PHASE DIFFERENCE OF VERTICAL SEISMOGRAMS OBSERVED ON SEVERAL FLOORS IN A HIGH-RISE BUILDING

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Abstract

Phase difference of vertical component of accelerograms for 34 events observed on the 1st, 5th, 10th, 15th and 19th floors in a 75-m high and 19-story RC building in Meisei University, Tokyo is investigated in terms of time difference. In order to obtain time difference, cross-correlation coefficient with respect to reference floors for the first motion (motion before S-wave arrival) or the whole motion of seismograms is evaluated.

In this study the peak value of cross-correlation coefficient and the time at which cross-correlation coefficient peaks are referred to be "PCC" and "Time difference", respectively. PCC and time difference are obtained for the following three conditions:

(a) For the first motion with respect to the top (19th) floor

(b) For the whole motion with respect to the top (19th) floor

(c) For the whole motion with respect to a middle (5th) floor

In the case (a), it is found that PCC becomes smaller and time difference becomes greater with the distance to the reference floor. The time difference is equivalent to the arrival time of P-wave velocity of concrete indicating that incident P wave is vertically propagated in the building.

In the case (b), it is also found that PCC becomes smaller with the distance to the reference floor. Shorter time difference is found among floors in comparison to that in the case (a). This is presumably because the cross-correlation coefficient evaluated from the whole motion is affected by the superposition of upward and downward P waves vertically propagated in the building. The waves constitute stationary wave which is substantially equivalent to vibration of vertically fundamental mode.

In the case (C), greater PCC and shorter time difference are obtained in comparison to those in the case (b). This is because the distance to the reference floor becomes shorter and therefore cross-correlation coefficient with respect to the reference floor becomes better.

The cross-correlation coefficient analysis for 34 events show that time difference is affected by the accuracy of recordings, distance to the reference floor, and the value of PCC. When the distance to the reference floor is shorter than 60m and PCC is greater than 0.7, then corresponding time difference is within 0.005s. The time difference is practically assumed to be zero.

The final result enables us to synchronize the recordings observed with three-component stand-alone seismographs vertically deployed in a building without any accurate clock or time-calibration system like GPS by evaluating cross-correlation coefficient for the whole motion in vertical component with respect to a reference floor.

An application of the synchronization of seismograms independently observed at a vertical array earthquake observation in another high-rise building during the Tohoku Pacific Ocean Earthquake of 11 Mar 2011 is introduced herein.

Keywords: phase difference; cross-correlation coefficient; vertical component; seismograph array; synchronization

1. Introduction

Vertical array earthquake observation in buildings is widely made to detect vibration characteristics of the buildings. In most cases seismographs are vertically deployed on some floors including the top and basement floors. The earthquake recordings are generally used not only for evaluation of natural period but depiction of vibration mode or interlayer-deformation estimates. Although a pilot study to investigate the characteristics of vertical vibration of buildings has been made recently [1], vertical-component recordings are seldom used except for evaluation of rocking vibration because buildings are mainly vibrated in horizontal directions.

Generally seismographs are installed in buildings with the building construction and the seismographs are connected to data recorders with cables (“Pre-install” case). In such a case, with a trigger at a pilot sensor, all seismograph recordings can be collected simultaneously and therefore synchronization can be made automatically. In a “Post-install” case, on the other hands, seismographs are installed after the building construction and therefore the connection of the seismographs with data recorders takes much effort. Then stand-alone observation with GPS synchronization sometimes has to be made instead. However, there still remains another problem of installing GPS antenna for each seismograph which is deployed inside buildings.

In this study phase difference of vertical-component seismograms simultaneously observed on several floors in a 74.60-m high and 19-story RC building (“Pre-install” building) is investigated. Cross-correlation coefficient with respect to a reference floor is calculated in order to obtain phase difference among the floors. The results are discussed and applied for a synchronization of stand-alone earthquake recordings in another high-rise building (“Post-install” building).

2. Cross-correlation coefficient

In this study cross-correlation coefficient is calculated to obtain phase difference among floors. Fig.1 shows Ricker wavelets with the same amplitude and characteristic-period but different phase. The red and blue wavelets are respectively preceding and following wavelets to the reference one with 1s time difference. When cross-correlation coefficient is calculated for the preceding wavelet with respect to the reference one the result can be shown as red line in Fig.2. Cross-correlation coefficient for the following wavelet with respect to the reference one can also be obtained as blue line in Fig.2. Cross-correlation coefficient for red and blue wavelets peaks at 1s and -1s, respectively with maximum amplitude of 1. Thus time difference to the reference wave can easily be obtained from the time at which cross-correlation coefficient peaks. In this study the peak value of cross-correlation coefficient and the time at which cross-correlation coefficient peaks are referred to be “PCC” and “Time difference”, respectively. The positive time difference means preceding phase arrival to the reference wave, and vice versa.

