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ON THE CERS METHODS FOR REALTIME EVALUATION ON A TRAVEL TIME AND DAMPING

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Abstract

The basic matters on the earthquake disaster prevention are to grasp properly an actual condition of ground and/or structures. Here proposes various methods to grasp the changing situation of a wave travel time and a damping factor for ground and structures in realtime. The proposed methods, the CERS methods, are verified with the results of other researches using waveforms recorded at 9F and 1F of Civil Engineering and Architecture Research Building of Tohoku University at the time of the 2011 off the Pacific coast of Tohoku Earthquake and compared with each proposed method. As a result, this paper confirms that the C method is applicable for proper investigation of the wave propagation time and damping and additionally makes clear partly the interrelationship between the E, R and S methods. It is expected to review the availability of the CERS methods applying to various targets as ground or structures for the next stage.

Keywords: CERS methods, realtime health monitoring, wave travel time, damping, ground, structures

1. Introduction

The wave travel time and/or the damping characteristics are used as an index to evaluate degradation level of ground and structures. Although there are various methods to measure a travel time between two points and other indices, this paper proposes new methods [1] for realtime processing and verifies their validity and availability with validation examples.

2. Outline of proposed methods

The "CERS <sə:rz> methods" is an inclusive name of four methods, C, E, R and S methods, as Fig. 1. The C method can calculate in realtime the wave propagation time and damping between a free end and a point among medium till the reflecting plane assuming a one dimensional wave field, and the E method can also calculate them between a free field and reflecting plane. Additionally, the R and S methods can generally calculate in realtime the time difference of waveforms between two points separated spatially based on the maximum cross-correlation basis and minimum simple error basis, respectively. The result of these four methods can be checked mutually.

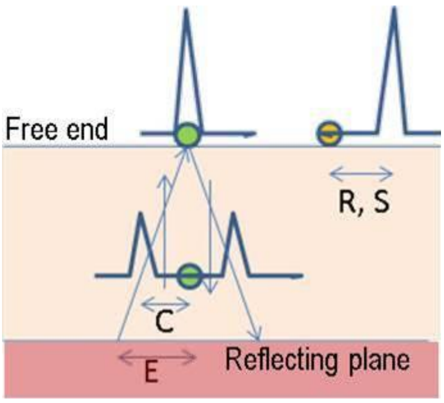

Fig. 1 – Concept of the CERS methods

2.1 Methods with waveform synthesis

For example in case of a horizontally two-layered ground, it is possible to describe the vibration situation of arbitrary point in surface layer as a sum of upward wave and downward wave where the upward wave is incident wave or reflected wave from base ground and the downward wave is reflected wave at the ground surface. From this, it is possible to derive the travel time from ground surface to the observation point in the ground using two observed waveforms at ground surface and the other point in the surface layer. This is called "C method" (Complete Travel Time Tracer). Specifically, once a travel time is assumed and waveform of a point in the surface layer is estimated from the observed waveform at ground surface. And then the travel time is determined as a time minimizing the difference between observed and estimated waveform. In case of no observed waveform in the surface layer, the difference becomes the estimated waveform itself and the minimum estimated waveform gives the travel time at the base ground layer or the main reflection layer. Thus, it is possible to estimate the travel time between the ground surface and the basement layer only from the observed waveform at the ground surface. This is called "E method" (Easy Travel Time Tracer). It seems to be possible in principle to estimate the layer structure with eliminating the reflect wave from the reflect layer after another. Additionally, it is possible to consider similarly the travel time between an edge point and an intermediate point of a thin rod.

2.2 Method with cross-correlation

A method with realtime cross-correlation "R method" (Relative Travel Time Tracer) is also available for deriving the travel time between two points.

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2.3 Method with simple process

This method estimates simply the travel time as a time minimizing the difference between two observed waveform, and is called “S method” (Simple Travel Time Tracer). This method sometimes requires contrivance to reduce the amplitude to half in case of including an edge point among the two observation points.

