Research Article

Quantitative Identification of Pulse-Like Ground Motions Based on Hilbert–Huang Transform

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Aiming to address the problem of pulse-like ground motions being difficult to identify, this paper refines the Baker’s wavelet-based pulse-like ground motions identification method, followed by a new pulse-like ground motion identification method based on Hilbert–Huang Transform (HHT) being proposed. In this method, HHT is used to decompose ground motions instead of wavelet. HHT can overcome the dependence of wavelet analysis on the selection of mother wave, and thus more complex velocity pulses can be identified. In order to compare the effects of two pulse-like ground motion identification methods, HHT-based method and wavelet-based method, respectively, are used to identify ground motions in Pacific Earthquake Engineering Research Center (PEER). After identifying the 3066 groups of ground motions selected from PEER, it is found that the HHT-based method can identify 229 pulse-like ground motions, and the wavelet-based method can identify 150 pulse-like ground motions. More complex shapes of near-fault velocity pulses can be extracted by the HHT-based method. By analyzing the seismic response, fault distance, and cumulative squared velocity (CSV) of these pulse-like ground motions, it is found that the pulse-like ground motions identified by the HHT-based method have strong near-fault characteristics. If a high recognition quality can be guaranteed, the proposed HHT-based method can identify many kinds of near-fault velocity pulses and thus provide more pulse-like ground motions for seismic researches.

1. Introduction

Pulse-like ground motions are considered to be one of the most dangerous types of ground motions. Many structures were destroyed by the pulse-like ground motions, such as buildings, bridges, and dams [1–4]. Several advanced techniques were used to simulate pulse-like ground motions [5]. These studies have shown that the pulse-like ground motions are quite different from the ordinary ground motions [6, 7].

The most important part of seismic analysis is to distinguish pulse-like ground motions from common ground motions, which is a huge challenge for researchers at present. Due to the complexity of ground motions, it is difficult to find a single criterion to classify all pulse-like ground motions [8]. The velocity pulses in pulse-like ground motions are considered to be the most important feature and the main cause of damage [9]. The velocity pulses are used by many seismic researchers to define pulse-like ground motions. Because of the diversity of the velocity pulse, the method for extracting the velocity pulse is different. There are three main reasons for the diversity of velocity pulses: seismic mechanism, released energy, and stratigraphic differences. The combination of these factors may lead to various forms of velocity pulses. Due to the difference of ground motion velocity pulse, it is difficult to identify ground motion with a single waveform [10]. The main existing methods include the piece-wise linear triangular velocity plus extraction method, sinusoidal velocity plus extraction method, and multiparameter decaying velocity plus extraction method [11]. Some scholars use the pulse energy to assist in judging the pulse ground motion [12] and even the response of structures [13].

Compared with other non-Gaussian signals, the non-linear characteristics of ground motion signals are more obvious [14–17]. Therefore, one limitation of these methods
is that the velocity pulse cannot be identified quantitatively
and autonomously. A convenient and repeatable method for
pulse-like ground motions identification is still needed for
seismic engineering. In this regard, Baker [18] proposed an
identification method based on wavelet analysis. This
method does not use a simple pulse shape to match the
velocity pulse but uses continuous wavelet transform to
decompose and reconstruct the signal to obtain the velocity
pulse. The pulse index of potential pulse is calculated, and
the near fault pulse is identified by judging the pulse index.
However, the accuracy of wavelet analysis depends on the
choice of mother wavelet. As for the pulse direction, an
algorithm that can identify pulses at arbitrary orientations in
multicomponent ground motions is proposed. Continuous
wavelet transform is used to identify the direction most
likely to contain pulses in the two orthogonal components of
ground motion. This recognition method greatly improves
the efficiency of recognition [19]. For the effect of pulse on
the structure, some scholars further divided the velocity
pulses into distinct acceleration pulses and nonacceleration
pulses according to the impact of earthquake on the
structure and the content of different frequency components
of ground motion [20].

In order to find a suitable mother wave which can
identify the velocity pulse as much as possible, many mother
waves are tried, and finally daubechies4 (“db4”) wavelet was
selected. Although the “db4” wavelet has good recognition
ability, there are still many pulse-like ground motions that
cannot be identified. This is because the shape of these
velocity pulses is quite different from that of the mother
wave, which leads to the incomplete extraction of velocity
pulse energy, and then the pulse-like ground motions are
mistaken for non-pulse-like ground motions [8]. Adaptive
wavelet transform is also used to improve [21].

