The curious case of Millikan Library:
Structural healing over 20 years' continuous seismic monitoring

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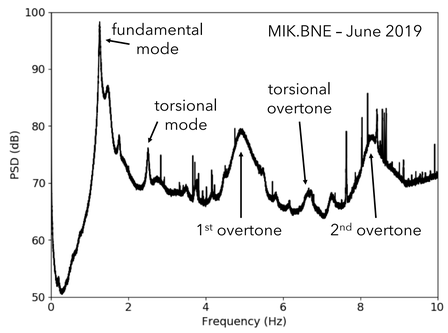
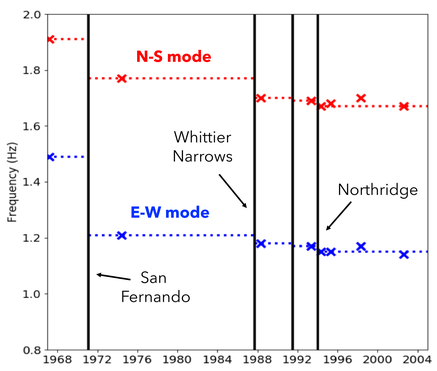
1. Background on Millikan Library

9-story reinforced concrete building

Strong-motion station CI.MIK on 9th story has been recording continuously since 2001





Forced vibration tests and earthquake strong motion records since 1967 show long-term reduction in natural frequencies

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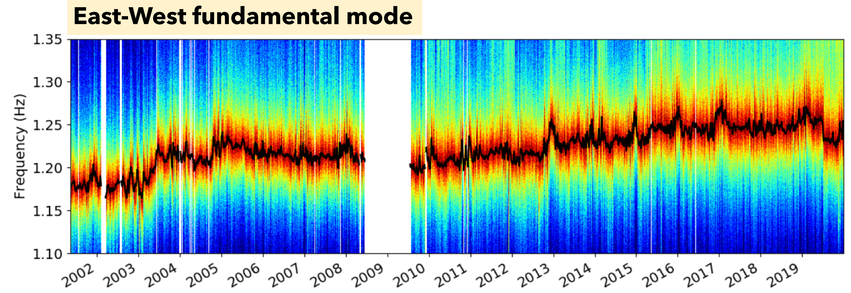
Permanent structural weakening after major earthquakes due to changes in the soil-structure system and/or minor structural damage

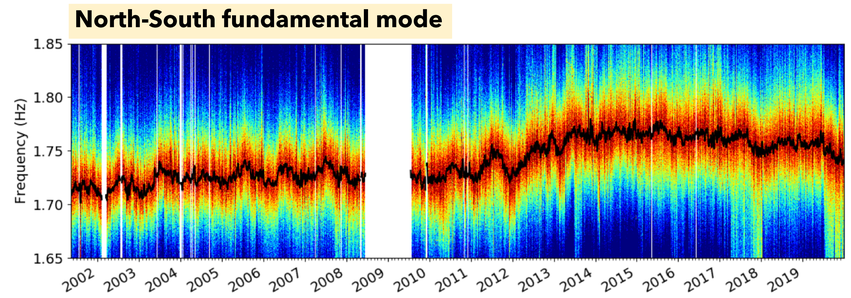
For more background, see Clinton et al. (2004) BSSA

2. Long-term structural healing: Increase in the fundamental frequencies

East-West fundamental mode



North-South fundamental mode



While abrupt increases in stiffness around 2003 can be connected to changes in the mass of the building from renovation work, the gradual and monotonic healing trend over 20 years is a robust and independent feature

Following Ridgecrest a small permanent reduction in the fundamental frequencies (weakening) is observed; whether the healing trend has continued after Ridgecrest is not yet clear

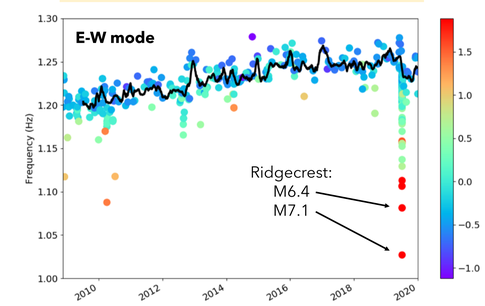
Over 20 years:

