**Eleventh U.S. National Conference on Earthquake Engineering**
*Integrating Science, Engineering & Policy*
June 25-29, 2018
Los Angeles, California

# TIME-LAPSE CHANGES IN SEISMIC RESPONSE OF BUILDING OVER 20 YEARS DUE TO EARTHQUAKES AND AGING

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## ABSTRACT

The natural frequencies and seismic-wave velocities of buildings and other civil structure are changing continuously due to earthquakes, weather especially temperature and precipitation, and aging effects. Strong motion related to earthquakes modify the seismic response of buildings. When earthquake waves are not strong (small strain), the natural frequencies nonlinearly decrease at the time of earthquakes because of shaking and bending, but it recovers quickly afterward. When earthquakes are large, strong motion gives permanent changes as a damage to the structure. For example, the 2011 M9.0 Tohoku earthquake in Japan caused about 20% of reduction in the fundamental frequency of a building, which is several hundred kilometers far from the epicenter. Even when we do not have strong earthquakes, buildings last for decades, and the natural frequencies are also changing over the time (i.e., aging). We study these effects of strong motion and aging using a building in Tsukuba, Japan. We apply spectral decomposition and deconvolution techniques to more than 1600 earthquake waveforms observed in the building over 20 years, including the 2011 Tohoku earthquake. The natural frequency and seismic velocities in the building have been decreased over the 20 years, caused by both strong earthquakes and aging. Interesting, nearby borehole seismometers do not show such large changes. The change caused by the Tohoku event is recovering slowly within two years from the mainshock; however, the response is still significantly different from the one before the earthquake. With this long-term observation, we analyze the effects of earthquakes and aging, and separate them.

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Nakata N, Kashima T. Time-lapse changes in seismic response of building over 20 years due to earthquakes and aging. *Proceedings of the 11th National Conference in Earthquake Engineering*, Earthquake Engineering Research Institute, Los Angeles, CA. 2018.

# Time-Lapse Changes in Seismic Response of Building over 20 Years due to Earthquakes and Aging

N. Nakata[1] and T. Kashima[2]


## ABSTRACT

The natural frequencies and seismic-wave velocities of buildings and other civil structure are changing continuously due to earthquakes, weather especially temperature and precipitation, and aging effects. Strong motion related to earthquakes modify the seismic response of buildings. When earthquake waves are not strong (small strain), the natural frequencies nonlinearly decrease at the time of earthquakes because of shaking and bending, but it recovers quickly afterward. When earthquakes are large, strong motion gives permanent changes as a damage to the structure. For example, the 2011 M9.0 Tohoku earthquake in Japan caused about 20% of reduction in the fundamental frequency of a building, which is several hundred kilometers far from the epicenter. Even when we do not have strong earthquakes, buildings last for decades, and the natural frequencies are also changing over the time (i.e., aging). We study these effects of strong motion and aging using a building in Tsukuba, Japan. We apply spectral decomposition and deconvolution techniques to more than 1600 earthquake waveforms observed in the building over 20 years, including the 2011 Tohoku earthquake. The natural frequency and seismic velocities in the building have been decreased over the 20 years, caused by both strong earthquakes and aging. Interesting, nearby borehole seismometers do not show such large changes. The change caused by the Tohoku event is recovering slowly within two years from the mainshock; however, the response is still significantly different from the one before the earthquake. With this long-term observation, we analyze the effects of earthquakes and aging, and separate them.


## Introduction

Seismic response of building to strong motion has been studied for long time (e.g., [1-3]) because of the importance of understanding the safety of such structures. With continuous or long-term triggered seismic observation, we can estimate the time-lapse changes in the frequencies of normal modes and/or stiffness of the building [4,5]. Clinton et al. (2006) [6] used the observation of Millikan library in the US for about 40 years and found that large earthquakes temporally decreased the fundamental-mode frequencies about 20%, and these reductions are recovered quickly after the strong motion was stopped. However, the response did not completely recover, and small fraction of these reductions is remained as damages of the building. Over 40 years, the fundamental frequency decreased about 10-15% total.

