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Transient and Long-Term Changes in Seismic Response of the Natural Resources Building, Olympia, Washington, due to Earthquake Shaking

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The Natural Resources Building (NRB) in Olympia, Washington, was shaken by three earthquakes (Mw = 5.8, 6.8, and 5.0) between 1999 and 2001. Building motions were recorded on digital accelerographs, providing important digital recordings of repeated strong shaking in a building. The NRB has 5-stories above grade with 3 sub-grade levels and a ductile steel-frame elongated in the E-W direction. The upper two floors extend significantly beyond the lower 3 on the southern and eastern sides. N-S motions dominate the fundamental modal vibrations of the building system. In the 1999 Satsop M5.8 earthquake, the frequency of this fundamental system mode was 1.3 Hz during motions of 10% g. The frequency dropped to 0.7 Hz during the 2001 M6.8 Nisqually strong motions. Moreover, the Nisqually recordings reveal both numerous high-frequency transients of up to 0.18 g, several of which are visible on widely spaced sensors, and long-term tilts of some of the sensors. The weaker 2001 M5.0 Satsop earthquake motions showed the frequency remained depressed at less than 1 Hz for the eastern side of the structure, although the western side had recovered to 1.3 Hz. An ambient noise survey in 2008 showed the fundamental frequency of N/S vibrations remains about 1.0 Hz for the eastern side of the building and 1.3 Hz for the western side. These results suggest that in the Nisqually earthquake, the east side of the NRB suffered a permanent reduction in fundamental mode frequency of 37% due to loss of system stiffness by undetermined mechanism.

Keywords Building Response; Structural Monitoring; Earthquake Effects; Nisqually Earthquake; Seismology

1. Introduction

It is well known that strong earthquake shaking can cause structural weakening or failure of structural systems, components and structural members. Seismic recordings in structures offer possibilities for monitoring their state of health. From seismograms it may be possible to: (1) compare recordings before and after damage to identify significant changes in structural response that may serve as indicators of damage; (2) directly record the transient signals from the damage (e.g., Rodgers and Çelebi, 2005, 2006; Rodgers *et al.*, 2007);

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and (3) assess thresholds such as drift ratios as indicators of damage using the actual structural geometry, member cross-sections and material properties [Çelebi *et al.,* 2004]. Each approach has challenges, but the real-time approaches are becoming increasingly practical with improvements in recording and telemetry efficiency [Çelebi, 2007, Çelebi *et al.,* 2004, Porter *et al.,* 2006]. Buildings and bridges may be monitored by such techniques [Çelebi, 2006, 2007; Çelebi *et al.,* 2004; Masri *et al.*, 2004; Siringoringo and Fujino, 2006]. Case studies such as this study of recordings that might bracket both damaging and non damaging motions allow calibration of the usefulness of such monitoring.

Changes in structural response indicative of damage have been reported, albeit usually with sparse and sometimes only analog instrumentation. Examples include the Imperial Country Services Building severely damaged during the 1979 Imperial Valley earthquake [Rojahn and Mork, 1981], and from buildings damaged by the 1994 Northridge earthquake (e.g., Anderson and Filippou, 1995; Naiem, 1998). An instructive and rare example is provided by a 7-story reinforced concrete structure shaken repeatedly over 24 years [Todorovska and Trifunac, 2008]. Vibrational frequencies observed in structures are affected by, and thus contain information about, structural stiffness and design, both within the structure and including the soil-structure interaction. Therefore, they can be problematic to assess because the "fixed-base frequency" of the building itself, may differ from that of the "soil-structure system frequency," and both must be separated from the frequency content of the seismic waves incident at the base of the building, which will in general vary from earthquake to earthquake. In addition, individual channels of motion have spectral holes and peaks due to non structural vibrations and difficult-to-model higher modes. At the building discussed in this article, we are fortunate to have multiple digital recordings at several levels in the building, so we are able to average out much of the noise. We can also use recordings from the lower building levels as a reference to remove the incident ground motions, and thus to isolate the structural response at higher levels.

Some studies have concluded that most increases in period due to shaking arise from damage to the ground around the building, and are temporary [Trifunac *et al.*, 2001b]. In contrast, there is one clear case of permanent period drop from 2.2 to 1 Hz in the Imperial County Services Buildings, which suffered serious damage in the 1979 Imperial Valley earthquake [Rojahn and Mork, 1981; Bradford, 2006; Todorovska and Trifunac, 2007]. Changes in period up to 40% in a survey of strongly shaken buildings using analog records have been reported, although without checking back later to see whether the changes are permanent [Li and Mau, 1997]. A temporary drop of 60% has been inferred from a single-station analog record in the case of a badly damaged building, and the mode is seen to return to its pristine period just weeks later [Trifunac *et al.*, 2001a]. Detection of permanent changes in response during digitally recorded earthquakes has been elusive [Rodgers and Çelebi, 2006].

Changes in resonant period lasting only minutes to days of 10–20% due to mild shaking, wind, rainfall, and temperature changes without significant damage have also been demonstrated [Clinton *et al.*, 2006; Kohler *et al.*, 2005, 2007; Luco *et al.*, 1987; Todorovska and Al Rjoub, 2006]. Repeated measurements widely separated in time in another study from analog (and digital) records showed 20% variations in estimates without a clear evolution or relation to shaking [Rodgers and Çelebi, 2006].

Direct recording of high-frequency transients within strong shaking also presents challenges, as the high-frequency nature of some damage signals can be problematic to recover from analog recording, and interpretation from single instruments is fraught with ambiguity. Only a few examples are of sufficient recording quality to examine [Rodgers and Mahin, 2006]. The extent of damage that crackling and response changes might reveal has proven difficult to ascertain [Krishnan *et al.*, 2004, 2006; Lee and Foutch, 2002; Righiniotis and Imam, 2004; Rodgers and Mahin, 2006].