In view of the shortcomings of wavelet technology in
identifying pulse-like ground motions, many improved
methods to define velocity pulse by using pulse energy are
proposed [22]. The results show that the ground motion with
the main velocity pulse with relative energy greater than 0.3
can be classified as pulse-like ground motion [23]. The
Empirical Mode Decomposition (EMD) was also used to
analyze the ground motion [24, 25]. The ground motions were
decomposed into high-frequency signal and low-frequency
signal, and the simple pulse is used to find the velocity
pulse in the low frequency signal. However, this
method is also difficult to repeat, and to divide a large
number of ground motions [26].

In this paper, the Hilbert–Huang Transform (HHT)
is used to identify the pulse-like ground motions. The newly
proposed HHT-based method combines the Baker’s quan-
titative identification method and the HHT analysis, for
which it has the advantages of both high automation and
strong usability from the two methods. HHT is used instead
of wavelet to analyze the ground motion. HHT method can
automatically decompose the ground motion signal into low
frequency component signal and high frequency compo-
nent. According to Baker’s criterion, the velocity pulse can
be found independently from the low-frequency signal.
Because the HHT method has high adaptability, it improves
the adaptability of the overall recognition method. Owing to
its high adaptability, the recognition errors caused by the
difference between the shape of mother wave and velocity
pulse are eliminated, and thereby more pulse-like ground
motions can be identified.

2. Pulse-Like Ground Motions Identification
Method Based on HHT

The Baker’s quantitative pulse-like ground motions identi-
fication method is shown in Figure 1. Continuous wavelet
transform (CWT) is used to decompose the ground motion
and find the potential maximum pulse by analyzing the
wavelet coefficients. The “db4” is selected as the mother
wavelet. Finally, the velocity pulse is recognized by the
velocity pulse criteria.

The HHT-based method is proposed in this paper, and
its flowchart is shown in Figure 2. The main procedures
include the following: (a) EMD is used to decompose the
velocity time history, and a series of intrinsic mode functions
(IMFs) are obtained. (b) The Hilbert transform is used to get
the frequency and amplitude functions of each IMF. The
average value of the frequency function is considered to be
the frequency of the IMF. (c) According to the frequency
function, IMFs are divided into high-frequency group and
low-frequency group. Then, the IMFs in each group are
separately summed up to obtain a high-frequency signal and
a low-frequency signal. (d) The maximum pulse is got in the
low-frequency signal. (e) The obtained maximum pulse is
inputted into the pulse indicator to calculate the pulse index.
(f) The above five steps are repeated in each direction to find
the most obvious velocity pulse. (g) The velocity pulse is
judged according to the standard listed in Figure 2.

The main difference between the HHT-based method
and Baker’s method is the technology used to extract velocity
pulse. Baker’s method uses continuous wavelet transform to
decompose and reconstruct the seismic signal to obtain
velocity pulse. In HHT-based method, HHT is used to
decompose the signal into low-frequency component and
high-frequency component, and the energy concentration
area is found in the low-frequency component to obtain
velocity pulse.

In order to explain the process of the proposed method
more concretely, the ground motion record No. 778 from
the PEER database is taken as an example. All the ground
motions used in this paper are from the PEER. The No. 778
ground motion is recorded in the Loma Prieta earthquake in
1989. The magnitude of the earthquake is 6.93. The two
horizontal components are shown in Figures 3 and 4. In
order to illustrate the identification process of pulse-like
ground motions, two-dimensional ground motions are
combined in the direction of 45 degrees east-northward.
The velocity time history after being synthesized is
shown in Figure 5. EMD is used to decompose this signal
and 9 IMFs are obtained. The first six order IMF is shown in
Figure 6. The velocity pulse only exists in the low-frequency
signal, but there is a different view on the frequency range
definition of this low-frequency signal. The researcher Zhang
believed that the period of the near-fault velocity pulse is
The most obvious velocity pulse

1. The pulse indicator value is greater than 0.85.
2. The pulse arrives early in the time history (based on CSV).
3. The original ground motion has an amplitude of greater than 30 cm/s.

Figure 1: The flowchart of improved Baker method.

The pulse-like ground motions

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2. The pulse arrives early in the time history (based on CSV).
3. The original ground motion has an amplitude of greater than 30 cm/s.

Figure 2: The flowchart of improved Baker method based on HHT.
Another period was defined by the Baker range from 0.26 s to 12.62 s [27]. Kurama and Farrow indicated that the period range of the velocity pulse is between 0.8 and 1.2 s [28]. By analyzing the ground motions of the Nepal Mw7.8 earthquake, it was found that the energy of the velocity pulse is concentrated in a short period range of 4–8 s [29].