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Analyses of transfer function (i.e., deconvolution) are powerful because we can increase the signal-to-noise ratio (SNR) of data [7]. We often look at the transfer function in the frequency domain, but we can also use them in the time domain [8,9]. The time-domain transfer function simplifies the physics/interpretation of wave propagation in the building, and we mostly cancel the effects of subsurface wave propagation and extract propagation in the building [10,11]. With this technique, Nakata et al. (2015) [11] found that the seismic velocity in a building in Tokyo decreased about 20% after the 2011 Tohoku earthquake, even though the building is about 400 km far from the epicenter. The Timoshenko beam model is useful to include rocking and bending effects in this deconvolution technique [12-15].

Here, we use earthquake data observed more than 20 years in a building in Ibaraki prefecture, Japan (Fig. 1). The building is well-instrumented, including a borehole array within 20 m from the building. We first introduce this dataset and deconvolution technique used. Next, we measure the changes in seismic velocities of more than 1600 earthquakes observed by this system. Then we discuss the changes according to large earthquakes and aging effects.

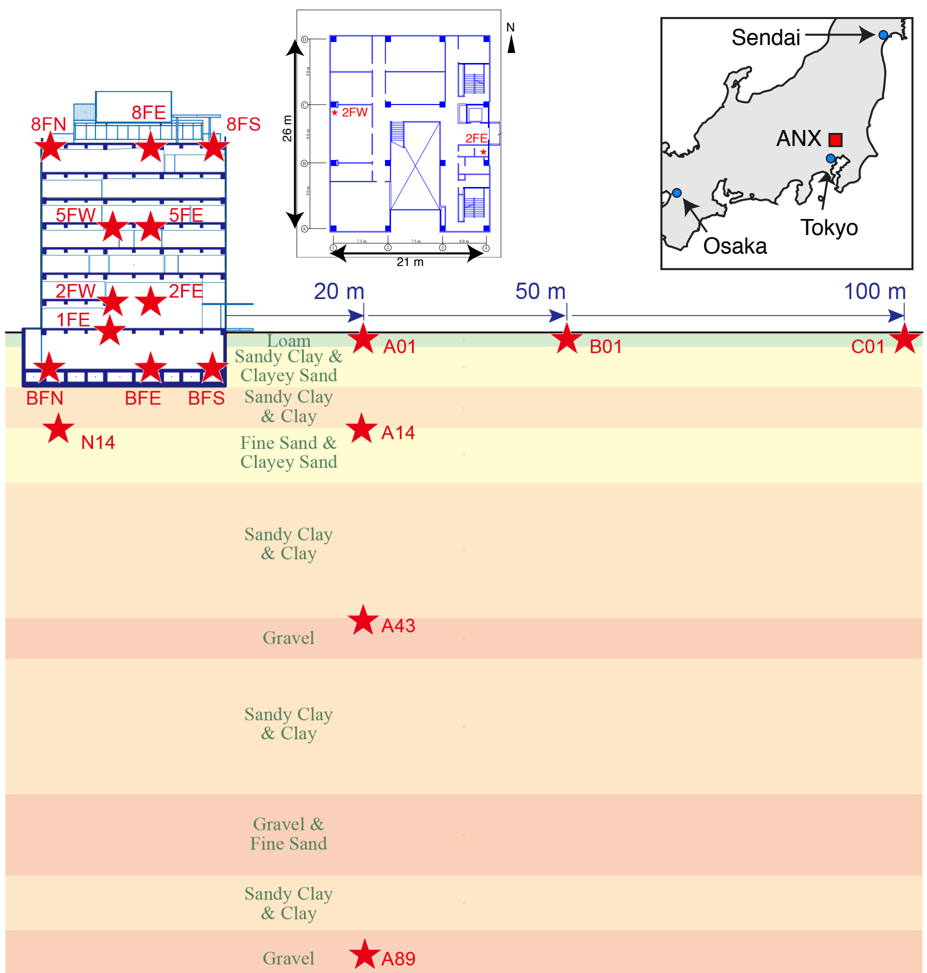


Figure 1. Location of receivers (red star) in the ANX building and ground. The inset of Japan map shows the location of ANX building, not in scale. The top-middle inset shows the floor plan of the building at 2nd floor.