The greatest challenge to interpretation of transients is the lack of digital recordings of past strong shaking to establish a baseline [Çelebi, 2007; Rodgers and Çelebi, 2005]. We ameliorate this shortcoming by describing a unique dataset of four recordings from a moderately well-instrumented building with digital dataloggers, the NRB Building in Olympia, Washington. Many buildings, mostly in California, now are well instrumented. However, no strong earthquakes suitably located with respect to relevant structures have followed the conversion to digital instrumentation in the late 1990s [Dunand *et al.*, 2004].

2. The Structure and Dataset

The NRB is a 549,500 sq. ft. structure, erected in 1992 to existing seismic code standards. Pursuant to Washington Seismic Safety Advisory Committee recommendations, the NRB was instrumented with multiple channels of strong motion accelerometers in a project jointly funded by the Washington Department of Natural Resources and the U.S. Geological Survey [Walsh, 1993]. The building has an unusual and complicated design. It is built into a hillside comprised by stiff soils of medium to dense sand to a depth of about 20 ft with dense silts below. The building has 5 above-grade stories and 3 partially or completely sub-grade parking floors (Swanson *et al.*, 2010; Fig. 1). The building is supported by steel beams, steel columns, and concrete shear walls on pile foundations. The 4th and 5th story are arcuate in plan and have cantilevered sections that extend beyond the lower 3 floors on the eastern and southern sides of the building, supported by steel trusses onto long concrete columns. The building is designed to resist lateral forces with concrete shear walls from basement to roof in each of 3 "cores" in the eastern, western, and central sections of the building (see Fig.1). Welded steel moment frames in the east and west arcuate sections are used to provide further lateral force resistance. There is an additional wedge-shaped "penthouse," or roof structure atop the 5th story roof, with a smaller footprint and that houses building mechanical systems not offices. In overall aspect, the building is elongated in the E-W direction, but is asymmetric and the deformation modes, which we did not compute for this study, may be expected to be complicated. Further structural details of the building are summarized by Swanson *et al.* [2010].

At the time of the 1999 Satsop earthquake, the building motions were recorded by five separate dataloggers. The clocks of the various dataloggers were not synchronized, and one datalogger triggered very late, however, the motions of the rest of the channels were recorded. Subsequent to 1999 and prior to the 2001 Nisqually earthquake, the separate dataloggers were replaced by a single "Mt. Whitney" recording system. In the February 2001 Nisqually earthquake, several of the 16 channels failed to trigger and thus did not record; only 11 records were recovered. All 16 channels recorded the June 2001 Satsop earthquake. A schematic map of the sensor locations in the building since 2001 is also shown in Fig. 1. Most of the sensor locations remained the same during the instrument upgrade, but a few of the recording sites for the 1999 Satsop earthquake may vary from current locations by up to a few feet, and for this study we used information from the NSMP to reconstruct the 1999 locations [Christopher Stephens, USGS, personal communication, 2008]. The sensors are all Kinemetrics force balance accelerometers with a range of ±2 g. They are attached by bolts secured into concrete of either the floor (in the case of the parking garage sensors) or structural elements. Data from the three earthquakes examined may be obtained from the USGS National Strong Motion Program website. Tables 1 and 2 summarize the data sets, event descriptions and peak accelerations at basement and roof of the DNR Building.