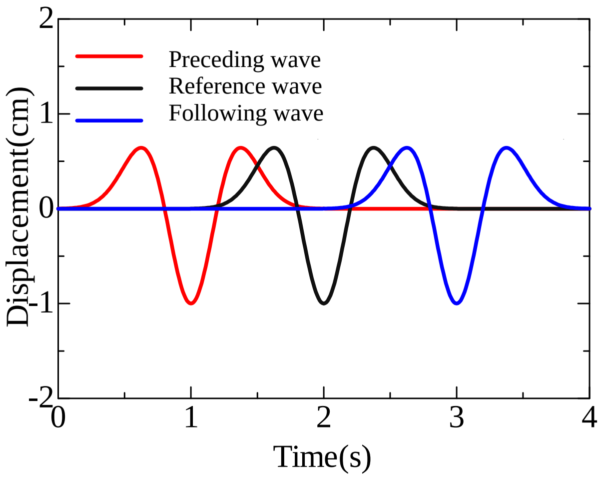


Fig. 1 – Ricker wavelets with different phase

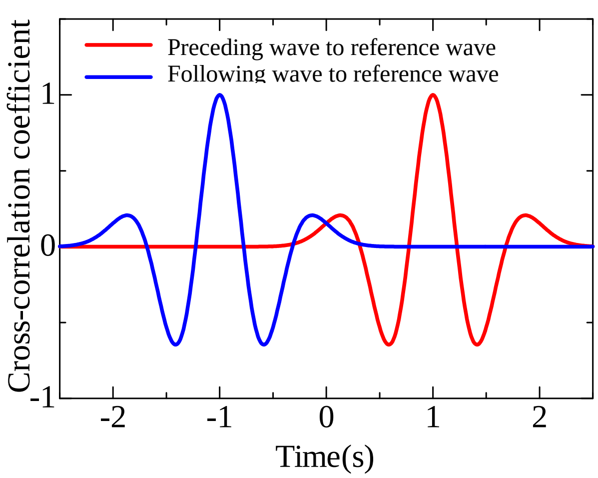


Fig. 2 – Cross-correlation coefficient of red and blue waves to the black one in Fig.1

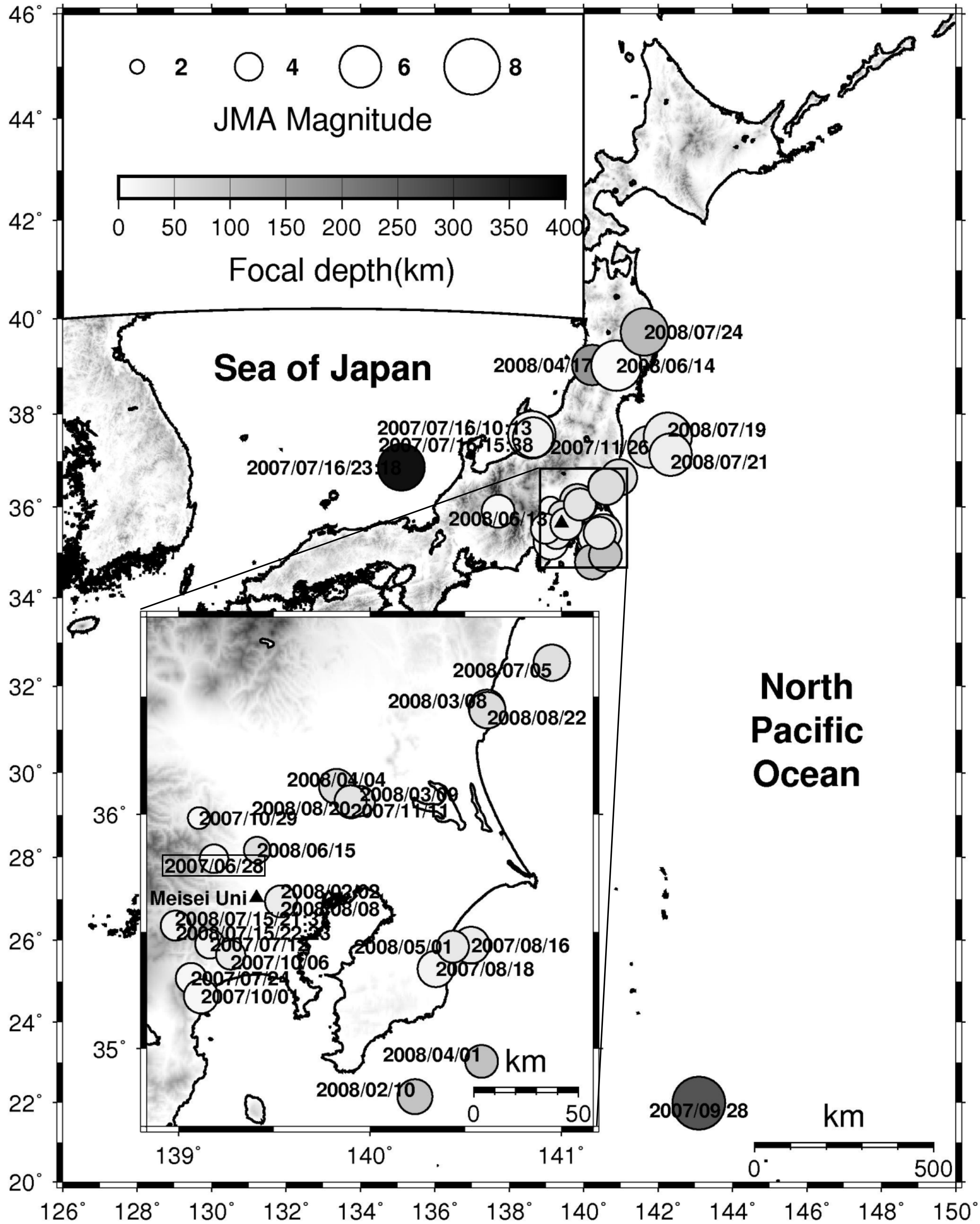


Fig. 3 – Location of the 27th building, Meisei University and epicenters of earthquakes used in the analysis