## Building and Earthquake data

The building is located at the Building Research Institute (BRI) in Tsukuba, Japan (Fig. 1). It is an annex of the main building, so the building code is ANX. The ANX building is an eight-story steel reinforced concrete (SRC) framed building, which has a basement floor as well. The height of the building is 34.55 m from the ground and bottom of the basement is 8.5 m below the ground. Eleven accelerometers with three components are installed in the building at different locations and have recorded earthquake waveforms since 1998, when the building was built. In addition, seven accelerometers are deployed around the ANX building in a borehole or the ground surface (Figure 1). The total number of earthquake records until 2017 is more than 1600, including the 2011 $M_W$9.0 Tohoku earthquake. This large number of earthquakes provide a unique opportunity to understand the dynamic characteristics of the building response.

The ANX building has been studied to understand the dynamic changes of the building based on natural frequencies and damping parameters over years, and even in each earthquake waveform [16-18]. In this study, we apply a deconvolution technique to this dataset and focus on the time-lapse changes of seismic velocities of the building.

## Deconvolution interferometry

We use deconvolution interferometry to study the earthquake data. Deconvolution interferometry is a technique to analyze the wave propagation while assuming that the wave propagation in the building is mostly one dimensional for simplicity [8,10]. Based on Nakata et al. (2013) [10], an earthquake record at receiver height $z$ can be represented in the frequency domain as

$$u(z) = \frac{S\{e^{ikz}e^{-\gamma|k|z}+e^{ik(2H-z)}e^{-\gamma|k|(2H-z)}\}}{1-Re^{2ikH}e^{-2\gamma|k|H}}, \tag{1}$$

where $S$ is the incoming waveform to the building, $k$ is wavenumber, which can be varied with height [10], $H$ is the height of the building, $\gamma$ is the damping parameter, and $R$ is the reflection coefficient due to the ground coupling. The denominator represents the reverberations of waves between the top and bottom of the building. When we use a receiver at the roof or close to the roof of the building ($z = H$), Eq. 1 becomes

$$u(H) = \frac{2Se^{ikH}e^{-2\gamma|k|H}}{1-Re^{2ikH}e^{-2\gamma|k|H}}. \tag{2}$$

With deconvolution interferometry, we compute deconvolution between different floors (i.e., transfer function). In this study, we deconvolve wavefields with the top receiver;

$$D(z,H) = \frac{u(z)}{u(H)} = \frac{1}{2}\{e^{-ik(H-z)}e^{\gamma|k|(H-z)} + e^{ik(H-z)}e^{-\gamma|k|(H-z)}\}, \tag{3}$$

where the first term shows the upgoing waves in the negative time and the second the downgoing waves in the positive time. Note that Eq. 3 does not have the term of incoming waves ($S$) nor reflection coefficient ($R$), so that we can dramatically simplify the waveforms as well as change the boundary condition at the base of the building into 0, which means we do not have