3. Details of each technique

Here describes the concrete procedure of the CERS methods, consisted of four methods, C, E, R and S methods. Symbols used below are defines as follows;

$T(t)$: Waveform observed at an end point
$G(x,t)$: Observed waveform in ground at distance x from the edge point, $G(0,t) = T(t)$
$O(x,t)$: Observed waveform at the point x
α: Distance damping factor (1/m)
h: Damping factor (%)
ω: Angular frequency (rad/s)
Δt: Sampling time interval (s)
V: Wave distribution velocity (m/s)
$Err(t)$: Error function
$RE(t)$: Relative error function
$TR(t)$: Cross correlation function

3.1 The C Method

Waveform observed in ground $G(x,t)$ is expressed as follows;

$$G(x,t) = \{T(t + x/V) \times e^{+\alpha x} + T(t - x/V) \times e^{-\alpha x}\}/2 \quad (1)$$

The travel time x/V from an end point to point x can be expressed below based on the sampling time interval Δt.

$$x/V = k\Delta t \quad (2)$$

Estimated waveform $H(I,j)$ at a point y $(= i\Delta tV)$ from the end point is expressed as follows when $t = j\Delta t$;

$$H(i,j) = \{T(j\Delta t + i\Delta t) \times e^{+\alpha i\Delta tV} + T(j\Delta t - i\Delta t) \times e^{-\alpha i\Delta tV}\}/2 \quad (3)$$

$$Err(i,j) = [(H(i,j) - G(x,t))^2] \quad (4)$$

Here the operator [*] means averaging of * for a time distance.

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$$Err(j) = \min[Err(i,j)] \tag{5}$$

$$R(j) = [G(x,t)^2] \tag{6}$$

$$RE(j) = \sqrt{Err(j)/R(j)} \tag{7}$$

When $y = x$, the estimated waveform fits with the observed waveform. When $i = k$, i makes $Err(i,j)$ minimize for each j changing in time. Thus, it is possible to estimate the travel time based on the sampling time interval. In general, because α is unknown, it is set 0 at first and after fixing the travel time, m can be derived as minimizing the error with calculating $H(k,j)$ for some m same as the travel time setting $\alpha = m\Delta$. Although this procedure delays for the estimated maximum travel time, it has characteristics as available to derive in realtime. It is also possible to shorten the resolution of the travel time with various interpolations. Additionally, the relationship between a distance attenuation α and damping constant h is as follows;

$$\alpha = \pi h/2H \tag{8}$$

This is derived from the following procedure. Here, H is a thickness of a surface ground or a height of a building. Attenuation Dx for a distance x is

$$Dx = e^{-\alpha x} \tag{9}$$

So attenuation Dt of a vibration with natural circular frequency ω during a time t is

$$Dt = e^{-h\omega t} \tag{10}$$

Setting equal Dx and Dt under $x = Vt$, we can get

$$\alpha V = h\omega \tag{11}$$

And then,

$$\omega = 2\pi f = 2\pi(V/4H) \tag{12}$$

So we can get the relationship mentioned above.

3.2 The E Method

This can get when the waveform in ground is set 0 in case of the C method.

3.3 The R Method

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A cross correlation function $TR(j)$ between two waveforms $O(x,j)$ and $O(y,j)$ can be derived as follows.

$$R(i,j) = [O(x,j) \times O(y,j-i)] \tag{13}$$

$$Rx(j) = [O(x,j)^2] \tag{14}$$

$$Ry(j) = [O(y,j)^2] \tag{15}$$

$$TR(j) = max[abs(R(i,j)] \times sign(R(i,j))/\sqrt{Rx(j) \times Ry(j)} \tag{16}$$

For two waveforms, in case of computing the correlation of the time difference between plus and minus as time difference i and $-i$, it is possible to consider the time difference with plus and minus using the waveform data till present time with changing the reference waveform. In other words, it is possible to calculate cross-correlation TR in realtime without time delay. An i giving maximum absolute $R(i,j)$ becomes the time difference between two waveforms $O(x,j)$ and $O(y,j)$ in an unit of sampling rate. It is also possible to make the resolution less than the sampling rate using proper interpolation.

3.4 The S Method

A root mean square $Err(i,j)$ of the difference on the amplitude between two waveforms $O(x,j)$ and $O(y,j)$ with time difference i can be derived as follows;

$$Err(i,j) = [(O(x,j) - O(y,j-1))^2] \tag{17}$$

$$RE(j) = \sqrt{min[Err(i,j)]/\{Rx(j) \times Ry(j)\}} \tag{18}$$

In case of calculating the root mean square of the difference on the amplitude between two waveforms for the time difference in plus and minus, it is possible to consider plus and minus of the time difference using waveforms up to this time with changing the based waveform. In other word, it is possible to calculate the Realtime Error RE without time delay in realtime. The minimum time difference i giving minimum square of the amplitude of two waveforms or minimum relative error becomes the time difference between these two waveforms in a unit of sampling interval. It is also able to make the resolution of calculation less than the sampling interval using proper interpolation.