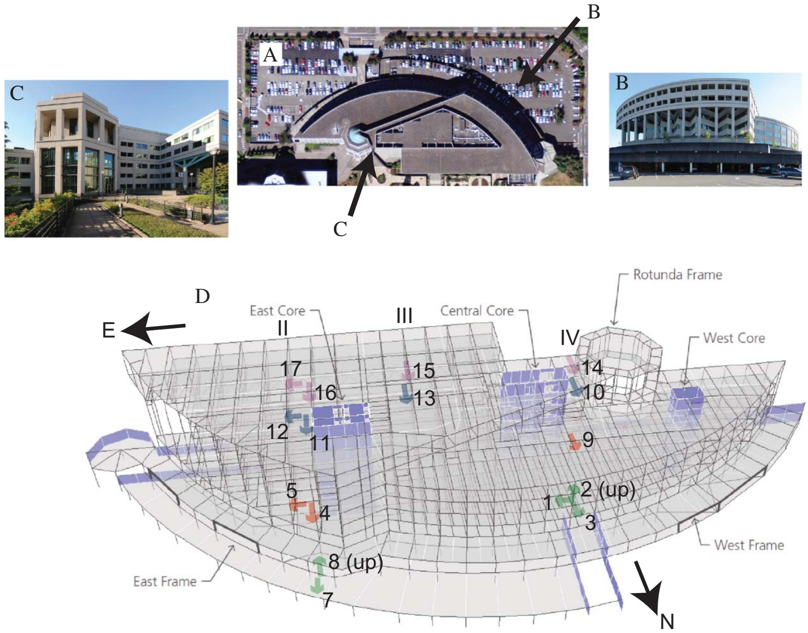

FIGURE 1 (A) Aerial view of the NRB; North is up. The overall dimensions of the building are approximately 180 m long in the East-West direction, and 60 m at the widest North-south point. (B) View of the east end of the NRB from the NE, showing the cantilevered upper stories and irregular plan of lower floors (from Swanson, 2010). (C) View to the NE showing main entrance to NRB at southwest part of building; note cantilevered 4th and 5th floors. (D) Wireframe schematic diagram of sensor locations and orientations in NRB during collection of datasets 2–4 (from Swanson, 2010). This diagram also shows the main structural elements of NRB. Blue shading shows locations of the concrete shear walls in the labeled "cores" Emphasized frame elements labeled "frame" show the positions of moment-resisting welded connections. Each accelerometer component may be assigned a 3-character location-orientation code where the first and second characters designates its vertical and horizontal position in the building, respectively, and the third its orientation (N, E, Z). Sensors are in roughly 4 vertical planes (1, 2, 3, 7, & 8 are on grade; 4, 5, & 9 in the parking structure; 10, 11, 12, & 13 are near the top of the 4th floor or base of the 5th floor; and 14, 15, 16, & 17 are within the penthouse above the 5th floor). They are also roughly in 3 horizontal planes (1, 2, 3, 9, 10, and 14 are in plane labeled "IV", the westernmost plane; 13 and 15 in the middle, labeled "III", and 4, 5, 7, 8, 11, 12, 16, & 17 in plane "II" on the eastern side of the building. The sensor numbers correspond to: 1 = B4_E, 2 = B4_Z, 3 = B4_N, 4 = P2_N, 5 = P2_E, 6 = unused, 7 = B2_N, 8 = B2_Z, 9 = P4_N, 10 = 44_N, 11 = 42_N, 12 = 42_E*, 13 = 53_N†, 14 = R4_N†, 15 = R3_N†, 16 = R2_N†, and 17 = R2_E†. (* indicates that orientation is reversed, and † indicates that the component failed to record the Nisqually earthquake) (color figure available online).

All three earthquakes we examine were deep, 40–60 km, and at hypocentral distances of about 60 km from the NRB. Motions in the three earthquakes differed greatly because of their magnitudes. Peak horizontal accelerations in the lower parking garage levels were 0.02, 0.19, and 0.006 % g for the 1999 Satsop, 2001 Nisqually, and 2001 Satsop earthquakes, respectively. The highest peak accelerations were all on the upper floors, 0.20, 0.42, and 0.04 % g for the 3 earthquakes, respectively.

TABLE 1 Datasets, event characteristics recorded at NRB building [Δ = hypocentral distance, km (epicentral distance in parentheses)]

Data Set	Earthquake	Date	Size	**Δ** (km)
1	1999 Satsop	07/03/1999	5.8 (Mw)	59.4 (43)
2	2001 Nisqually	02/28/2001	6.8 (Mw)	62 (19)
3	2001 Satsop	06/10/2001	5.0 (Ml)	63.1 (48.4)
4	Ambient	01/23/2008	–	–

TABLE 2 Channel locations, names, and locations for earthquake motions recorded at the NRB building. Descriptions and peak accelerations (in cm/s^2) from National Strong Motion Project website

Fig 1. Channel #	Channel code	Descriptive location in building (from NSMP)	Notes	1999 Satsop, pk. acc.	2001 Nisqually pk. acc.	2001 Satsop, pk. acc.
1	B4_E	P3 (Ground) Level at M-16.5	episensor	42.4	144.3	−15.36
2	B4_Z	P3 (Ground) Level at M-16.5	episensor	−16.4	−92.25	−6.10
3	B4_N	P3 (Ground) Level at M-16.5	episensor	36.8	215.4	−11.81
4	P2_N	P2 (Ceiling) at K/L-27		69.4	−271.50	−32.11
5	P2_E	P2 (Ceiling) at K/L-27		199.1	−252.70	18.33
7	B2_N	P3 (Floor) at F-27		100.8	−240.50	−20.87
8	B2_Z	P3 (Floor) at F-27		−69.9	−81.22	−6.53
9	P4_N	P2 (ceiling) at M-16.5		76.6	229.4	−24.04
10	44_N	5^{th} level (Floor) W at M-16.5		69.6	374.40	−8.52
11	42_N	5^{th} level (Floor) E at K/L-27		55.6	−252.90	5.41
12	42_E	5^{th} level (Floor) E at K/L-27	rev. pol.	182.4	322.80	−6.90
13	53_N	5^{th} level (Slab below raised floor) at L-22		48.9		−9.49
14	R4_N	Penthouse (ceiling) at M-16.5		−38.5		−27.27
15	R3_N	Penthouse floor at L-22		103.1		42.03
16	R2_N	Penthouse floor at K/L-27		43.3		−27.23
17	R2_E	Penthouse floor at K/L-27		−22.3		13.38

The strength of shaking in this building during the 2001 Nisqually earthquake is clear from anecdotes [Lasmanis, 2001], but only minor, non structural, damage was found by physical inspection [Smith, 2001; Filiatrault *et al.,* 2001].

We also present results from a recording of ambient building motions made in early 2008 using the permanent building sensors that recorded the earlier earthquake, and analyzed using the same spectral techniques as the earthquake recordings, with the goal of identifying the NRB's ambient vibrational modes years after the studied earthquakes.

3. Observations

3.1. Transients and Tilt

Potential seismic proxies for shaking-induced damage include bursts of high-frequency energy that we refer to as "pops," a long-term increase in the periods of the oscillation modes of the structure, and strong baseline offsets in acceleration that may reveal permanent structural tilts. We examine evidence for each below.

Figures 2–5 illustrate some general features observed in datasets 1–3. Figure 2 shows records of the North and East motions from a sub-ground level and the Roof level for the 1999 Satsop earthquake. The simple- and small-amplitude ground motions observed at the lower levels become highly amplified, and the motions are dominated by an apparent resonant frequency that depends on the sensor orientation. These frequencies represent fundamental oscillation modes of the building in the two directions. Higher-frequency resonance is observed in the East/West direction than in the North/South direction because the building is relatively elongated—and therefore probably stiffer—in the East/West direction. There is some suggestion of beating between the two directions.

