The Real Relationship Between Cracks and Vibrations: Are Cracks in Buildings Really Created by Vibrations?

Thierry Bernard, TBT

Abstract

It was in the 1980s that USBM published one of the first regulations to protect constructions from the effects of vibrations caused by mine blasts. Several countries have made their own regulations or recommendations since then with vibration limits that are often lower. However, on many sites, operators choose vibration limits that are lower than those of the existing standards, in order to limit the number of complaints received. The real question is how can we know what level of vibration is susceptible to create or worsen an existing crack in a construction. MCM, to the north of Quebec, is working a deposit on the periphery of the town of Malartic. Within the scope of its environmental monitoring programme, together with the joint monitoring committee, MCM has equipped four sample houses for over 18 months, in order to learn if there is a relationship between the evolution of damage to existing constructions and the seismic levels of vibrations created by mine blasts. The publication presents the results of this unique study that has analyzed millions of measurements (seismic, extensometric, and temperature) to define what relationship exists between the levels of vibration and the movement of cracks. Some surprising results versus some published previously (see ref) might change our perception of the subject.

Scope

It was in the 1980s that USBM published one of the first regulations to protect constructions from the effects of vibrations caused by mine blasts. Several countries have made their own regulations or recommendations since then with vibration limits that are often lower. However, on many sites, operators choose vibration limits that are lower than those of the existing standards, in order to limit the number of complaints received. The real question is how can we know what level of vibration is susceptible to create or worsen an existing crack in a construction. MCM, to the north of Quebec, is working a deposit on the periphery of the town of Malartic. Within the scope of its environmental monitoring programme, together with the joint monitoring committee, MCM has equipped four sample houses for over 18 months, in order to learn if there is a relationship between the evolution of damage to existing constructions and the seismic levels of vibrations created by mine blasts

Data Acquisition

In order to carry out this study, MCM fully equipped four houses that were thought to be representative of the chief types of existing disorders, i.e.: cracks in structural parts (foundations, load-bearing walls) and cracks in non-structural parts (indoor wall-covering). The buildings were equipped with five types of instruments to measure the static opening of cracks, the dynamic opening of cracks, building tilt, seismic tremors and temperature.

The static opening of cracks

The static data show the measurement of the opening of cracks on a regular time basis. Depending on the sensors, the measurement is taken every 2 hours (12 times a day) or every 12 hours (twice a day).
The photograph below (Figure 1) shows an "extensometric" type sensor which measures the gap or the opening of the crack.

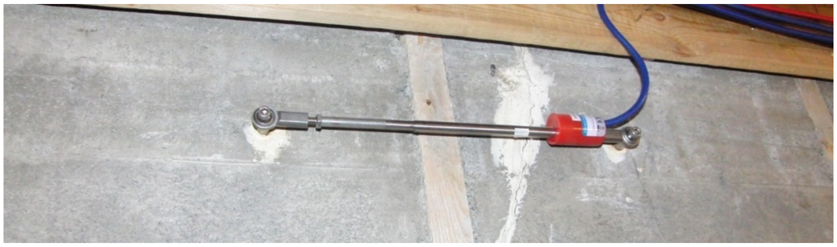


Figure 1: Extensometer

The graph below (Figure 2) illustrates the movements of an extensometer in house #1 according to time.

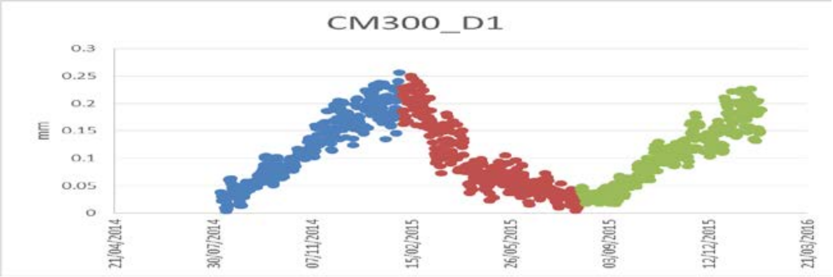


Figure 2: Example of the evolution of the opening of a crack

The dynamic measurement of the opening of cracks

The dynamic data represent the evolution of the opening of the crack in a short lapse of time (30 seconds). The measurement is taken 100 times a second with an extensometer and is triggered by the recording of seismic sensors (Figure 4), which in turn is triggered by the vibrations of the mine blasts. The graph below (Figure 3) illustrates a dynamic measurement of the opening of a crack throughout time.