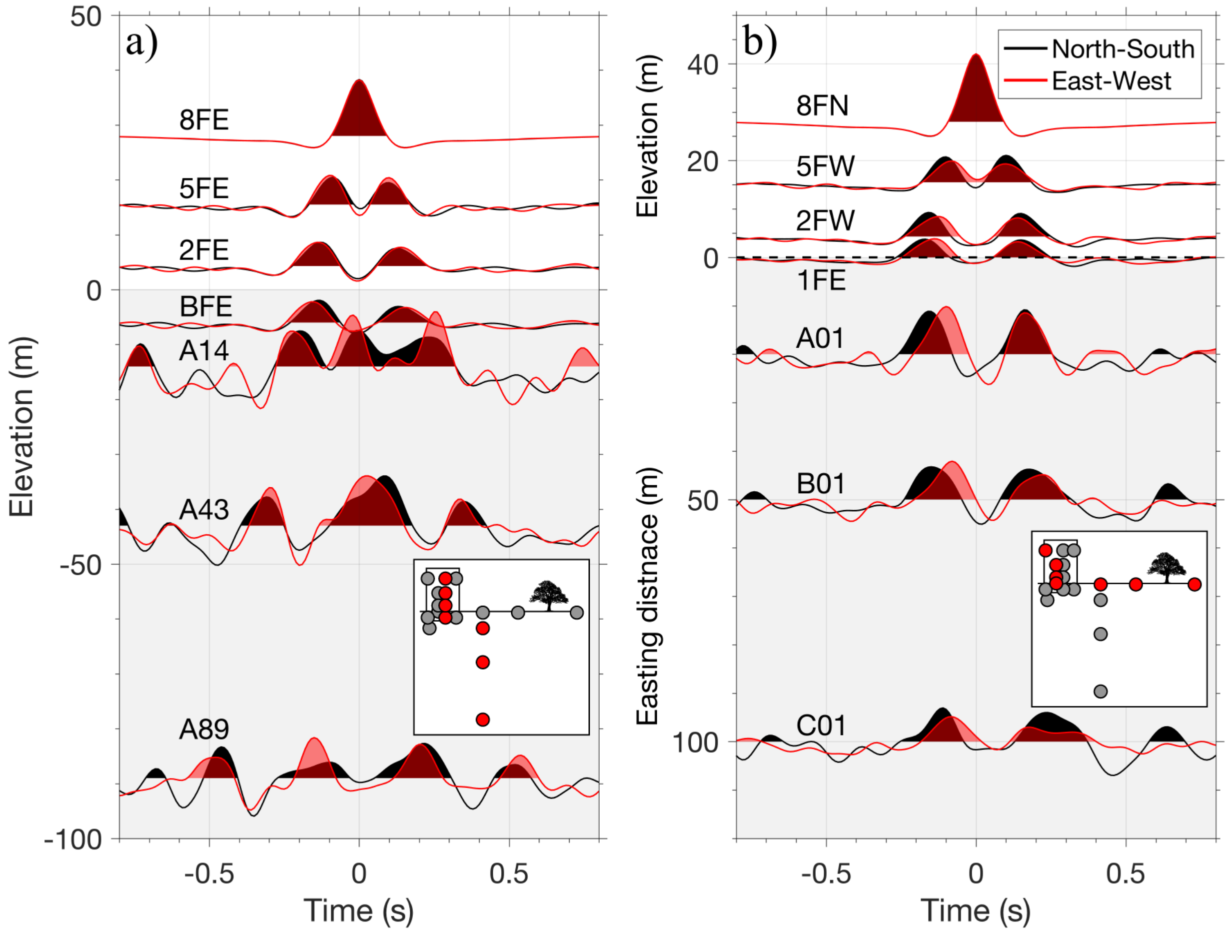


Figure 2. Deconvolved waveforms with the reference receiver at (a) 8FE and (b) 8FN extracted from an earthquake ($M_{JMA}$ 3.4, June 14, 2002). The black and red lines show the waveforms in the North-South and East-West components, respectively. Positive amplitudes are filled for display purpose. The red dots in the inset shows the location of receivers used in each panel. The frequency range of these waveforms are in 0.5—5.0 Hz.

any reverberations. This modified boundary condition was discussed in previous studies [9,10,19]. Importantly, because we do not modify the model parameter $k$ and the attenuation parameter $\gamma$, we can extract the building response by using the deconvolution.

Fig. 2 shows an example of deconvolved waveforms in two different paths. The building part (above BFE and 1FE) shows two different waves in the negative and positive times, which are upgoing and downgoing waves, respectively [9]. The propagation velocity of this wave is about 300 m/s for both components. Because this site also has borehole and ground-surface sensors, we can connect the wave propagation to the outside of the building [20]. The borehole records (Fig. 2a) show that the waves are propagating back to the ground, about $\pm 0.5$ s at receiver A89. Also, due to the surface reflection, some waves are reflected at the ground surface ($\pm 0.15$ s at A89). The surface records (Fig. 2b) show that the arrival time of the waves at 1FE, A01, B01, and C01 are almost identical each other, which means that the waves are not propagating along the surface, but mostly vertically incident. This confirms our assumption of 1D wave propagation.

## Monitoring the Building with Deconvolution Interferometry

We apply the deconvolution interferometry to all earthquakes observed by the accelerometers in the building. Over 20 years (1998-2017), more than 1600 earthquakes have been observed and Fig. 3 shows the deconvolved waveforms at receiver BFE (e.g., the black line of BFE in Fig. 2a). Although the size, location, and complexity of incoming wave of each earthquake are varying, the deconvolved waveforms are extremely coherent over different earthquakes. Based on the theory shown in Eq. 3, the times of the positive amplitude show the arrival time of the waves, and because we know the traveling distance, we can compute the seismic velocities from these waves. Interestingly, the arrival time of the waves are lager in the later years, and we interpret this as the weakening of the building stiffness over the years (i.e., aging effect). On March 11, 2011, the building experienced the $M_W$9.0 Tohoku earthquake, and strong changes of deconvolved waves are observed, and the number of earthquakes increased as aftershocks.