One seismogram from each earthquake (datasets 1–3) is shown in Fig. 3. The raw acceleration records from the parking garage show that the duration of strong shaking

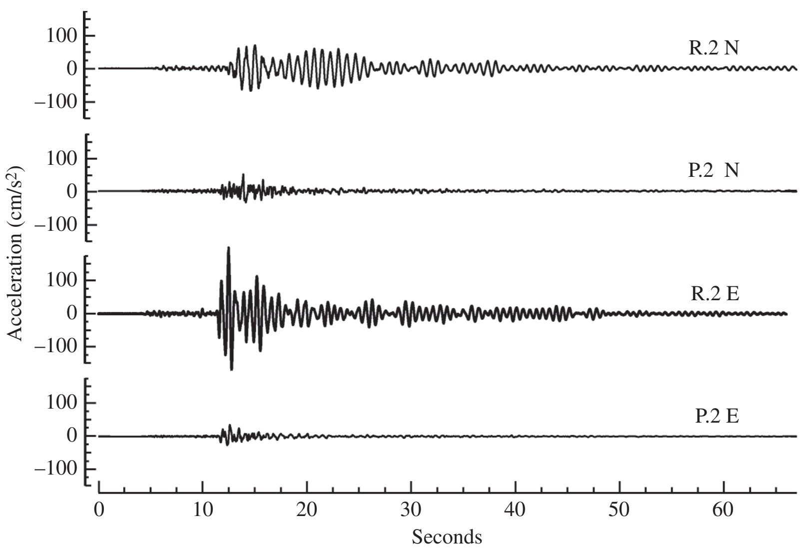

FIGURE 2 Comparison of motions high in building with input motions in the 1999 Satsop earthquake. P2 is a lower level station, R2 is at the roof level. There is a clear N-S resonance of the NRB building from 18–28 s, and a similarly strong but briefer E-W resonance from 12–18 s. Timing between P2 and R2 components is not synchronized. Amplitudes of P2 records have been halved from those distributed by the National Strong Motion Program, following review of field notes [Christopher Stephens, personal communication, 2008] that corrected an error in the metadata. Perhaps there is beating between the E-W and N-S modes. The pulses visible on P2 are the direct S at 12 s followed by the Love wave at 14 s.

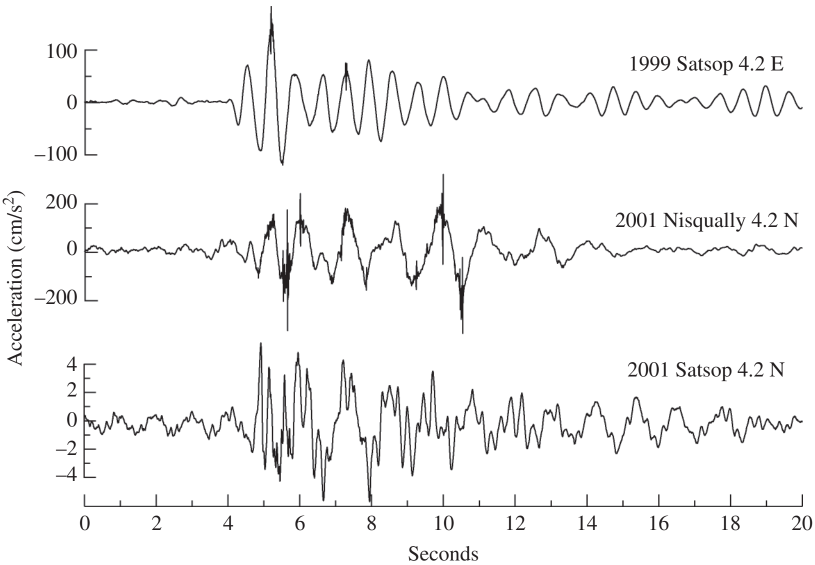

FIGURE 3 (top) Strong-motion record from 1999 Satsop earthquake. (middle) Record from 2001 Nisqually earthquake. (bottom) Record from the 2001 Satsop earthquake. Note the weak pops in 1999 and stronger pops in Nisqually, also note that the amplitude in the 2001 Satsop earthquake is much smaller than the previous two events. These records are from the upper stories of the building.

in each event was about 10 s, and that the dominant period in the incoming wavefield increases with earthquake magnitude. Nisqually had stronger N-S excitation. In general, the Satsop 1999 input ground motion was dominated by signal close to the building's fundamental resonances, Nisqually ground motions were relatively enriched at periods longer than the building response, while Satsop 2001 input motions were generally higher frequency.

The component shown in the figure recorded the most numerous and strongest high-frequency bursts and generally the largest overall motions amongst the components. The same seismograms subject to a 20-Hz high-pass filter are shown in Fig. 4. Two sharp pops are visible for the 1999 Satsop earthquake, a nearly continuous but staccato stream of pops shows up for the 2001 Nisqually earthquake, while the 2001 Satsop events shows no discernable pops. The bursts during the 2001 Nisqually earthquake were particularly energetic, exceeding 100 cm/s^2 at high frequencies, about 10 times stronger than those during the 1999 Satsop earthquake, which in turn exceeded the high-frequency energy during the 2001 Satsop event by up to a factor of 10.