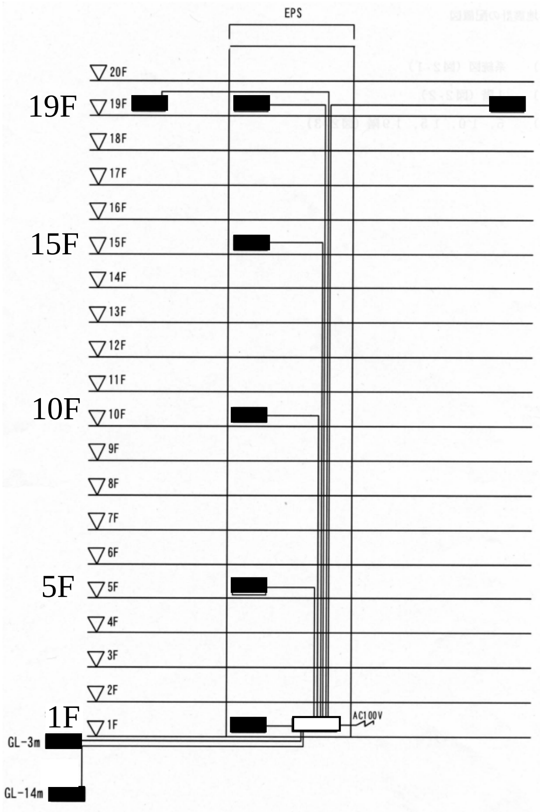


Fig. 4 – Location of seismographs deployed at the 27th building, Meisei University

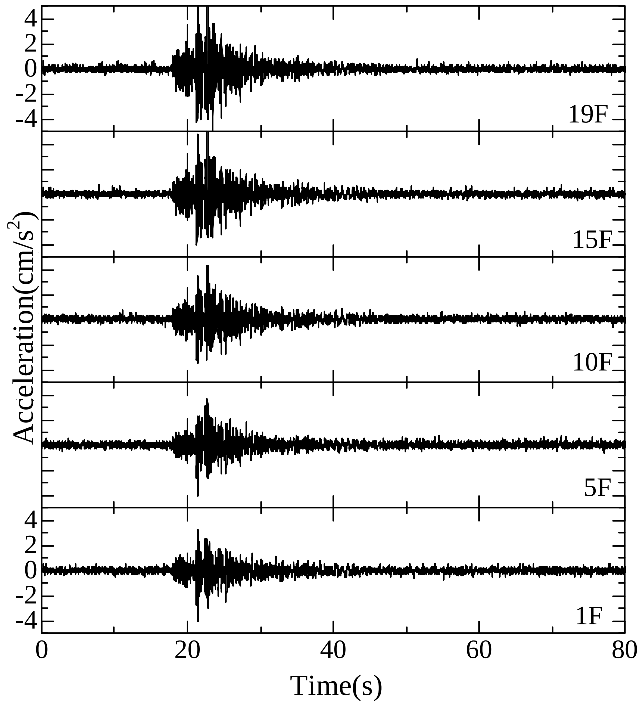
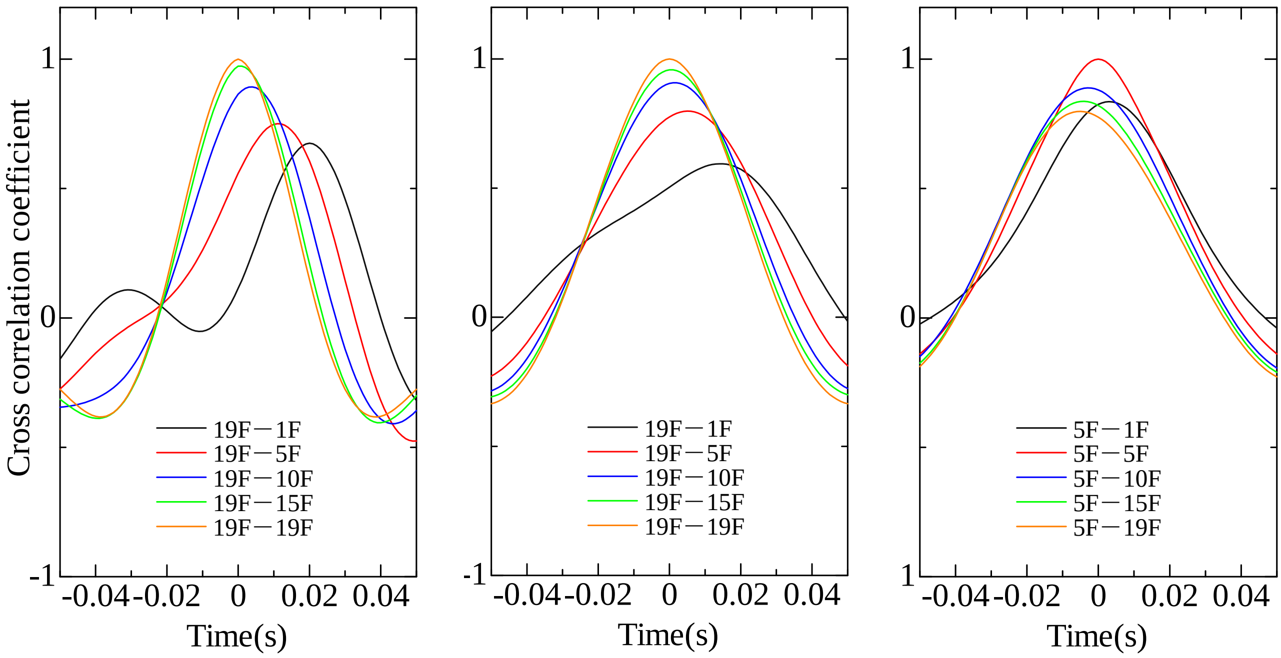


Fig. 5 – Seismograms in the vertical component observed during an event on 28 June 2007 (D=15km, M=4.1)