4. Validation examples of the methods

The CERS methods are applied for Civil Engineering and Architecture Research Building of Tohoku University using recorded waveform at the time of the 2011 off the Pacific coast of Tohoku Earthquake (hereinafter "311 Earthquake"). This building had been completed in 1969 and had damaged severely by the 1978 Miyagi-ken Oki Earthquake. Then it was retrofitted largely for anti-seismic in 2000. Please see the papers [2, 3] for damage situation, strong motion observation or other details of this building. Fig. 2 shows the accelerogram of the 311 Earthquake observed at 9F and 1F of this building.

The waveforms used for the CERS methods are averaged by exponential smoothing with setting the half-life period of 5 seconds. At first the result of the C method is compared with change of the predominant frequency or the damping factor during the earthquake motion identified by other researchers. And then the travel time estimated the CERS methods are compared mutually.

4.1 Comparison of the result between the C method and other researchers

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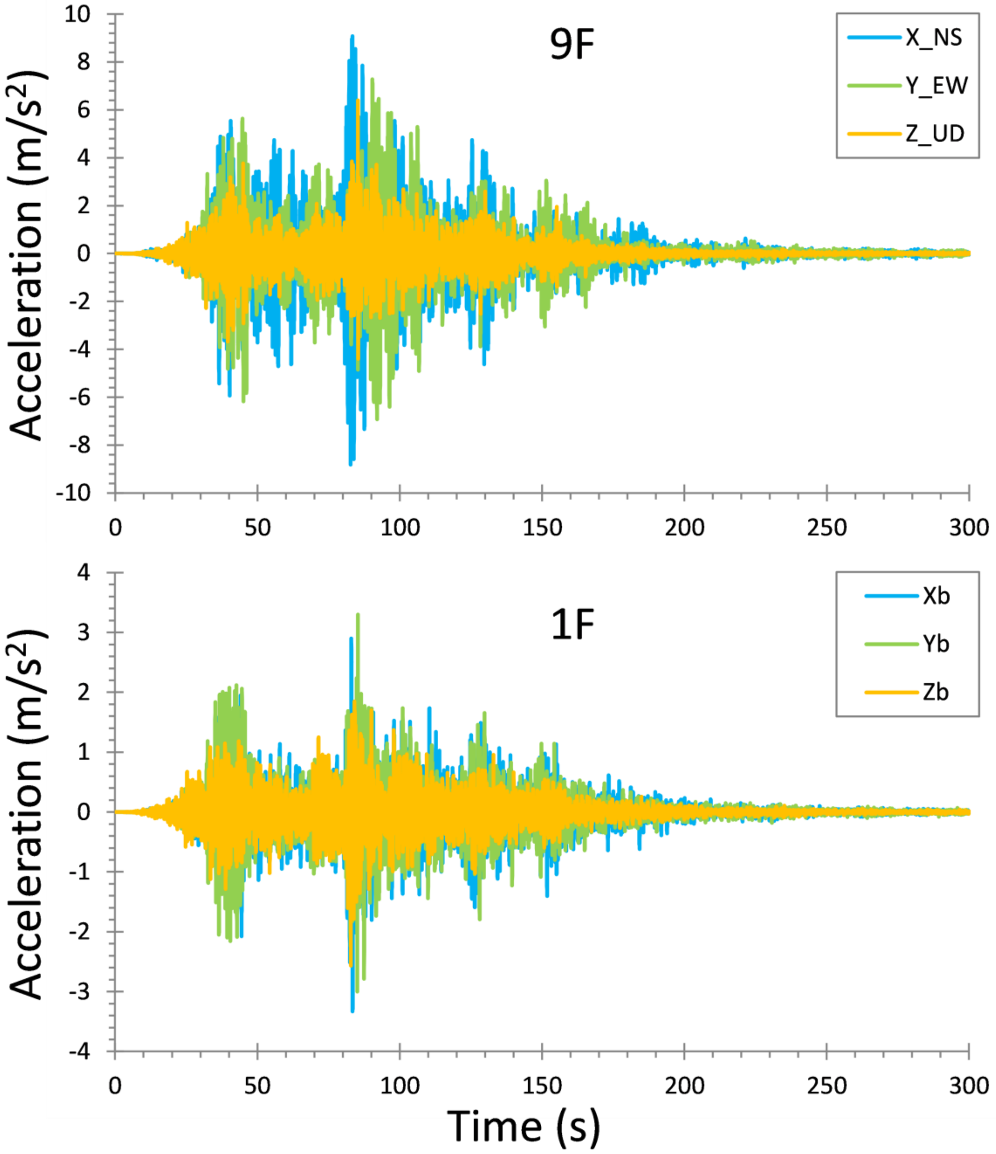

Fig. 2 – Accelerogram of the 311 Earthquake observed at 9F and 1F of Civil Engineering and Architecture Research Building of Tohoku University

Fig. 3 shows the result of comparison between the change situations of the predominant frequency during the 311 Earthquake identified by BRI, Building Research Institute [2] and the estimation result of the C method. Here, the predominant frequency of the C method is derived as the inverse of quadrupled travel time between 9F and 1F. Although it is hard to say that continuous estimation result of the C method fits closely with the predominant frequency determined discretely by BRI, the trend of both results roughly agrees with each other.