For the 2001 Nisqually earthquake, high-frequency bursts were found on many components. However, perhaps because they were so numerous, we were unable to correlate many individual bursts at different sites in the building unambiguously. Also, we note that generally (but not always) bursts occurred simultaneously with longer-period peaks in the accelerations. These times are maxima in both the dynamic stresses within the structure local to the sensor and displacement of the structure. We feel that most of the high-frequency bursts observed are the result of impulsive sources close to the sites that recorded them, but a few bursts appear to have traveled some distance through the building. The signals are extremely similar to those derived in laboratory testing of structures to failure by Rodgers *et. al.* [2007], and from recordings of real earthquake motions in

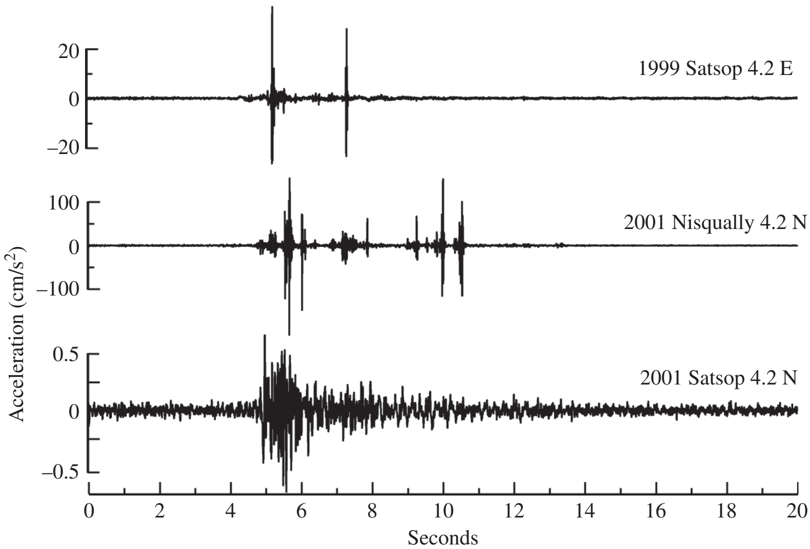

FIGURE 4 The same records as in Fig. 3, high-passed at 20 Hz. Note the shorter time window and the great variation in amplitude.

damaged buildings [Rodgers and Celebi, 2005]. Numerous cracks in non-structural building elements that might possibly represent sources of high-frequency pops were recognized during post-Nisqually reconnaissance [Smith, 2001], and are still visible today. We cannot, however, point to any given crack in the structure as the definitive source of any particular pop.

We next investigated whether strong shaking in the Nisqually earthquake caused long-lasting changes in the NRB by studying the accelerometer recordings for permanent offsets. Static offsets in acceleration time histories (baseline shifts) are not possible, and instead are due to either instrumental problems or to local rotations (e.g., Pillet and Vireux, 2007, and references therein; Graizer, 2007, and references therein). Figure 5 shows how we can reveal baseline shifts by low-pass filtering the accelerogram. The baseline shift begins at about the time of the most energetic pops seen in the high-pass filtered accelerations, which are the bottom time series of each pair. The largest baseline shift, in the 5.2.E component shown in Fig. 5, is a static offset of about -1.79 cm/s^2 and would correspond to a tilt of about 1.6° to the west. Graizer [2007] estimated tilt resolution with inertial accelerometers is better than 0.5°, so this observation represents a significant rotation. Only a handful of apparent tilts were larger than 0.5°. Moreover, the pattern of apparent tilts we observed, even given the incomplete coverage of sensors, is not consistent with a uniform rotation of the entire building. Rather there seemed to be generally stronger tilts at the top floor, above the cantilevered portion of the building. Also, tilts in the N/S directions at the deepest parking level were toward the north but toward the south in the high floor. While the strongest shaking was in the N/S direction, the strongest static tilt was in an E/W component on the 5th floor. We conclude that the observed tilt pattern suggests localized quasi-static deformations near the affected sensor.

Given our interpretation of the offsets and high-frequency pops, as well as the amplitude of shaking, we infer the greatest response changes may have been associated with the Nisqually earthquake, with perhaps some in the 1999 Satsop earthquake, and not much in the 2001 Satsop event.