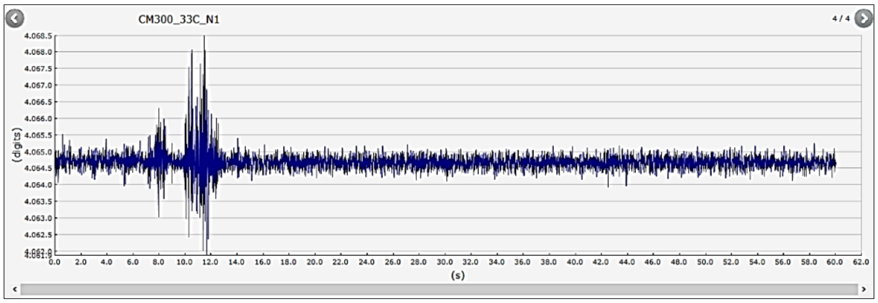
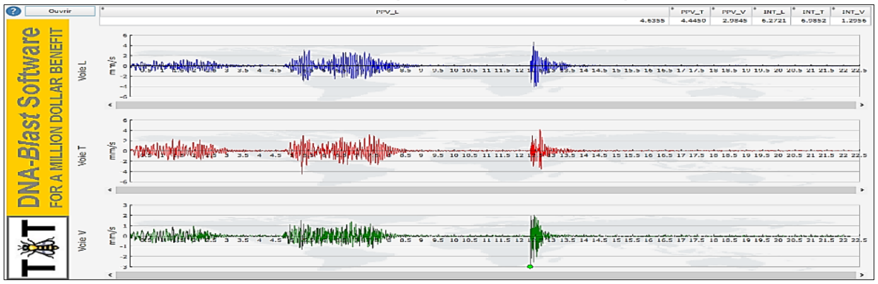


Figure 3: Example of the dynamic evolution of a crack with no effect

It should be noted that the opening of the crack vibrates with the rhythm of the vibrations in the ground (See Figure 7) and that after the blast, the opening returns to its original value.



PPV_L	PPV_T	PPV_V	INT_L	INT_T	INT_V
4.6355	4.4450	2.9845	6.2721	6.9852	1.2956

Figure 4: Recording of vibrations associated with the measurements of an extensometer

Measurements of the tilt of buildings

The tilt of some building is measured via a tilt meter (Figure 5). This equipment measures the variation of the angle of the construction compared with the vertical axis. The measurement is taken every 12 hours (twice a day).

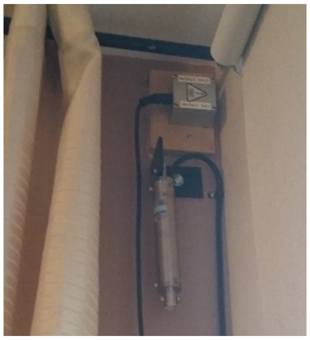


Figure 5: Tilt meter

Seismic data

Seismic sensors are installed in each house (outside in the ground, on the foundations and on some walls). They enable us to measure the seismic levels of the waves emitted by mine blasts. (Figure 6 & 7)