Motosaka et al. [3] identified the change situation of the predominant frequency and the damping factor during the earthquake motion using extended Kalman filter, and Fig. 4 shows the comparison between the change situation above and that derived from the C method. The predominant frequency derived from the C method agrees well with that by Motosaka et al. The damping factor derived from the C method is distributed as an envelope curve of the result by Motosaka et al., and it is possible to say that the changing situation is similar to each other.

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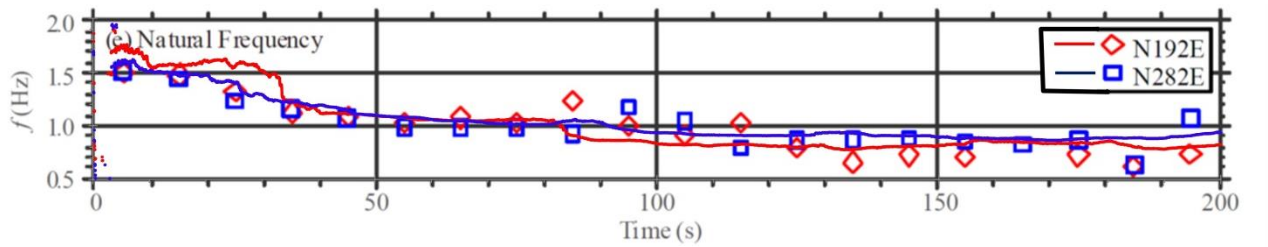

Fig. 3 – Comparison of the estimated natural frequencies; derived natural frequency from the C method is overlaid as blue and red lines on the identified natural frequencies by BRI [2] as square and diamond marks.