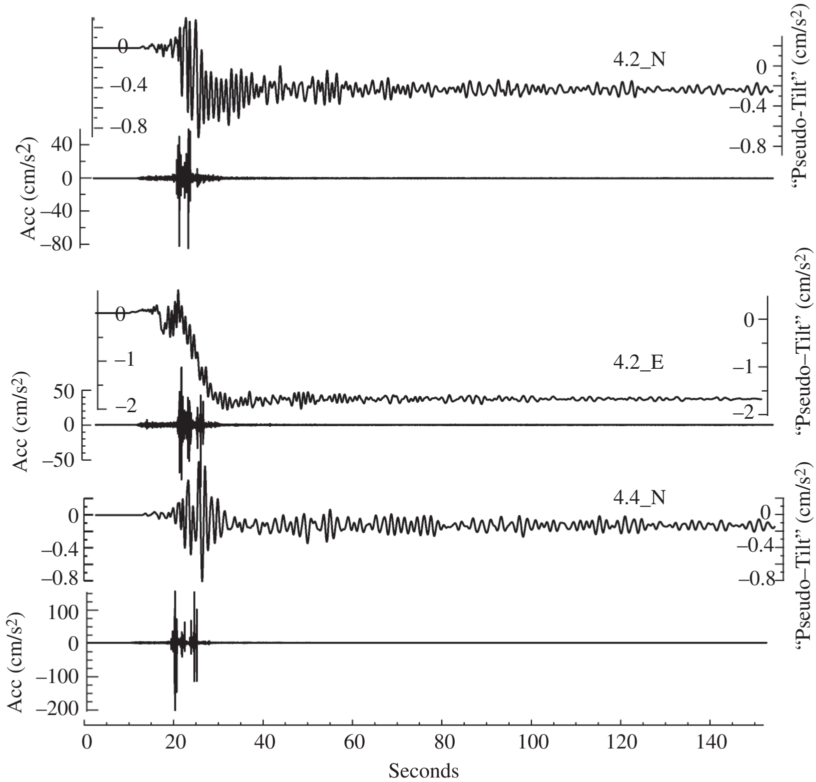

FIGURE 5 NRB permanent tilts associated with Nisqually high-frequency transients. Nisqually accelerations from 3 sensors on the 4th floor of the NRB high passed at 20 Hz to reveal "pops," and low-passed at 0.05 Hz to show permanent baseline offset in acceleration. We feel the most plausible explanation for the baseline offsets are permanent tilts in structural member to which the sensors are attached. The onsets of the apparent tilt signals are closely tied to the large pops. The duration of the apparent tilt transient is controlled by the filter, and we attribute it no physical significance. The top two traces showing the largest tilts are from the east side, the bottom from the west.

3.2. System Frequencies

Approximate theoretical fundamental mode periods for the NRB structure were computed by Swanson *et al.* [2010] for a finite element model of the building (shown in Fig. 1). The periods (frequencies) found were: 0.44 s (2.273 Hz) for the North-South (transverse) direction, 0.35 s (2.85 Hz) for the East-West (longitudinal) direction, and a 0.07 s (14.286 Hz) fundamental torsional mode.

The ambient vibrations of the NRB recorded in 2008 on the same instruments and locations that had been in place since at least 1999 revealed that the fundamental modes of the structure are complicated, as might be expected for an asymmetric and unusual structure. However, the recordings also suggest that the fundamental modes differ from those computed by Swanson *et al.*, [2010] for a finite-element model of the building as designed, both by being generally of longer period (lower frequency), and also having a more complex character. The largest ambient motions as of 2008 were in the N/S direction at the eastern end of the structure at about 1 Hz (Fig. 6), and were systematically largest in the

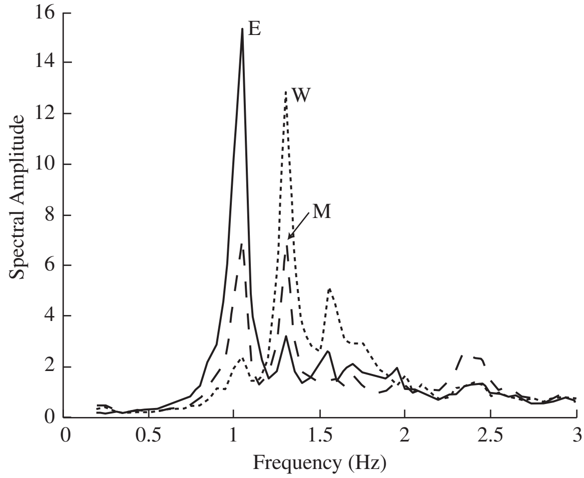

FIGURE 6 Spectra of ambient NS motions in 2008 from dataset 4 (Table 1). Shown are medians of the noise spectra computed for many small windows in the 5,000-s recording, to avoid unduly emphasizing irrelevant noise bursts. The solid curve labeled "E" is for the easternmost stations, long dashed line (labeled "M") for the middle, and short dashed line ("W") for the westernmost.

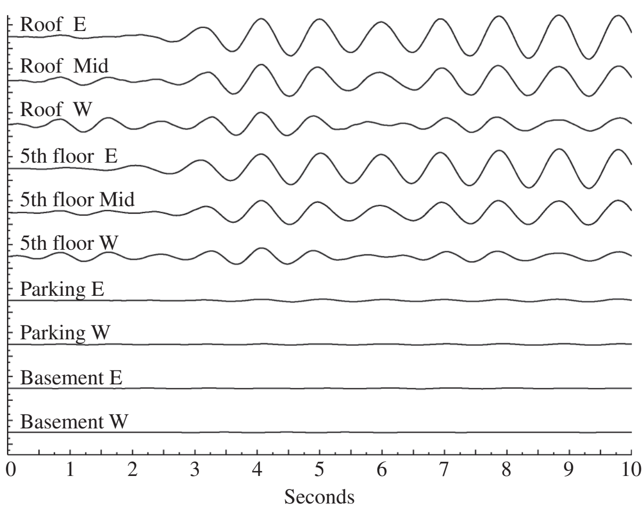

FIGURE 7 Time series of a typical 10-s segment of selected channels of 2008 ambient motion recordings (N/S components) from dataset 4. These have been band-passed between 0.8 and 1.2 Hz. Traces are labeled with the story (Roof, 5^{th} Floor, Parking level #2, and Basement) and location (East, Middle, or West). Note the coherence and amplitude pattern of traces revealing that these motions are sampling a fundamental N/S resonance mode of the building system.

upper floors of the building. The motions were also systematically much larger on stations in the east than the west.

The synchronous phasing as well as the spatial pattern of these motions in the time series of Fig. 7 indicates that this is the fundamental N/S mode. At the west end of the building, the largest N/S motions are at ~1.3 Hz. The E/W motions (not shown) are similarly amplified although peak at a higher frequency (~1.6 Hz), which is appears as a weak peak in the N/S motions, consistent with a stiffer structure in the building's widest dimension. While we have not independently computed a modal analysis of the structure, Swanson *et al.*'s [2010] study neither suggests, nor leads to the expectation of, a difference in modal frequencies on eastern vs. the western portion of the building that is suggested by the observations. The cause of this difference is uncertain. In addition to variations of stiffness, the data are consistent with coupling between torsional and linear-motion modes of the building that could be a vibrational manifestation of its complex and asymmetric structure (particularly of the upper 2 stories). A similar analysis of the broad and much smaller peak in Fig. 6 at ~2.4 Hz., suggests that this is a first higher mode of N/S building motion. An unfortunate dearth of instrumentation in the middle floors does not permit more detailed study of possible higher modes.