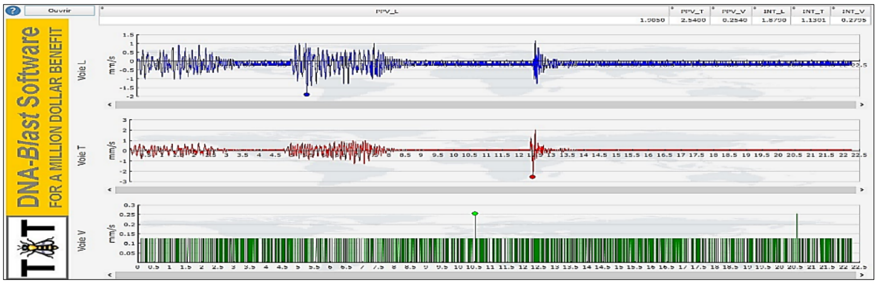


Figure 6: Vibration sensor installed / Figure 7: Example of a seismic recording
on a load-bearing wall of house #1

In this study, to analyse the evolution of structural cracks, we have solely considered the sensors installed in the ground or directly on the foundations or on a load-bearing wall of buildings. Other seismic sensors were installed on wall coverings, or finishing panels inside the buildings. Originally, they were installed to assess how mine blasts were felt by neighbouring residents. Their use for the study of the structural behaviour of housing is practically impossible due to the fact that they begin to vibrate according to the natural modes of the panels and their ranges do not necessarily reflect the range of the vibration of the load-bearing structures. The example below (Figure 8) shows the seismic signal measured in the ground at the corner of a house. The level of vibration at the foundations is 0.57 mm/s (0.022 in/s). When measured on a sensor on the finishing panel of the same house (Figure 9), the level reached 1.7 mm/s (0.067 in/s) and oscillations of the natural mode of the partition (red circle) were noted.

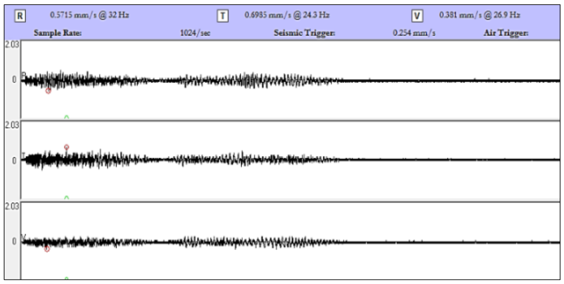


Figure 8: Vibrations measured in the ground

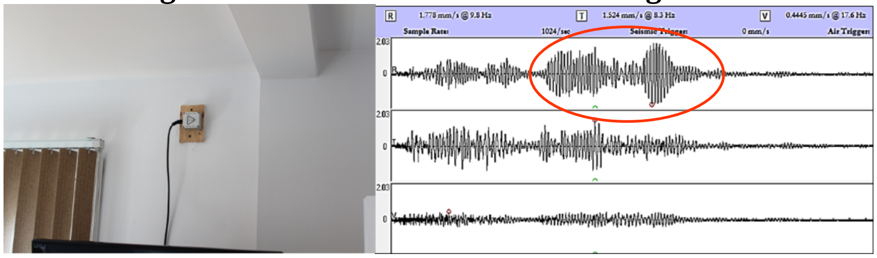


Figure 9: Vibrations measured on a finishing panel

Temperature

Each extensometer is equipped with a temperature sensor that measures the ambient temperature when the opening of the crack is measured. The graph (Figure 10) below illustrates the variation of the temperature measured near an extensometer in house #1.