Based on the arrival times of the deconvolved waves, we estimate the wave velocities at each earthquake (Fig. 4). We measure the velocities at different floors independently. Because the stiffness, and the accuracy of the measurement, can be different at each floor, the velocities at each floor are different. Due to the shape of the building (Fig. 1), the seismic velocities in the North-South direction are slightly larger (i.e., stiffer). We do not know why the velocity measurement in the East-West component is more stable over different earthquakes, but probably because normal modes are easier to be excited in this component. As we expected from Fig. 3, the velocities had been continuously and gradually decreased for the first eight years (1998-2006), and strongly changed caused by the Tohoku earthquake. The reduction of the velocities recovered slightly after two-three years from the mainshock.

The gradual decrease of fundamental-mode frequencies over years has been observed at Millikan library as well [6], but they did not show as high temporal resolution as we do. Also, because we use deconvolution interferometry and cancel the reflection coefficient at the base of the building (Eq. 3), we can separate the effect of the building from the subsurface changes, which means that

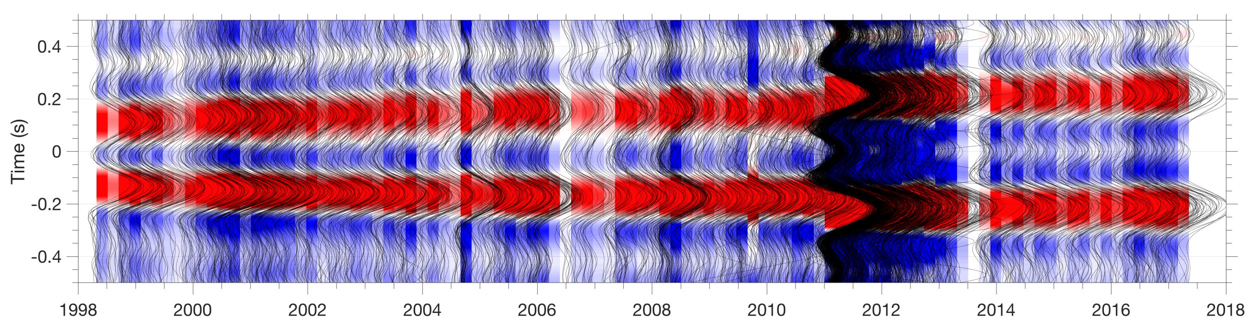


Figure 3. Waveforms at receiver BFE deconvolved by the observation at receiver 8FE. The receiver component is the North-South direction. Each black line shows the deconvolved waveforms computed from each earthquake, and the background image shows the averaged waves in each bin, where red and blue show positive and negative amplitudes, respectively.

the velocity changes in Figure 4 are mostly related to the building.

By using the deconvolution interferometry for borehole data, we find that the velocities in the borehole is stable and not similar to the changes in the building (Fig. 5). The seismic velocities, and stiffness, of the entire building are much easier to change compared to subsurface structure. Although the absolute velocities are different, the velocity changes are about the same between the North-South and East-West components. Over the first eight years, the velocity decreased about 25%, which are caused by both intermediate-large earthquakes discussed below and the aging effect. The Tohoku earthquake provides another 25% reduction. Nakata et al. (2015) [11] found that the seismic velocity decreased about 20% in a building in Tokyo, and the amount of reduction is comparable to the ANX building. Then the velocity recovered about 10% within three years from the Tohoku event and stable afterward.