In order to track the temporal evolution of modal frequencies during the earthquakes, we processed the recordings into a series of spectrograms, being cognizant of the pattern of the NRB modal response discussed above. In order to focus on the building system response, as distinct from the ground input motions, we form spectral ratios between components high in the building (floors 4 and above) and those at the lowest sub-surface sites. Because at the resonance period of the dominant mode of the components were in phase, we sharpened the resolution, where possible, by summing the upper-story N/S components before forming the ratios. Due to changing station layout and failures of some channels to trigger during the Nisqually earthquake, the ratio spectrograms shown in Figs. 8 and 10–11 sometimes include different components. Moreover, we did not attempt to extend

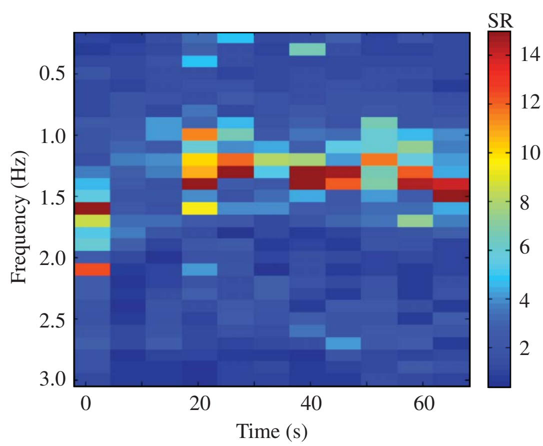

FIGURE 8 Spectral ratio (SR) of the sum of the three NS sensors that measure the fundamental mode of the east side of the NRB in the 1999 Satsop earthquake, divided by the two least amplified N channels, B2_N and P4_N. The plot has been clipped at a spectral ratio of 15. Notice the distinct peak about 1.6 Hz before the strong motion. The resonance peak shifts to 1.25 Hz during strong motion, which arrives from 10–25 s, settling back to about 1.4 Hz by 30 s later (color figure available online).

this analysis to higher modes, as the absence of sensors from the middle stories provided no data constraints where one would expect these motions to be the largest.

The 1999 Satsop records from the east end of the NRB (Fig.8) start with a resonance peak at ∼1.6 Hz. During the strongest shaking, the resonance peak frequency decreases ∼22% to 1.25 Hz, recovering to ∼1.4 Hz by the end of the record, for an overall observed drop of ∼12%. We have no data to reveal if it recovered more in the hours to days afterward. However, the seismic observations suggest it hadn't recovered. The next available recording, of the Nisqually earthquake in 2001, begins with N/S resonance peak at about 1.3 Hz, with the E/W peak at ∼1.9 Hz. (Fig. 9). Within 20 s, the N/S peak reduced nearly 50% further to about 0.7 Hz (Fig. 10). By the end of the Nisqually recording, the peak in the N/S spectral ratio has recovered slightly to ∼0.8 Hz. Then in June 2001, the recording of the second Satsop earthquake starts with an apparent N/S resonance peak at ∼0.8 Hz (Fig. 11), which stays at 0.8–0.9 Hz throughout the recording. In the ∼6.5 years between the 2001 Satsop earthquake and the 2008 ambient motion samples illustrated in Figs. 6 and

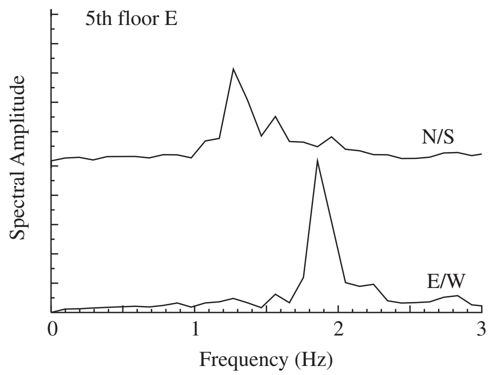

FIGURE 9 Spectra of the initial 9.5 s (pre-event) of Nisqually records (top = N/S, bottom = E/W) from the east end of the 5th floor of the NRB.

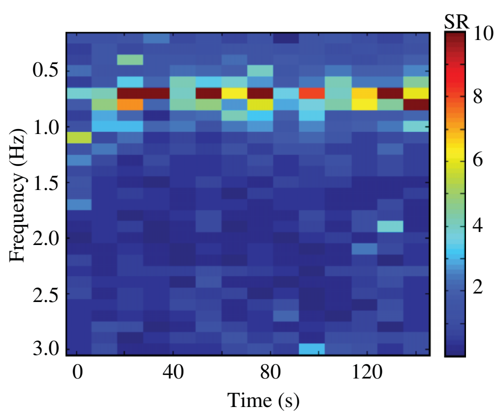

FIGURE 10 Spectral ratio (SR) of the one working NS sensor that measured the fundamental mode in the Nisqually earthquake divided by the average spectrum of the two basement NS channels. The plot has been clipped at a spectral ratio of 10. The amplification is less than in the 1999 earthquake, probably due to increased damping (color figure available online).