(a) 1s after P-wave arrival with respect to 19F

(b) 80s after P-wave arrival with respect to 19F

(c) 80s after P-wave arrival with respect to 5F

Fig. 6 – Cross correlation coefficient for the recording of 28 June 2007

3. Data set

Earthquake recordings used for cross-correlation coefficient study were observed at the 27th building, Meisei University, Tokyo. The building location is indicated in Fig.2 with a solid triangle. This RC+S building is 74.60-m high and 19 story constructed in 2007. Nine accelerographs were installed during the construction ("Pre-install" building). Time sampling rate is 100Hz and the resolution of A/D conversion is 0.08cm/s^2. Figs.4 and 5 respectively show the location of the accelerographs deployed in the building and time history of the vertical component observed in each floor during an event on 28 June 2007 (Focal depth=15km; JMA magnitude=4.1), the location of its epicenter is shown as a circle with a squarely surrounded date "2007/06/28" in Fig.3. The vertical time histories look similar with a slight amplification as the height of location implying the recordings are highly coherent. In addition to this event the location of epicenters of 34 events used in this study are shown as filled circles with radius and gray shade proportional to magnitude and focal depth, respectively. Seismograms of the events were observed from 28 June 2007 to 22 August 2008 with JMA magnitude 2.9 to 7.2 and focal depth 8 to 374 km.

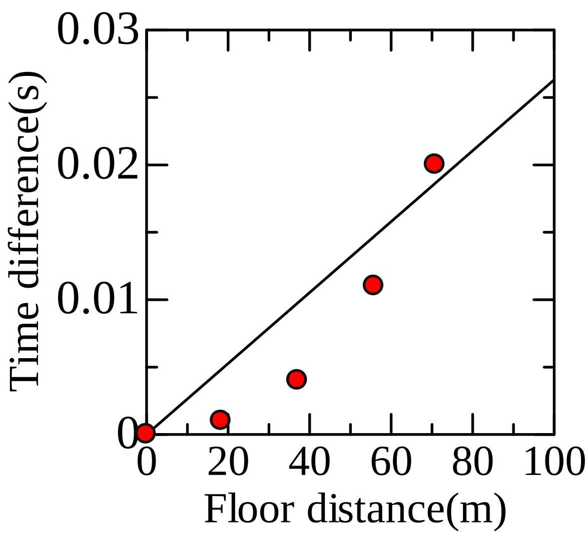


Fig. 7 – Plot of time difference vs. floor distance for the recording of 28 June 2007

4. Time difference among floors

4.1 Cross-correlation coefficient for an event on 28 June 2007

Fig.6 shows cross-correlation coefficient for the recording of 28 June 2007. Each cross-correlation coefficient has a marked peak with value larger than 0.5. Before the calculation of the coefficient, the original sampling rate is divided into 1000Hz so that variation of the coefficient vs. time can smoothly be obtained. The coefficient is obtained for the following three cases:

(a) For the first motion (1s after P-wave arrival and before S-wave arrival) with respect to the top (19th) floor

(b) For the whole motion (80s after P-wave arrival) with respect to the top (19th) floor

(c) For the whole motion (80s after P-wave arrival) with respect to a middle (5th) floor

In the case (a), PCC is greater than 0.6 showing high coherence in primary motion among the recordings. PCC becomes smaller and time difference becomes greater with the distance to the reference floor. Because the reference floor is 19F, the time difference is positive for all floors (i.e., phase at 1F, 5F, 10F and 15F are precedent to 19F). Fig.7 shows a plot of time difference vs. floor distance. When Young's modulus, Poisson's ratio and mass density of concrete are respectively assumed to be 30GPa, 0.2 and 2.3t/m^3, the P-wave velocity is estimated to be 3,800 m/s. The corresponding P-wave arrival time is shown with solid line in the figure. The time difference is equivalent to the P-wave arrival time indicating that incident P wave is propagated upward in the building during the initial motion.

Except for "19F-1F" in the case (b), PCC becomes greater and time difference becomes shorter in comparison to the case (a). This is probably because upward and downward P waves constitute stationary vibration for the whole motion. The longer the distance to the reference floor becomes the smaller PCC and the greater time difference become, respectively.

In the case (c), PCC becomes much greater and time difference becomes shorter. This is presumably because distance to the reference floor becomes shorter in comparison to the case (b). Because the reference floor is 5F, time difference is negative for "5F-10F", "5F-15F" and "5F-19F" (i.e., phase at 10F, 15F and 19F is behind 5F) while the time difference is positive for "5F-1F" (i.e., phase at 1F is precedent to 5F).