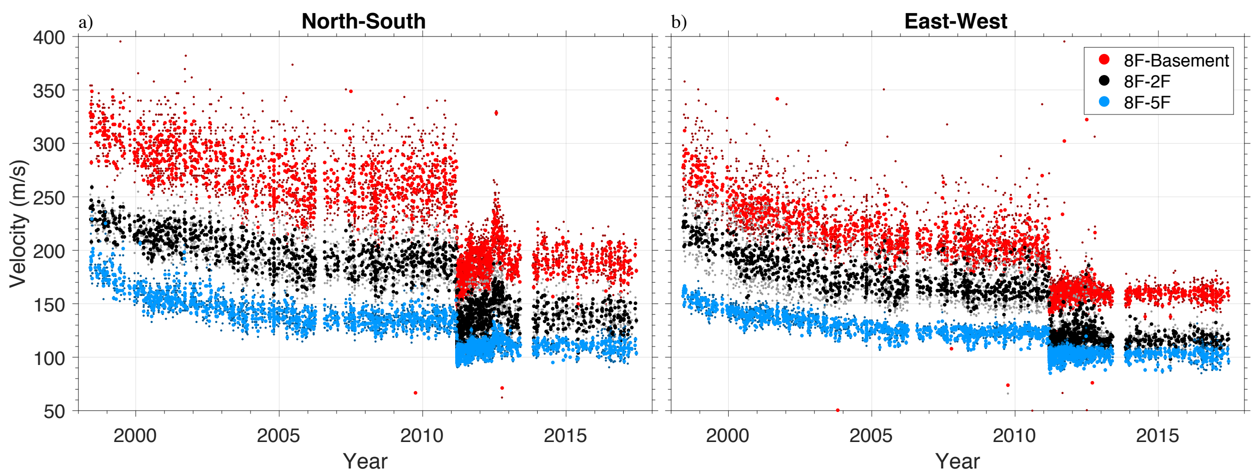


Figure 4. Time-lapse travel times estimated from the deconvolved waveforms shown in Figs. 2 and 3. Each color indicates different pairs of floors, and the small and large dots in each color are velocities of upgoing/downgoing waves and their mean, respectively.

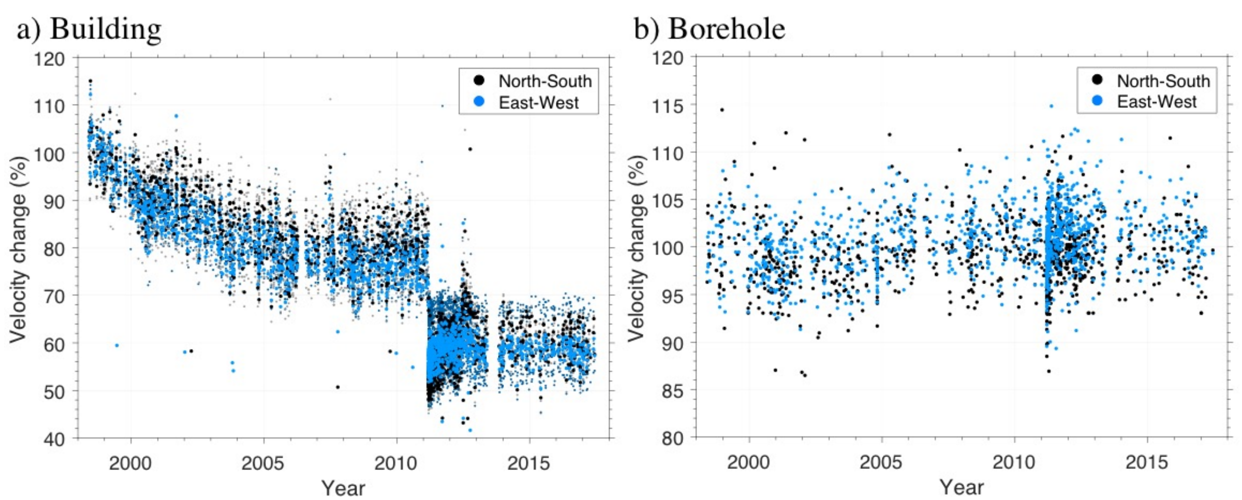


Figure 5. (a) Averaged velocity changes over all floors in the building in two different components. The 100% velocity is defined as the averaged velocity in 1998. (b) Similar to panel (a), but at the nearby borehole (A89-A01).