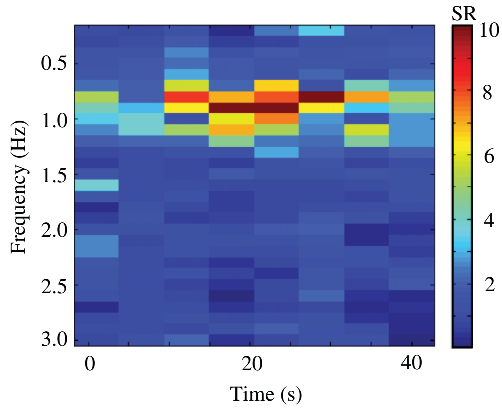

FIGURE 11 Spectral ratio (SR) of the sum of the four NS sensors that measure the fundamental mode from the 2001 Satsop earthquake, divided by two basement NS channels. The plot has been clipped at a spectral ratio of 10. Notice the distinct peak about 0.9 Hz during the moderate shaking from about 10–15 s (color figure available online).

7 the fundamental period of N/S motions at the east end of the NRB has only partially recovered, to ~1 Hz. The NRB has apparently lost stiffness in this mode, leading to an overall drop in resonance frequency of ~37% between 1999 and 2008.

Analyses of both E/W motions, and N/S motions at the west end of the building (not shown) reveal large temporary reductions in resonance period during strong shaking that were nearly fully recovered during the recording. However comparing the clear 1.9 Hz peak in the pre-Nisqually E/W motion at the east end of the building (Fig. 9), to the strong spectral peak at ~1.6 Hz at these stations in the ambient motions of 2008 (not shown) leads to the inference of a long-term drop in resonance period of ~16% in the E/W resonance there.

4. Discussion

Figure 12 condenses the observations of the North-South building response frequencies presented above to more clearly reveal the history of this dominant deformation mode. During the 1999 Satsop earthquake, the NRB N/S resonant frequency temporarily dropped about 22%, and may have permanently dropped 12%. The larger Nisqually shaking reduced the frequency much further, and the 2008 ambient recordings reveal the changes to be a long-term change. From early in the 1999 Satsop recordings to 2008 the N/S motions in the eastern side of the building dropped ~37%. An estimate of the long-term reduction in resonant frequency of E/W motions from early in the Nisqually records to the recordings of ambient motions made in 2008 is ~16%. While the short-term frequency shifts during strong shaking likely reflect the effect of structural ductility, the long-term decreases in modal frequencies represent a reduction in stiffness that could factor into assessment of seismic response in future earthquakes.

The 22% drop and 12% recovery in frequency in the N/S motions of the fundamental mode during the first Satsop event is comparable to values observed in the Millikan library due to the San Fernando earthquake, although the NRB experienced lower acceleration levels [Luco *et al.*, 1987]. The additional ~53% drop during the Nisqually earthquake (although partially recovered by 2008) is without precedent for undamaged buildings in the literature, to our knowledge. It is an order of magnitude greater than estimates of

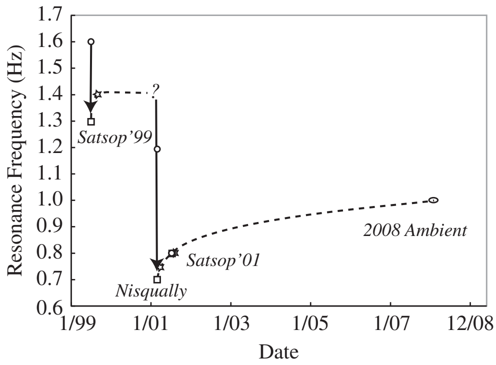

FIGURE 12 History of resonance frequencies of the fundamental mode of N/S motions at the East end of the NRB. Circles are peak frequencies early in each dataset, squares in the middle of each recording, during strongest shaking, and stars at the end of each recording. Dashed lines are schematic trajectories connecting datasets. Arrows are frequency drops at the time of strong shaking. The query at the time of the Nisqually earthquake reflects the fact that our earliest time window included some shaking which may have already reduced the resonance peak somewhat.

changing temperature, rainfall, and wind [Clinton *et al.*, 2006]. However, a direct mapping of frequency changes into stiffness reductions is fraught with uncertainties about how much loss of stiffness is generated by degeneration of the horizontal stiffness as opposed to loss of rocking stiffness controlled by soil-structure interactions (e.g., Luco *et al.*, 1987; Todorovska and Trifunac, 2008). Such an interpretation would demand a more complete analysis of the building deformation modes and seismic response than we have done (e.g., Todorovska *et al.,* 2001a,b; Snieder and Safak, 2008).

The causal relation between pops and permanent tilts and the loss of stiffness is not well known, perhaps due to paucity of digital records, with a fairly complete review of results recently published [Rodgers and Çelebi, 2005]. A 10% reduction in resonant frequency in an Alhambra building from the Whittier Narrows quake was not accompanied by audible cracking, however the limitations of analog recording prevents a sensitive analysis [Rodgers and Çelebi, 2006]. Inspection in that case revealed weld defects or small cracks in 30 of 52 welds inspected. The problems were attributed to construction, but further damage during shaking cannot be ruled out [Rodgers and Çelebi, 2006].

Monitoring changes in building translational and torsional modes can resolve significant reductions in stiffness in this case, and such techniques may prove of general usefulness in monitoring structural health. To understand fully the stability and resolution of modal frequency tracking, continuous—or at least regular and frequent sampling—of the ambient motions would be quite helpful, and high-quality seismic instrumentation and a thorough understanding of building vibration modes are essential. Similarly, the presence of high-frequency transients and permanent baseline offsets in digital accelerograph recordings of structural motions may help to locate and characterize the sources of localized failures, given sufficiently dense instrumentation. More experimental and theoretical work is needed to understand the forensic significance of the signals we observe. None of the analyses we present take a lot of time to carry out and all might be done within minutes after a large earthquake. We conclude that seismic monitoring of structures, given the caveats above, have the potential to contribute to rapid (and even automatic) assessments of structural state-of-health very soon following a potentially damaging event.

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