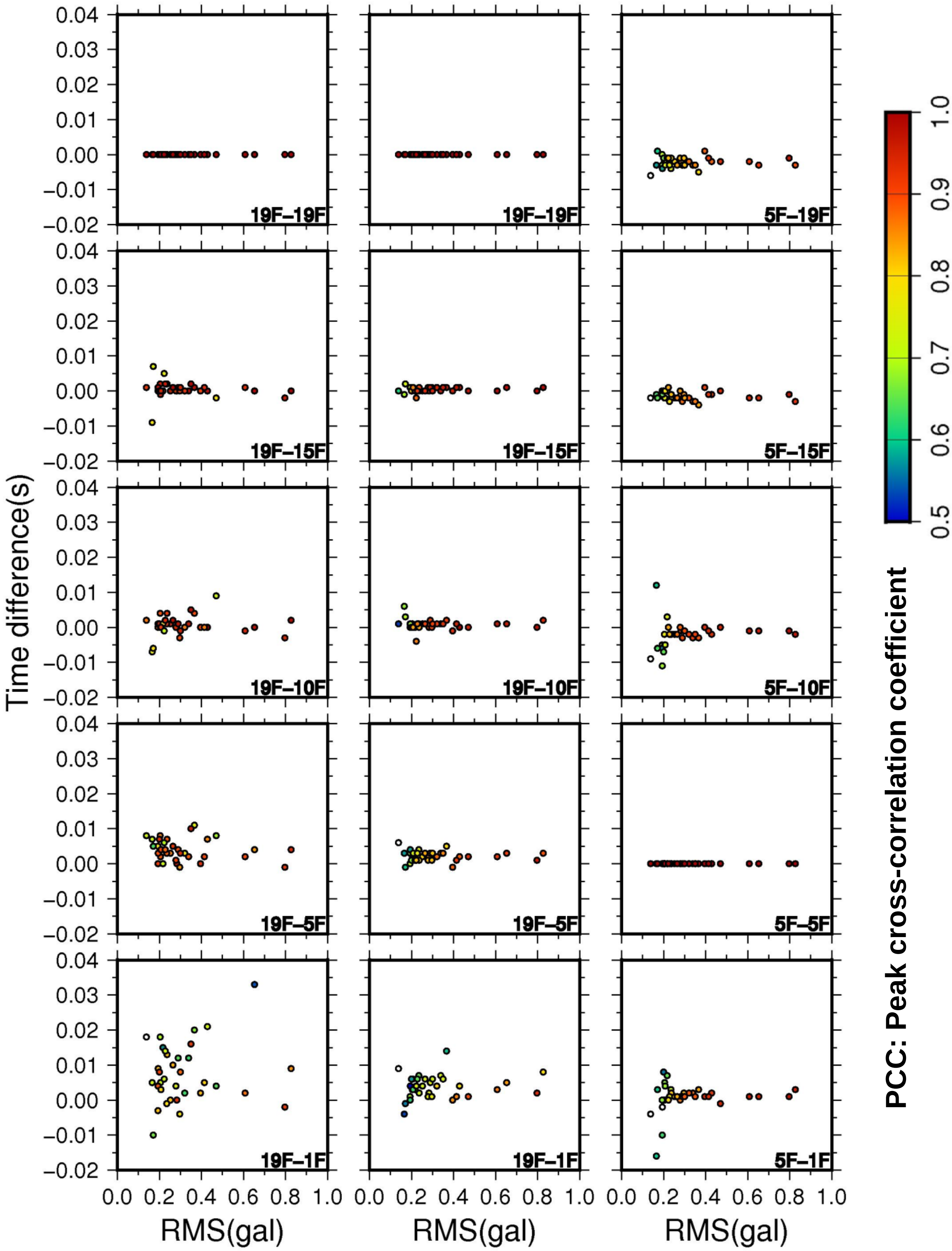
4.2 Cross-correlation coefficient for 34 events

In the same way as 28 June 2007 event, PCC and time difference for other 33 events are obtained. Fig.8 shows plots of time difference to the reference floors vs. RMS of vertical-component seismograms at 1F. PCC is also shown with filled colors. It can be seen that time difference is short and PCC is great for RMS greater than 0.4cm/s^2 indicating that PCC and time difference are affected by the accuracy of recordings. Because the resolution of A/D conversion of the recording system is 0.08cm/s^2, 0.4cm/s^2 is 5 times as the resolution.

Comparing with cases (a) and (b), time difference for the case (b) is shorter than that for the case (a) indicating that stationary vibration, constituted by upward and downward P waves, decreases phase difference with respect to the reference floor.

For RMS greater than 0.4cm/s^2, time difference for the cases (b) and (c) is within 0.01s. It should be noted that time difference and PCC for "5F-1F" are shorter and greater than those for "19F-1F" for the case (b) indicating that shorter distance to the reference floor produces shorter time difference and greater PCC.

Fig.9 shows plot of time difference to 19F vs. PCC for the case (b). Distance to the reference floor is shown with filled colors. As is described in Fig.8, shorter distance to the reference floor produces shorter time difference and greater PCC. For the distance shorter than 60m (from green to red) and for PCC greater than 0.7, time difference is within 0.005s that is practically assumed to be zero for 100Hz time sampling.



(a) 1s after P-wave arrival with respect to 19F
(b) 80s after P-wave arrival with respect to 19F
(c) 80s after P-wave arrival with respect to 5F

Fig. 8 – Plot of time difference to the reference floors vs. RMS of seismograms at 1F