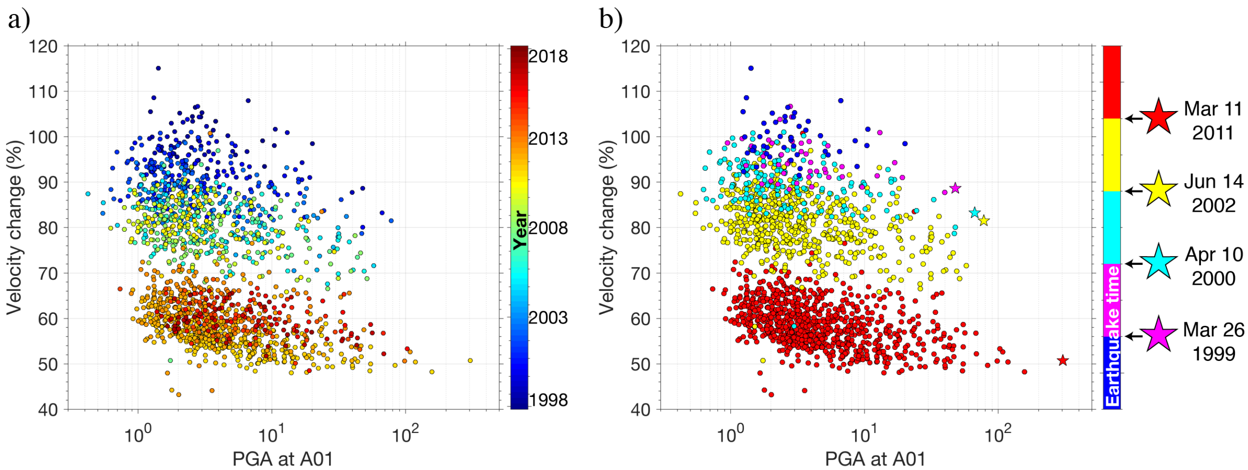


Figure 6. Crossplot of the velocity changes in the building (Fig. 5a) with observed PGA of each earthquake at receiver A01. The color indicates (a) year and (b) earthquake time. The earthquake time is defined by the timing of strongest event exposed at each time, and such events are indicated by stars. The NS component is used for this plot.

## Velocity Changes Caused by Strong Motion and Aging Effect

As we discovered, seismic velocities and stiffness of the building are continuously changing. Clinton et al. (2006) [6] concluded that the permanent reduction is mostly due to large earthquakes with some fluctuation caused by other factors such as small events and weather parameters. The large number of earthquakes we used gives high temporal resolution of this measurement.

We can measure the peak ground acceleration (PGA) for each earthquake using the nearby station (A01) and crossplot them with the measured velocity changes (Fig. 6). At each time (i.e., each year), we can fit the velocity changes and PGA by a nearly straight line as like Nakata et al. (2013) [10]. The fact that we can fit the data with a straight line indicates that the building response is nonlinear and modified by the size of the input data. The fit lines are changing over years because the velocities are decreasing (Fig. 6a).

The velocity reduction, especially for the first three years, can be caused by the largest experienced strong motion (Fig. 6b). The stars in Fig. 6b indicate the earthquakes that cause the strongest ground motion to the building at that time, and the color of each dot is classified due to these earthquakes. Seismic velocities of most of purple dots are larger than the purple star, which means that the large fraction of permanent velocity changes are caused by this star event. Then the event shown by the cyan star occurred and the response changes (cyan dots are lower than the purple star). This is also true for the red star, which is the Tohoku earthquake. This strong motion defines the state of the building and all events after the Tohoku (red dots) show larger velocities. The complexity is that the velocities are partially recovered after a few years from the Tohoku event (Fig 6a). The time of yellow (2002—2011), however, does not follow this rule that the strongest experienced strong motion modified the building response. The largest event at that time shows the velocity change of 80% (yellow star), and although we do not have larger strong-motion events between 2002—2011, the velocities are decreased due to some other aging effects. Overall, we conclude that the majority of seismic velocity changes are caused by the largest