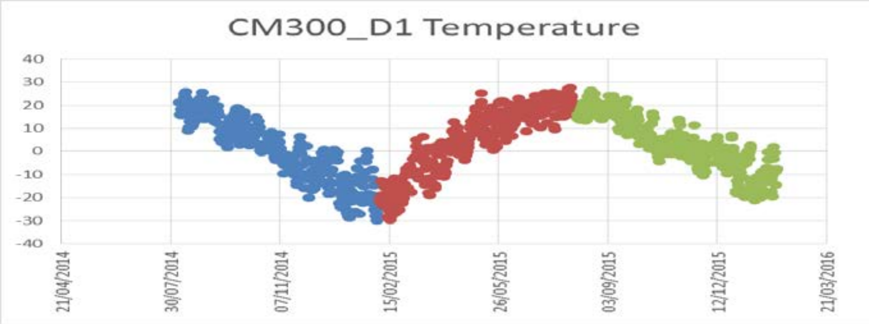


Figure 10: Evolution of the temperature near a crack

Please note the wide range of the evolution of the temperature, from -30°C to +30°C (-22°F to 86°F). Due to the length of time the instruments were installed from May 2014 to February 2016 and the high frequency sampling of the measurements, the analysis concerned several million measurement points. Therefore, the instrumentation system implemented was very comprehensive regarding the monitoring of existing cracks (Figure 11).

Figure 11: Example of the equipment of a house

Static data analysis

The extensometers data represent the basis of this study. They reveal the behaviour throughout time of existing cracks. The maximum variation range throughout the 21 months of measurement is widespread. We can note the low (1/10 mm)(0.004 in) or even very low (1/100 mm))(0.0004 in) ranges measured for houses #3 and #4 and the significant ranges (1 mm)(0.04 in) for the foundations of houses #1 and #2. In the example in Figure 12, it can be noted that the opening of the crack evolves by almost 0 to 0.25 millimetres (0.01 in) according to the seasons. In July 2015, the opening of the crack returned practically to zero as in July 2014 after having reached a maximum in January 2014. On the graph in Figure 12 it can be noted that in addition to the seasonal evolution, there is an evolution of the opening of the crack linked to the day/night cycle.

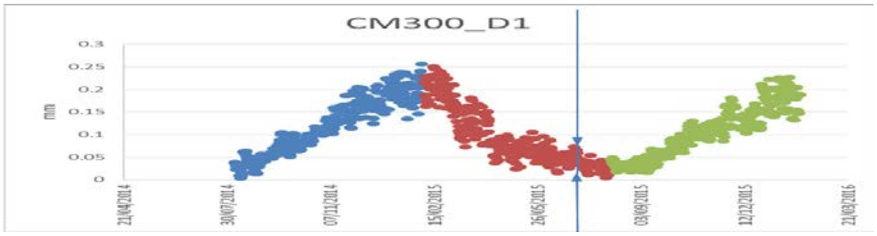


Figure 12: Example of static data

This type of behaviour is visible on all the extensometers installed in all the houses and reveals the behaviour of the crack according to the climatic conditions and in particular according to temperature.

The tilt meters variations in angle are extremely low, less than a tenth of a degree and also evolves according to the seasons (Figure 13)

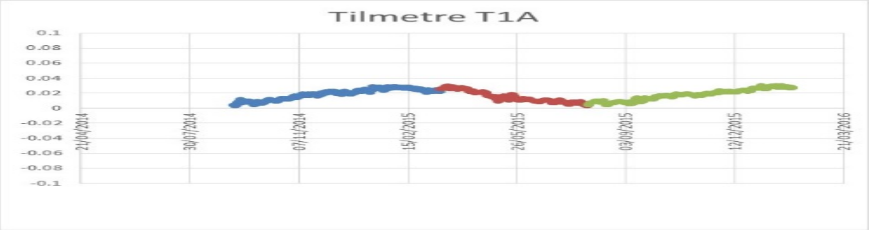


Figure 13: Example of the measurements of a tilt meter

Dynamic data analysis

Two scenarios are visible in the analysis of the dynamic data of the extensometers. The first one is an oscillating movement of the crak around its average value with no visible evolution. This is the case for the recording below (Figure 14). The vibration from the mine blast simply vibrates the crack and its average opening (red line) is not modified throughout time. The vibrations of this mine blast have no influence on the crack.