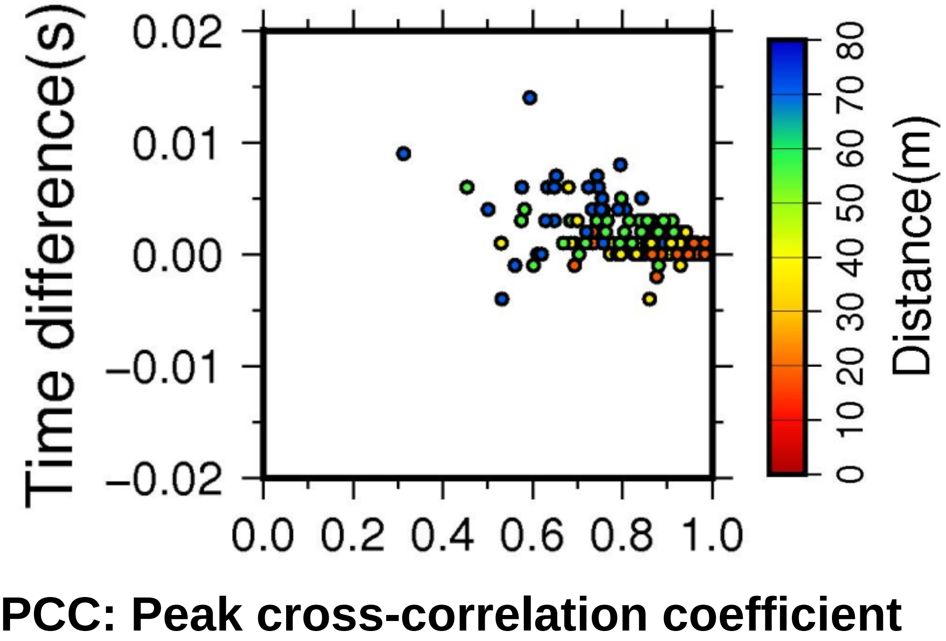


Fig. 9 – Plot of time difference to 19F vs. PCC

5. Procedure of synchronization of EQ recordings

The final result in the previous chapter that "time difference in the vertical component with respect to the reference floor for greater PCC is practically assumed to be zero for 100Hz sampling" allows us to synchronize vertical-array seismographs observed on floors without any accurate time record.

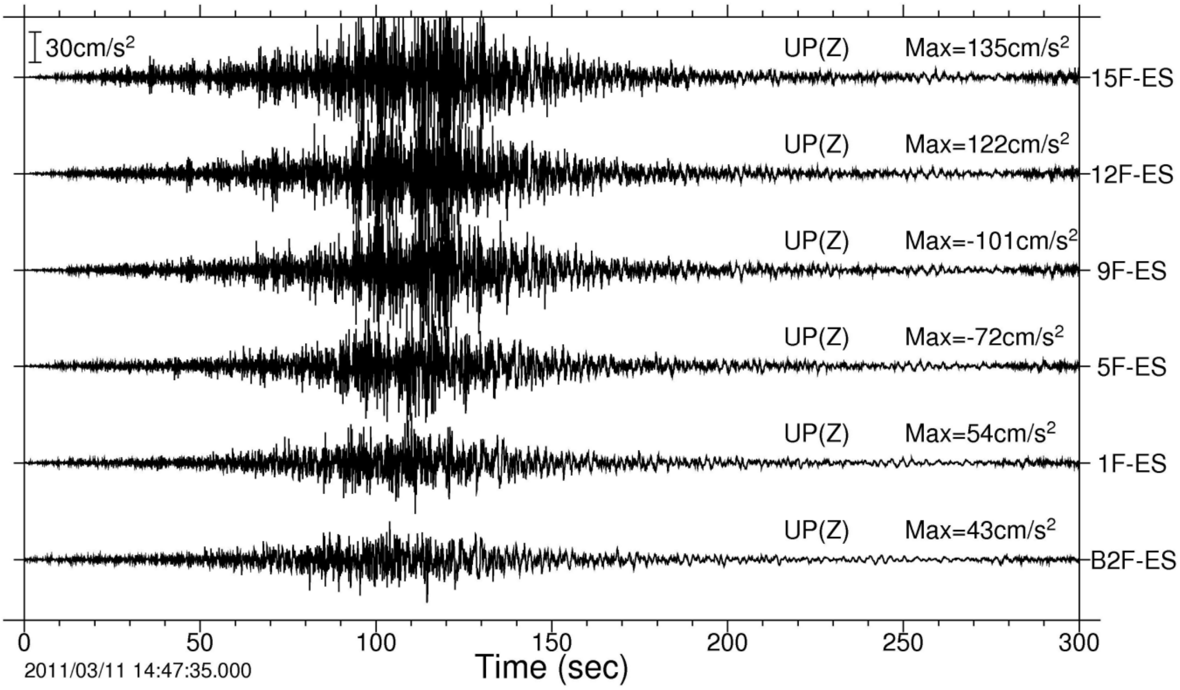
5.1 Example of synchronization

Fig.10 shows an example of synchronization of time histories at another high-rise building of this campus (29th building, Meisei University) observed on the Tohoku Pacific Ocean Earthquake of 11 Mar 2011 [2]. This SRC building is 74.17-m high and 17 story constructed in 2007. Accelerographs were deployed on 15th, 12th, 9th, 5th, 1st and B2nd floors in 2008 after the building construction ("Post-install"). GPS antenna was connected to the accelerographs on the 15th floor to calibrate the clock.

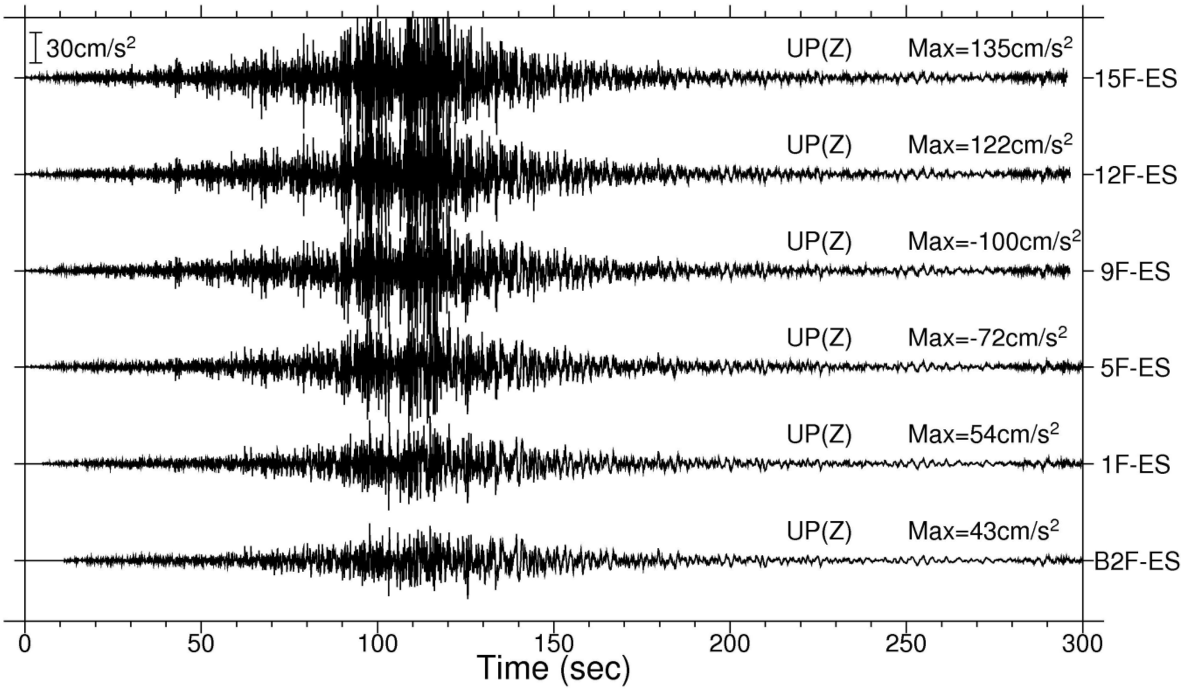
The upper figure (a) of Fig.10 is the original time histories (As observed) and the lower one (b) is after the synchronization. 5th floor is adopted as the reference floor. It can easily be seen that marked phases are synchronized to the reference floor.