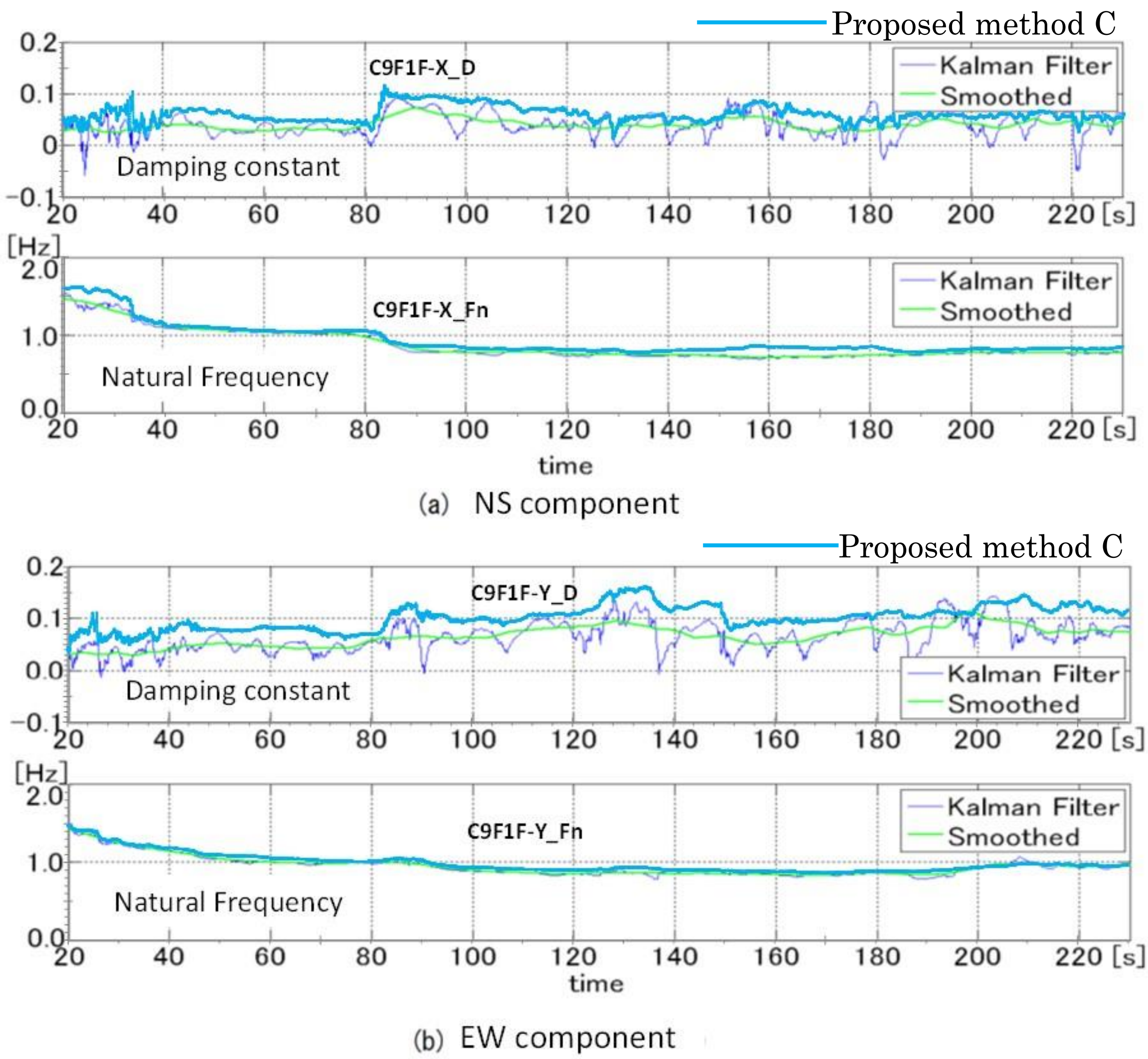

Fig. 4 – Comparison of the estimated natural frequency and damping factor; the estimated results applied proposed C method are overlaid as a blue line on the evaluation results of existing method [3] as purple and green lines.

The result of the C method can derive the change situation clearer than the past researches and is reminiscent of the damage situation. Thus, it is possible to estimate that a corner column at north-south side was suffered serious damage by the first attack and then destroyed completely by the secondary shock after 80 seconds.

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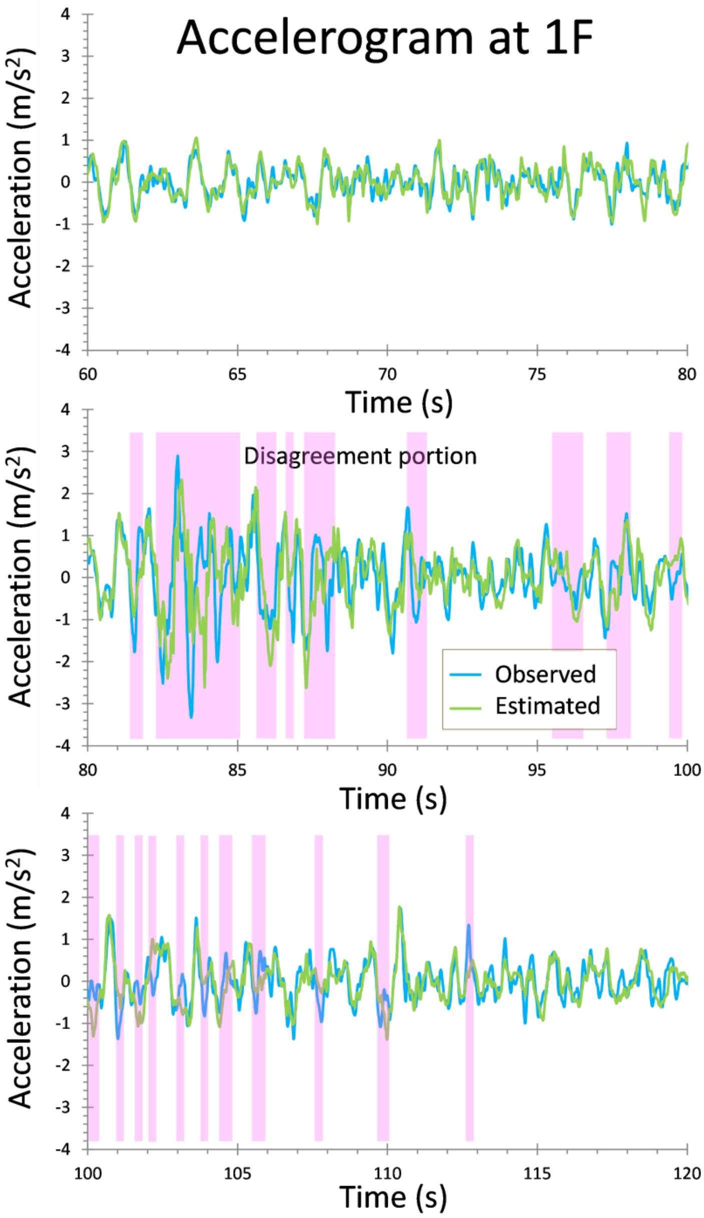