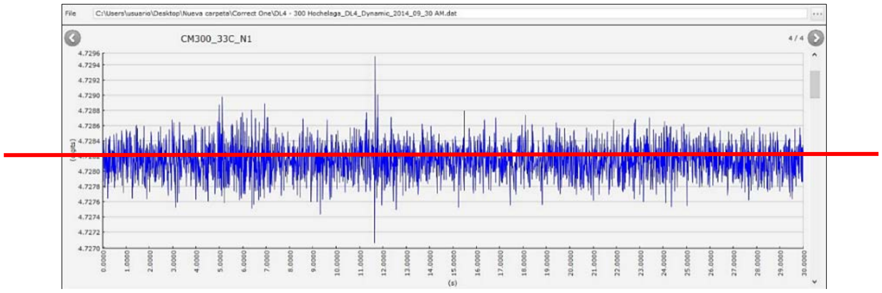


Figure 14: Vibration of a crack with no evolution

The second is in oscillating movement of the cracks with a visible evolution. In some cases (Figure 15) during the blast vibration, the average opening of the crack changes value. It can be noted that the jump, although clearly visible on the graph, represents a variation of 5 microns (thousandth of a millimetre) (195 microin). In addition, the opening will disappear throughout time (decreasing slope in dotted red in Figure 17) to return to its original value (in a few minutes) that can be found in the static values.

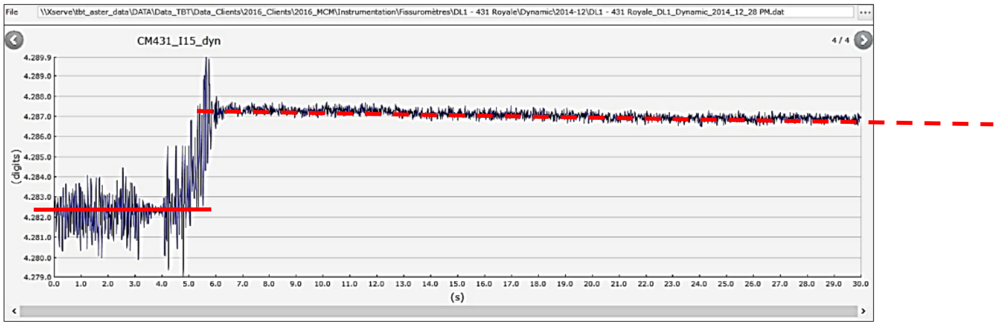


Figure 15: Vibration example of a crack with a simple evolution

In the example below (Figure 16), we can see several successive evolutions of the average value of the opening; the jumps are due to several blasts occurring one after another. In the same way as in Figure 15, the evolution of the opening of the crack is 6 microns (234 microinch), which is insignificant.

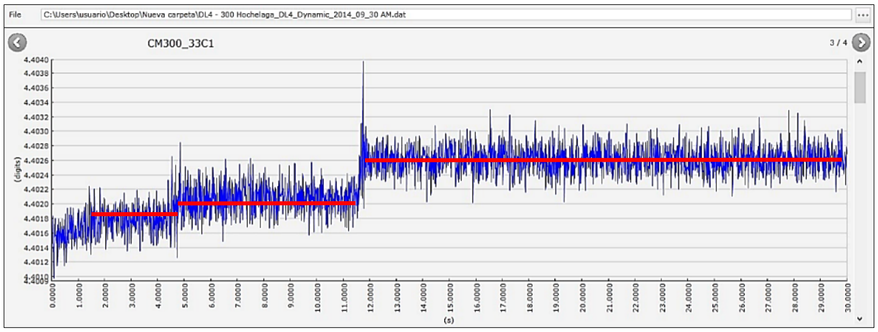


Figure 16: Example of the vibration of a crack with multiple evolutions

It can also be noted that in some cases, cracks close during the solicitation of the mine blast and also return to their original position after a few minutes. This behaviour depends on the orientation of the blast compared with the cracks. For all the data used, the maximum dynamic evolutions measured are all below 8 microns (312 microinch), except one value in hundredths of a millimetre (0.039 in). In all the cases, these opening evolutions of the cracks due to seismic solicitations are negligible compared to the variations due to the heat effect of the seasons or the day/night cycles.