EW 6.8 % increase in frequency ⟹ ~14% increase in stiffness

NS 3.0 % increase in frequency ⟹ ~6% increase in stiffness

Millikan Library appears to have returned to a structural stiffness comparable to before the 1988 Whittier Narrows earthquake

Earthquake frequency vs. PGA



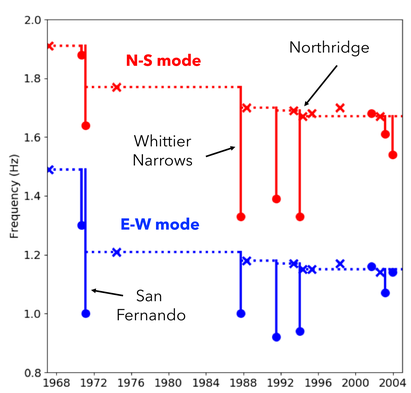
Fundamental frequency measurements from regional earthquakes >M3 correlate closely with ambient vibration results

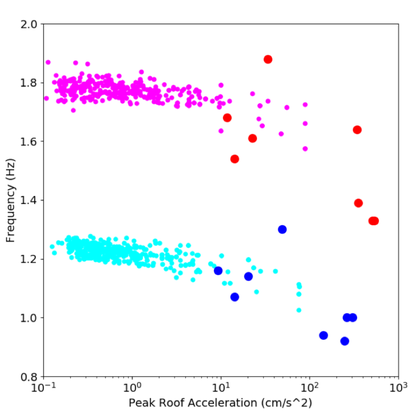
3. Non-linear response to strong motion

During strong shaking, the fundamental frequencies of Millikan library decrease temporarily by as much as 25%

Previous estimates of the non-linear response were limited to only eight regional earthquakes that triggered the strong motion system

Since 2001, ~300 regional earthquakes >M3 have been recorded on CI.MIK including the 2010 Chino Hills and 2019 Ridgecrest events





The transition between linear and non-linear response occurs around a peak roof acceleration of 1 cm/s²

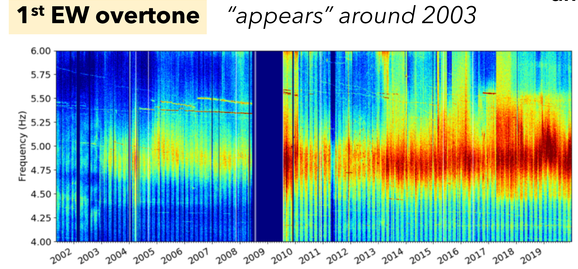
The slope of the non-linear response above 1 cm/s² is similar to previous results and does not appear to change over time

Non-linearity begins at a similar peak acceleration as where permanent structural weakening (hysteresis) becomes apparent

Other curiosities:

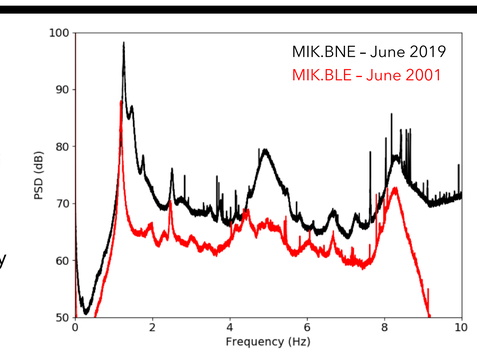
Pervasive changes in the response to ambient vibrations over 20 years

1st EW overtone *"appears" around 2003*

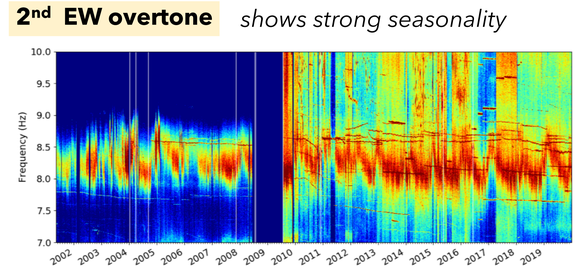


EW 1st overtone first appeared in 2003 when books were removed, reducing the mass of the library

EW 1st overtone changes in strength by a factor of 3 and changes in frequency by up to 5% over 20 years