Fig. 5 – A partial result of comparison between the observed waveform and estimated one applying the C method to the observed waveform at 9F

Fig. 5 shows the result of comparison between the observed waveform at 1F and the estimated waveform by synthesizing technique mentioned above. This figure shows the waveform during 60 seconds, from 60 second to 120 second from the beginning of observed waveform, and includes the portion with drastic change of the travel time and the damping factor at around 82 second. Both observed and synthesized waveforms generally agree, but they dissociate at the portion with drastically change as shown as pink bands in this figure. Dissociation between observed and synthesized waveform means departure from expected wave field. There is singular distinction especially between 83 second to 85 second, and it suggests interruption of continuity between observed waveform at 9F and 1F because of fracture of columns and so on.

Fig. 6 shows change of relative error. Purple and blue lines in this figure indicate considering and not considering damping, respectively. The relative error decreases significantly with considering damping, before and after the large change of the travel time and so on. It is estimated that irreversibly damage was caused because the relative error becomes large as stepping after the secondary shock.

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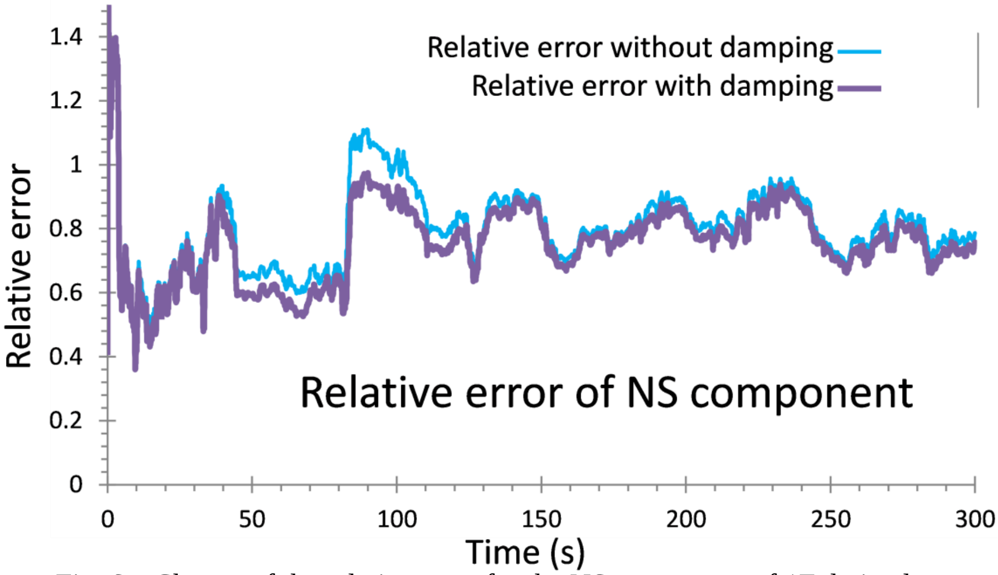

Fig. 6 – Change of the relative error for the NS component of 1F derived from the waveform at 9F applying the C method

4.2 Intercomparison of the CERS methods

Fig. 7 compares the change of the travel time derived from the CERS methods for north-south and east-west directions. This figure indicates the C method as purple dots, the E method as orange dots, the R method as blue dots and the S method as green dots. It is confirmed that the R and S methods give almost similar result. Although it is hard to find the result of the R method because of overlapping with that of the S method, it is possible to see the result of the R method at the portion with large difference of the result between the R and S methods, around the first and the secondary shock.

The result of the C method agrees well with the result of identification with extended Kalman filter as mentioned above, and it is confirmed that the results of the CERS methods also behave centering on the result of the C method. The result of north-south direction shows large variation especially for the R method same as the S method. In cased of east-west direction, the results and variation are almost similar to each method. It seems that the large variation at north-south direction reflects the significant damage for this direction. The estimation result of the E method corresponds to the travel time between the top of the building and the reflecting base layer and is similar to that of the C method in this time. It suggests the possibility of judgement on damage situation roughly only from the information at 9F.

The change of the travel time corresponds to the change of the physical property, and it is possible to utilize as a direct index for the damage degree. In case of this building, the travel time was around 16 (in unit of 1/100 seconds, the same hereinafter) at beginning of the waveform. And then after the first shock, it reaches drastically about 23 and then keeps increasing for NS direction, and increases to about 28 for EW direction. Although it tends to recover for each direction, the travel time becomes around 27 and 23 at the time of recording termination for NS and EW direction, respectively. The rigidity of NS direction seems to decrease passingly to quarter against the initial value, and it suggests the intensity of the damage.