The correlations

The search for a correlation consists of displaying the value of a parameter according to the other to see if there is a correlation between the two.The example below (Figure 17) illustrates the correlation between the opening of a crack and the ambient temperature nearby. On the "Value of the extensometer/temperature" graph, we can see that the points are lined up, which signifies that there is a linear correlation between the two parameters. Therefore, the opening of the crack is directly proportional to the temperature.

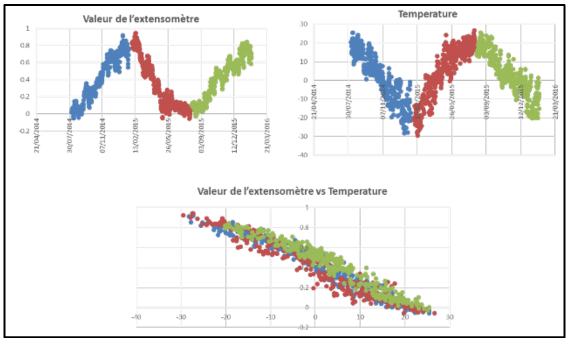


Figure 17: Example of the correlation Value of the extensometer/Temperature

Many correlations were tested and the main results are as follows. The correlation, as explained above, of the movement of the opening of the crack with temperature is the main correlation obtained. A linear correlation is noted in 77% of the cases (see the example in Figure 19). In 23% of the cases, it is almost linear and shows a linearity anomaly which, due to the extremely low absolute movement values (a few tenths of a millimetre) (0.0039 in), could be the result of the following:

- An erroneous consideration of the temperature due to the measurement being only on one side of the wall (whose thickness cannot be ignored, hence inducing heat inertia)
- A variation in the measurement: for the outside sensors not protected from the weather (frost, wind); for the sensors inside, a sudden rise in temperature
- A real evolution of the crack

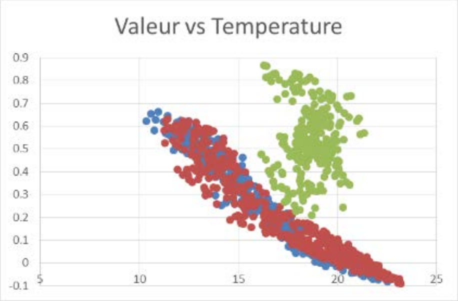


Figure 18: Example of an almost linear measurement

The search for a link between the dynamic movement of the crack during a mine blast, and the static opening of the crack, that was different to the opening resulting from the temperature. The first stage consisted of analysing all the dynamic measurements and measuring the main characteristic, i.e. the deviation of the opening measured between before the mine blast and after the mine blast. The dynamic data from an extensometer were automatically analysed by specially developed software. The dynamic opening of cracks disappears after a few minutes, so the next stage consisted of comparing the cumulative evolution of the dynamic opening of the crack with the static data corrected for the effect of the temperature, in order to check if the accumulation of energy could be associated with a static evolution anomaly. In the example below (Figure 19) there are 3 graphs. The top graph represents the static opening of the crack according to time. An arbitrary colour was allocated according to the visible opening cycles (increase) or closure cycles (decrease) of the crack. The second graph illustrates the correlation between the opening of the crack with temperature, which is perfectly linear, i.e. the crack dilates and contracts solely according to the variations in temperature. The colours of the previous graph were transferred to the points according to the dates. It should be noted that there is no visible anomaly. The third graph illustrates the cumulative dynamic opening of the crack according to time.

The same colours were transferred to the graph. It should be noted that there is no correlation between the cumulative dynamic values and the perfectly linear static values.

