present and typical vibrations do not induce sufficient distortion to exceed this historical state. This influence of weather as well as occupant activity should be taken into account

when assessing the impact of resource recovery activities.

## 7. CONCLUSIONS

Similarity of ground motion characteristics of micro seismic events from oil field production activities and low excitation frequency surface coal mining blasting allows experience to be transferred from mining to petroleum production. Large surface coal mine blasting events produce ground motions and pseudo velocity response spectra similar to that from unusual oil production events. Effects of and structural response to these surface coal mining events can be summarized as follows:

- 1) Dynamic crack responses are an order of magnitude smaller than those induced by changes in temperature and humidity from a passing weather front.
- 2) Cracks respond more than weak un-cracked joints to both ground motions and climatological effects
- 3) Low frequency (~ 5Hz) ground motions that exceed 10 mm/s did not extend a highly responsive crack nor did they produce new cracks in the weak, paper-plaster joints between sheets of gypsum wall board.

## 8. ACKNOWLEDGEMENTS

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