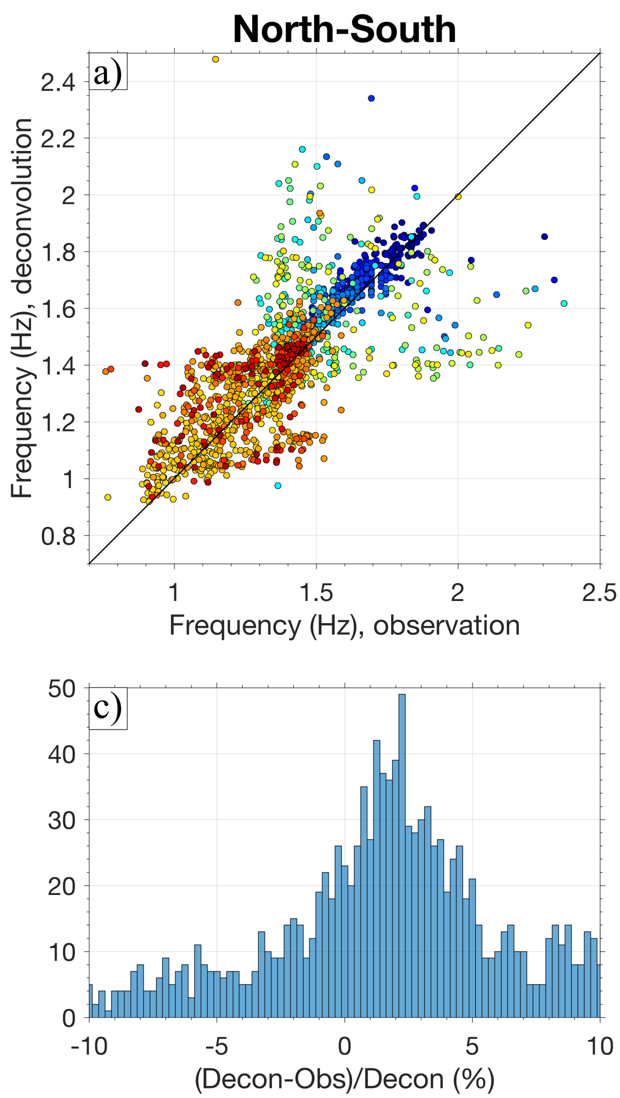


Figure 7. (a,b) Crossplots of fundamental-mode frequencies between observed and deconvolved data. The color indicates the time and is the same as used in Figure 6a. (c,d) Histograms of the normalized differences of fundamental-mode frequencies for the North-South and East-West components, respectively.

experienced strong motion of the building, but we cannot ignore other aging effects such as repeating intermediate events and/or strong wind and precipitation. Note that at each stage of stiffness, building still shows nonlinearity and seismic response varies due to the strength of seismic motion.

## Natural Frequencies of Observed and Deconvolved Wavefields

In the previous sections, we analyze data in the time domain, but we can also estimate frequencies of normal modes after deconvolution and compare them with the estimation from observed data (Fig. 7). The general features of the time-lapse changes, such as gradual and drastic decreases of frequencies over first eight years and at the Tohoku earthquake, respectively, are similar between the measurements using observed and deconvolved waves. Because we cancel the signature of incoming waves and ground coupling (Eq. 3) with the assumption of 1D propagation, we expect that the deconvolved wavefields are only related to the building, and the fundamental-mode frequencies are slightly increased after deconvolution. For the ANX building, the differences of frequencies are about 2-3% (Figs. 7cd), which is important differences when we need accurate measurements. This effect can be changed according to buildings, and Nakata et al. (2015) [11] found that the difference of fundamental-mode frequencies is about 5% for the different building. Some earthquakes in the North-South component show large discrepancies, and we speculate that there might be physical reasons, which is a future study topic.

## Conclusions

We use more than 1600 earthquakes observed over 20 years in the building at BRI to study the time-lapse changes of building stiffness and its nonlinearity. We apply deconvolution interferometry, which is useful for separating the response of the building from the influence of subsurface. The seismic velocity decreased gradually for the first eight years of observation caused by large earthquakes and aging effects, and significantly decreased caused by the 2011 Tohoku earthquake. The reduction of the Tohoku event recovered partly in the following years, but the velocity of this building is about 60% of the original state now. The largest experienced strong motion decreased the seismic velocities significantly, but also the aging effect (not caused by the strongest motion) cannot be ignored for this building. The frequencies of the fundamental mode of deconvolved and observed raw data show similar features, gradual decrease over years and significant change caused by the Tohoku earthquake, but the frequency of the deconvolved wavefields is slightly higher as expected because of the cancellation of the subsurface effect.

## Acknowledgments

We are grateful to Building Research Institute in Japan for providing data analyzed here.

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