Fig. 8 shows the behavior of the coefficient cross-correlation between 9F and 1F derived from the R method. The coefficient for each direction was about 0.6. It increases drastically by two shocks and then decreases sharply for NS direction. The variation of EW direction is smaller than that of NS direction, and the coefficient keeps basically over 0.6. Contrary with this, the coefficient of NS direction becomes over 0.8 after second shock at 80 seconds and decreases close to 0.3 at 140 seconds. Although it recovers with repeatedly increase and decrease, it reaches up to about 0.4. This variation of the coefficient of cross-correlation suggests the severe damage on NS direction.

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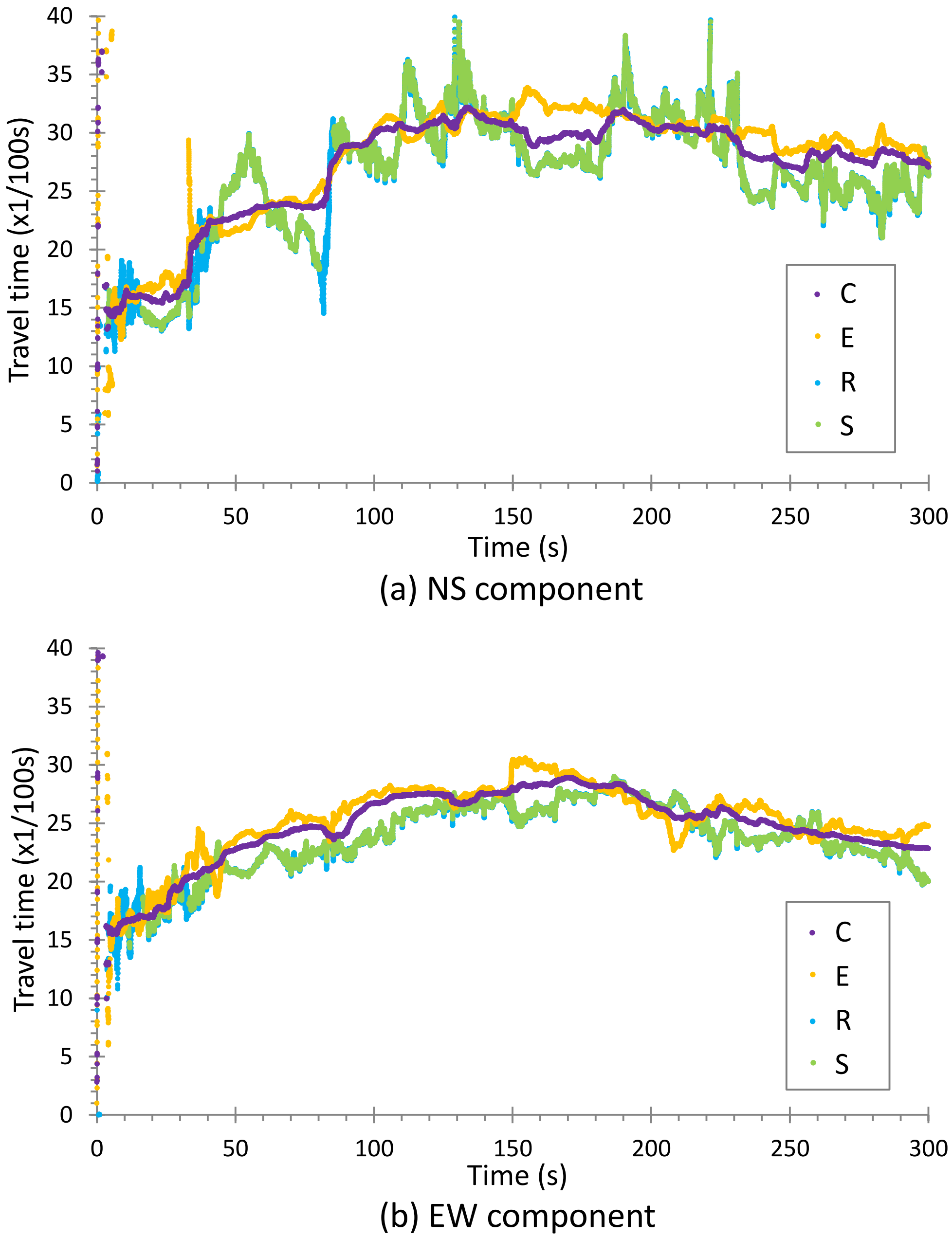

Fig. 7 – Comparison between the travel times estimated by the CERS methods

5. Discussion on application of proposed methods

5.1 The wave travel time in the ground

It seems that two horizontal components and a vertical component correspond to S and P waves, respectively. This may be similar to buildings. In any case, these proposed methods can use not only strong motion records or microtremor but also impact vibration. Although each type of waveform can be applied for the CERS methods, it is necessary for each object to be applied individually to rigorously consider the location and direction of input wave, in case of the R and S methods. Examples of usage are shown in the papers [4, 5].