Fig.11 shows cross-correlation coefficient of each floor with respect to the reference floor (5F). The upper figure (a) shows the cross-correlation coefficient for the original time histories (As observed) whereas the lower one (b) is after the synchronization. PCC and time difference can be obtained from Fig.11 (a), then synchronization can be carried out by using the time difference. After the synchronization, cross-correlation coefficient peaks at 0s (Fig.11 (b)). Table 1 shows time difference and PCC at each floor. Although PCC for B2F to 15F is 0.61 before the synchronization, the value exceeds 0.8 after the synchronization.

Fig.12 shows displacement mode shapes of the lateral building vibration for this event using the synchronized time histories. The synchronized accelerographs are integrated and band-pass filtered at the periods of fundamental and first higher modes (2.2s and 0.76s). Typical mode shape for the fundamental and first higher mode can be found (e.g., one node can be found around 12F for the first higher mode, etc.)

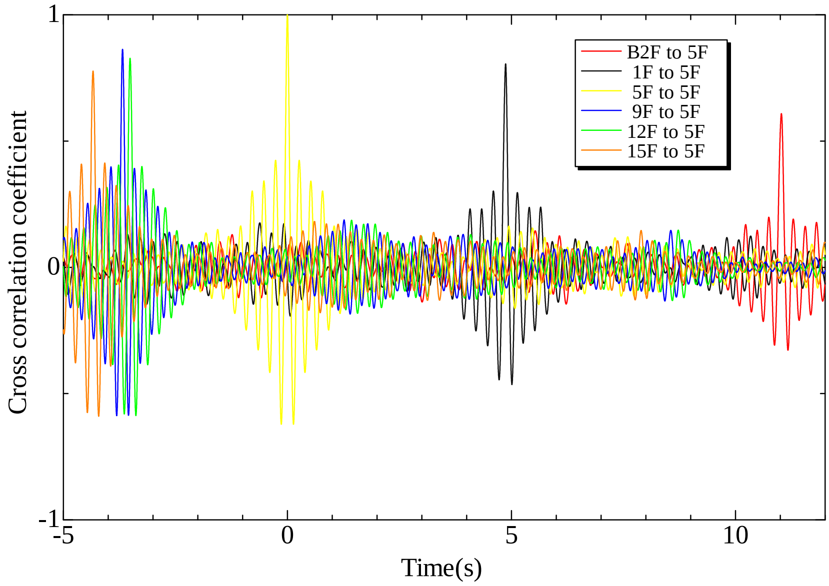


(a) As observed

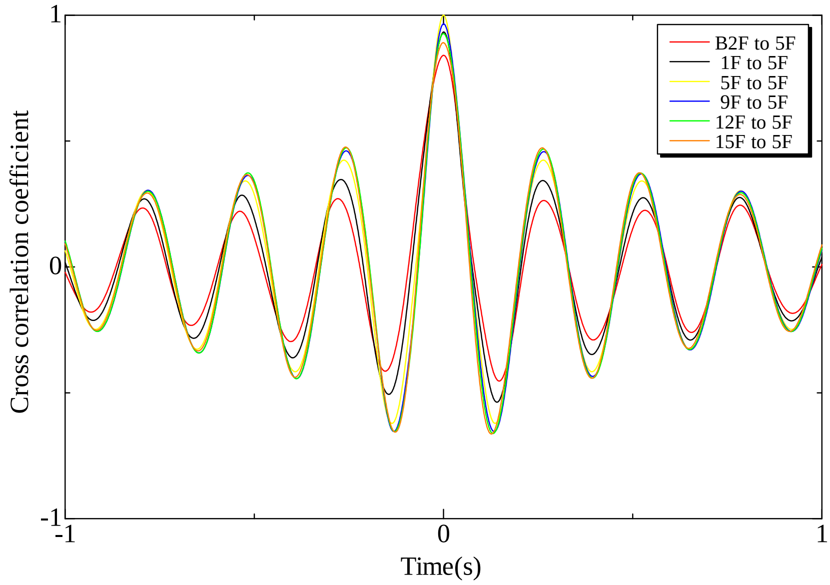


(b) Modified with vertical-component syncronization

Fig. 10 – Vertical time histories of accelerograms obtained at the 29th building of Meisei university during the Tohoku Pacific Ocean Earthquake of 11 Mar 2011