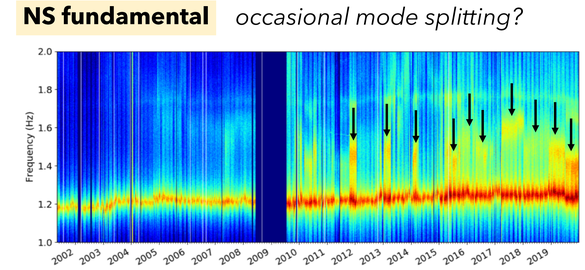
2nd EW overtone *shows strong seasonality*



EW 2nd overtone shows strong seasonality: higher in winter, lower in summer

NS fundamental mode has second peak that appears and disappears seemingly randomly and at different frequencies

NS fundamental *occasional mode splitting?*

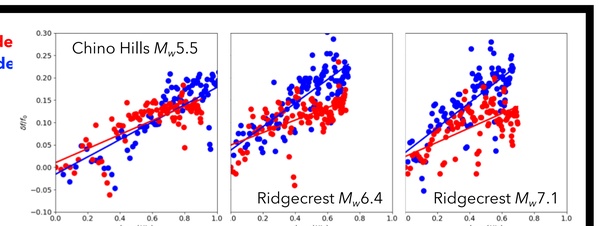


4. Short-term log-linear recovery

The fundamental frequency reaches dynamic minimum at time of maximum acceleration and remains low after shaking has subsided

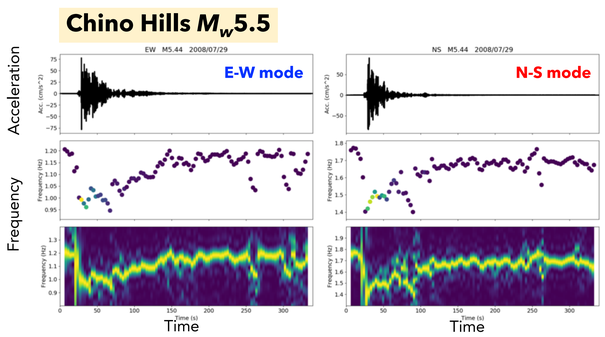
Log-linear time scale of short-term healing (order 5 mins) to ~95% of the original frequency

The N-S system recovers more rapidly than the E-W system

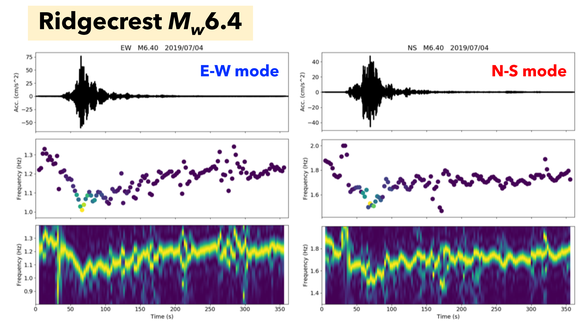


Recovery rate is similar for each mode among different earthquakes

Chino Hills M_w5.5



Ridgecrest M_w6.4

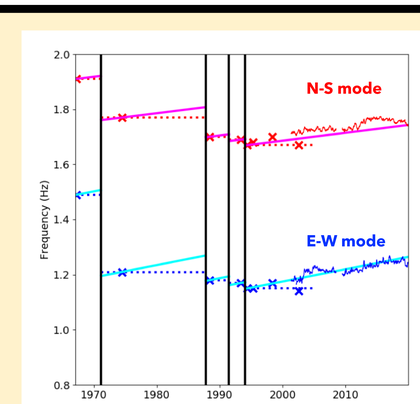


Preliminary conclusions

The EW and NS fundamental frequencies of Millikan Library have increased by 6.8% and 3.0% respectively since 2001.

If this healing trend is representative of the building's behavior, then past estimates of strong motion hysteresis may have significantly underestimated the degree of weakening (damage) during historical earthquakes.

Reinforced concrete structures are highly dynamic. Whether such extreme long-term changes in response are common in RC structures must be more widely investigated by the earthquake engineering community.



Future work:

Is the increase in the fundamental frequency due to changes in soil-structure interaction OR healing of the structure itself?

Currently we are working on seismic interferometry using CI.MIK (2001-present) and CI.MIKB (2009-present, in the basement) to isolate velocity changes of high frequency waves propagating in the structure which should be independent of the soil system