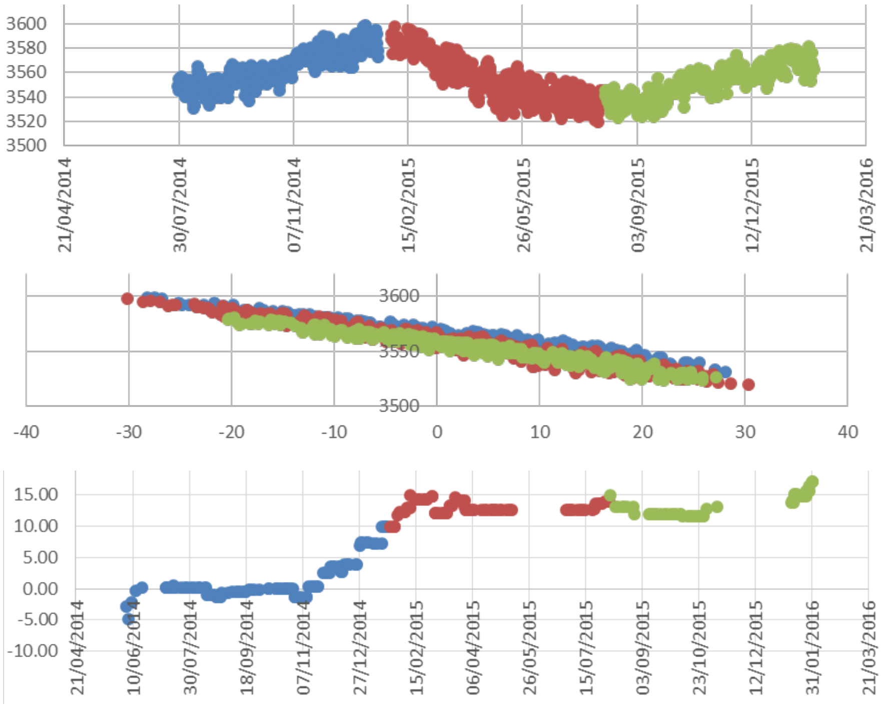


Figure 19: Analysis example between cumulative dynamic opening and static opening

For each extensometer, by tracing a graph whose horizontal axis represents the level of vibration (PPV) and whose vertical axis represents the dynamic opening of the crack in mm (or in), we obtain a graph of the following type:

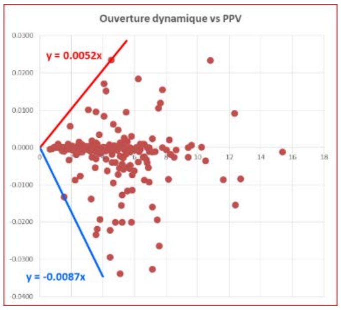


Figure 20: Example of the dynamic opening correlation (Y axis)/PPV (X axis)

In this graph we can clearly see that all the points are situated in a cone following the dynamic opening correlation of the crack according to the level of vibration. The maximum dynamic opening increases with the level of vibration. The straight red line represents the straight envelope (positive values) and is the expression of the correlation: maximum dynamic opening of the crack in relation to the PPV. The straight blue line represents the straight envelope (negative values) expressing the correlation: maximum dynamic closure of the crack in relation to the PPV. By making the hypothesis that this correlation (dynamic opening of the crack/level of vibration) continues to be linear for higher vibration levels, it is possible for each crack to extrapolate the level of vibration (Figure 21) that would lead to a dynamic opening of 0.2 millimetres (0.008 in) that represents an average value frequently quoted in reports as being a significant visible evolution threshold of a crack. As a result, we obtain a rough probabilistic PPV of 90 mm/s (3.54 in/s), which in some cases, might make some cracks evolve by opening 0.2 millimetres (0.008 in), a value which is significant when the solicitations are repeated. This value is taken as the hypothesis of a threshold that can dynamically change the crack beyond the elastic field, permanently.