(a) As observed

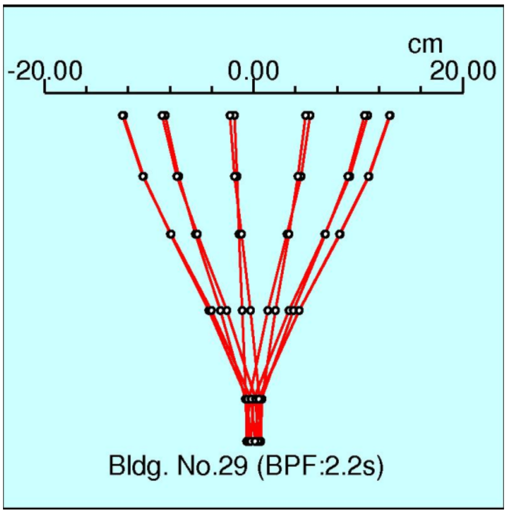


(b) Modified with vertical-component syncronization

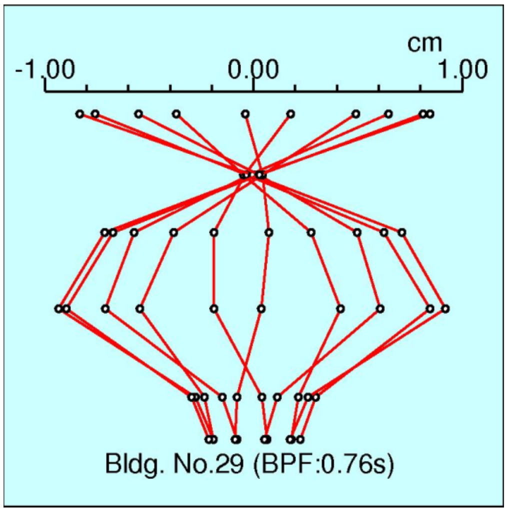
Fig. 11 –Cross correlation coefficient with respect to 5th floor for the veritcal recordings obtained at the 29th building of meisei university during the Tohoku Pacific Ocean Earthquake of 11 Mar 2011

Table 1 –Time difference and PCC evaluated from cross correlation coefficient with respect to the reference floor (5F) for the vertical recordings obtained at the 29th building of Meisei university during the Tohoku Pacific Ocean Earthquake of 11 Mar 2011. Distance to the reference floor is also shown.

Floor	Distance to 5F(m)	Time difference(s)	PCC (before sync.)	PCC (after sync.)
15F	40.75	-4.337	0.78	0.89
12F	28.00	-3.511	0.83	0.93
9F	16.00	-3.679	0.86	0.97
5F	0.00	0.000	1.00	1.00
1F	18.50	4.870	0.81	0.93
B2F	27.35	11.025	0.61	0.84



(a) Fundamental mode(2.2s)



(b) First higher mode(0.76s)

Fig. 12 –Longitudinal displacement modal shapes of the 29th building of Meisei university obtained from synchronized time hisotries for the Tohoku Pacific Ocean Earthquake of 11 March 2011

5.2 Summary of synchronization procedure

The synchronization procedure consists of the following operations:

1 The original time-history recordings are resampled at 1000Hz.

2 Determine the reference floor. Each floor is possible. For high-rise building, middle floor is preferable to reduce the distance to the reference floor. If the precise time is required, the floor at which the clock is calibrated should be selected.

3 Calculate cross-correlation coefficient for the vertical seismograph with respect to the reference floor.

4 Evaluate PCC and time difference from each cross-correlation coefficient.

5 Shift the time history by the amount of time difference. Shift backward when PCC is positive and vice versa. Check PCC whether the value is great enough to determine time difference. PCC greater than 0.7 is preferable.

6 Resample the synchronized time histories at 100Hz or any desirable time steps suitable for further analysis.

6. Conclusions

In this paper time difference of vertical component of accelerograms observed on several floors in a 75-m high and 19-story RC building is investigated. Followings are conclusions obtained herein:

1 Significant time difference is found from cross-correlation coefficient for 1s after P-wave arrival. The time difference is equivalent to the P-wave arrival time indicating that incident P wave is propagated upward in the building during the initial motion.

2 Shorter time difference is found from cross-correlation coefficient for 80s after P-wave arrival. This is presumably because the cross-correlation coefficient evaluated from the whole motion is affected by the superposition of upward and downward waves vertically propagated in the building. The waves constitute stationary wave which is substantially equivalent to vibration of vertically fundamental mode.

3 Much shorter time difference is found when middle floor is employed as a reference floor. PCC also becomes greater according to the reduction of the distance to the reference floor.

4 Time difference depends on the resolution of the recordings, distance to the reference floor and PCC. Time difference is practically assumed to be zero when the distance to the reference floor is shorter than 60m and PCC is greater than 0.7.

5 The previous finding allows the synchronization of vertical-array seismograms observed on floors without any calibrated clock.

7. Acknowledgment

The earthquake recordings used in the study were supplied from Mr. Takashi Hayakawa, Shimizu Corporation. GMT is used to depict a couple of figures.

8. References

[1] Kinoshita T, Nakamura N, Kashima T (2019): A study on characteristics of the first-mode vertical vibration of buildings based on earthquake observation records. *Journal of Structural and construction engineering*, **84** (766), 1545-1555 (in Japanese with English abstract).

[2] Toshinawa T, Kato K, Koketsu K (2011): Strong-motion Response of the 17-story SRC Building for School of Science and Engineering, Meisei University, *Summaries of Technical Papers of Annual Meeting, Architectural Institute of Japan*, 329-330 (in Japanese).