5.2 The wave travel time at the ground surface

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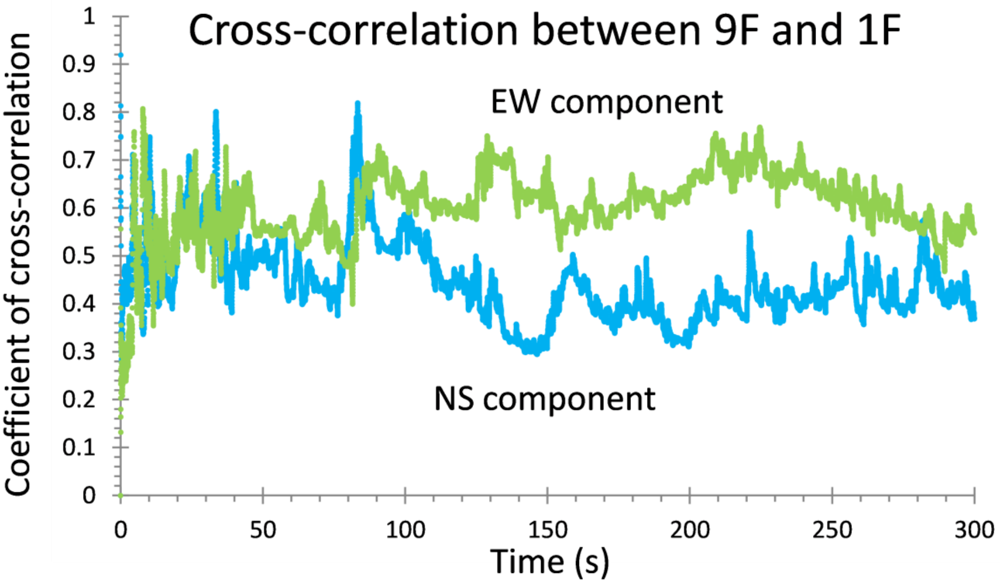

Fig. 8 – Behavior of the cross-correlation coefficient between 9F and 1F derived from the R method

The wave motion propagating horizontally with hitting ground surface vertically is considered as S wave (SV wave). The propagation of P wave is expected by hitting horizontally the ground surface toward the direction form a site 1 to a site 2 or the opposite direction, and then the propagation of S wave (SH wave) is expected by hitting horizontally across the P wave. Because the wave kind and propagating direction of microtremor is uncertain, it is necessary to adopt a value giving maximum travel time with high correlation for R method or with small relative error for S method. Examples of usage are shown in the papers [6, 7].

5.3 The wave travel time of buildings

Generally in case of vibration in buildings, it is considered that horizontal two components correspond to S wave or bending wave, vertical component corresponds to axial vibration as P wave in a rod-like structure, and torsional vibration corresponds to S wave. Although it is possible for these vibrations to adopt each of the CERS methods, it is necessary to rigorously consider the location and direction of input wave in case of R and S methods.

5.4 Application in general

The CERS methods proposed here is a breakthrough technique to confirm the state of structures and ground in realtime and realize providing a correct way of responding, because the CERS methods can be processed in realtime. Additionally, the E method can be also applied as a technique to confirm the natural or predominant frequency of the surface ground or target structures. In case of conventional methods finding the travel time with comparing rises of the waveform, the found propagation velocity is considered to the phase velocity. On the other hand, the propagation velocity derived from proposed the C, E and S methods with synthesizing waveforms is seems to correspond to group velocity because of minimizing the energy of error. Meanwhile, it seems that the R method detects a phase velocity.

6. Conclusion

This paper proposes new methods to confirm the wave travel time and damping in realtime. It is expected that these proposed methods can be applied to monitor accurately various targets as buildings or ground. Thus, it is expected to realize various merits as seismic assessment before an earthquake occurrence, state monitoring during an earthquake, and determining a damaged part and confirming an extent of it promptly after an earthquake. I have compiled many applied cases though unreleased and developed with trial of a realtime processing instrument for actual application of these methods.

7. Acknowledgement

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