WARNING: these values have no link with the level of vibration that might create a new crack in healthy material. To do so, we would need to attain the tensile breaking point, which for concrete, whose average compressive strength is 40 Mpa (5801 psi), and which has a density of 2.4, is approximately 4 000 mm/s (157.4 in/s).

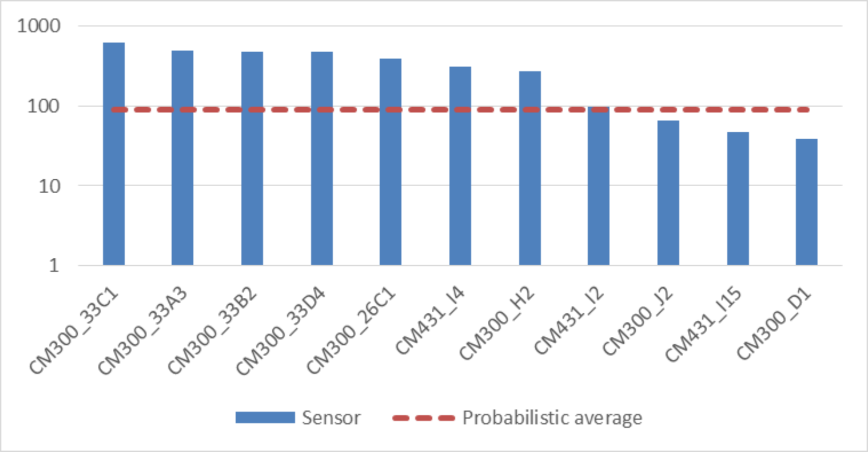


Figure 21: PPV (mm/s) susceptible to changing a 0.2 mm (0.008in) crack

Structural analysis of buildings

The structural analysis of a building requires us to understand its architecture, the type of foundations, the building method, and the materials in order to define the mechanical behaviour of the various parts. This analysis is carried out with drawings, existing calculation notes, different measurements, and in-situ trials or sampling. For this study, we undertook a "light" structural analysis with a minimum of investigations in order to have an idea of the origin of the existing problems and their possible evolution. For the 4 houses, we discovered that the main structural problems that existed before the measurement period were undoubtedly created by poor drainage of runoff water, causing ground subsidence. Cycles of freezing/thawing aggravate the phenomenon in areas that are not drained and amplify a differential movement of the foundations whose concrete walls are, a priori, not armoured.

Conclusion

Based on a relatively comprehensive equipment system for the surveillance of existing cracks, it has been possible to obtain the following findings:

The main evolution of the opening of cracks is linked to variations in temperature. The linear behaviour, the proportionality between the static opening of a crack and temperature, is clearly identified in 77% of the cases with opening variations of a few tenths of millimetres. The analysis of the dynamic opening of cracks (seismic solicitations) shows that cracks evolve with extremely low ranges (from a few microns to a hundredth of a millimetre). The opening is within the elastic field and the cracks return to their original opening a few minutes after the blasts. An extrapolation of this dynamic opening enables us to provide a rough probabilistic estimate of 90 mm/s (3.54 in/s), which in some cases, might make some cracks evolve by opening 0.2 millimetres (0.008 in), a value which is significant when the solicitations are repeated. According to the direction of the mine blasts with regard to the houses, the cracks can react by closing during the seismic solicitation. The 23% of almost linear behaviour between the temperature and the opening of cracks could certainly be explained, by improving the equipment system by repositioning the sensors:

- Extensometers outside buildings protected from frost and bad weather
- Temperature sensors inside outer walls.

Regarding the 4 sample houses, we found that the main structural problems, that existed before they were equipped, were most probably created by subsidence caused by runoff rainwater not being drained. The freeze/thaw cycles aggravate the phenomenon in non-drained areas and amplify a differential movement of foundations for which the concrete walls were a priori not armoured. All these factors have not enabled us to bring to light a significant and permanent evolution of an existing crack in a construction, due to the vibrations of a mine blast.

Acknowledgements

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