Roumelioti considered that the signal with a frequency below 3 Hz is a low-frequency signal and higher than 3 Hz is a high-frequency one [30]. Based on the above research, it can be found that the determination of frequency threshold is very complex. In this paper, the frequency threshold is assumed to be 2 Hz.

From the frequency function of each IMF, it is found that the frequency values are varying with time. On average, if the
FIGURE 6: IMF components of the ground motion. (a) IMF1. (b) IMF2. (c) IMF3. (d) IMF4. (e) IMF5. (f) IMF6.
average frequency of one IMF is less than 2 Hz, the IMF is considered to be a low-frequency signal; otherwise, it is considered to be a high-frequency signal. Superimposing all the low-frequency IMFs and the high-frequency IMFs, respectively, the results, a low-frequency signal and a high-frequency signal, are shown in Figure 7.

With regard to the aspect of extracting velocity pulse from low-frequency signal, this method takes the maximum amplitude as the feature. Two complete pulse waveforms are extended forward and backward centered on the maximum amplitude, and the signals in this range are taken as velocity pulses. The velocity pulse extracted in this way is considered to have a very similar waveform to the pulse extracted by Baker method using the ”db4” wavelet. Then, the velocity pulse can be defined as portrayed in Figure 8, and the residual signal after the extraction is shown in Figure 9.

An index is proposed by Baker [18] to determine the near-fault characteristics of a velocity pulse, and it is formulated as

\[
P = \frac{1}{1 + e^{-23.3+14.6(\text{PGV ratio})+20.3(\text{energy ratio})}}
\]

where PGV ratio represents the PGV of the residual record divided by the original record’s PGV; the energy ratio represents the energy of the residual record divided by the energy of the original signal. The energy of the signal can be calculated by the square of the amplitude of each time from velocity time history. By analyzing the pulse-like ground motions, Baker found that the pulse index of the near-fault velocity pulses are usually higher than 0.85. For this velocity pulse of No. 778 ground motion, the pulse index is 0.9821, and therefore the velocity pulse is considered to be a pulse-like ground motion according to the velocity pulse index standard.

After calculating the velocity pulse index, the arrival time of the velocity pulse needs to be judged to remove the delay arrival velocity pulse. According to Baker’s research [18], the early arrived pulse is usually considered the forward directivity pulse. Arrival time can be defined using cumulative squared velocity (CSV) as

\[
\text{CSV}(t) = \int_0^t V^2(u)du,
\]

where CSV(t) is the value of the square velocity accumulated at time t; V(u) is the ground motion velocity at time u. For expressing clearly, \( t_{\text{10\%, pulse}} \) is defined as time instant when the CSV of the extracted velocity pulse reaches 10% of its total CSV, and \( t_{\text{10\%, orig}} \) is defined as the time instant when the CSV of the original signal reaches 10% of its total value. According to Baker’s research [18], the \( t_{\text{10\%, pulse}} \) of pulse-like ground motion needs to be earlier than the \( t_{\text{20\%, orig}} \). The locations of \( t_{\text{10\%, pulse}} \) and \( t_{\text{20\%, orig}} \) in the ground motion are shown in Figure 10. For this velocity pulse of No. 778 ground motion, its \( t_{\text{20\%, orig}} \) is calculated to be 6.915 s, and \( t_{\text{10\%, pulse}} \) is 6.425 s. And, the amplitude of the pulse is greater than 30 cm/s.

Two ground motion components are synthesized in all directions. Using the above method in each direction, the pulse index in each direction is calculated and drawn in the polar coordinates (Figure 11). 0 degrees indicates the direction of the north, and 90 degrees indicates the east direction. It can be seen from the polar diagram that the maximum index of velocity pulse should be between 9 degree and 0 degree. The velocity pulse with maximum velocity can be obtained by dichotomy. The most obvious velocity pulse of the ground motion is in the direction of 9 degrees and the pulse index is 0.9903. The velocity pulse and pulse-like ground motions are shown in Figure 12.

For comparative purposes, the wavelet-based method is also used to identify this ground motion, and this ground motion is considered to be a nonpulse-like ground motion. The pulse index of the most obvious velocity pulse is 0.7937. The most obvious velocity pulse identified by the wavelet-based method is shown in Table 1 and Figure 13.

It is observed that the velocity pulse identified by wavelet-based method is not complete, and some of the pulse energy is not extracted. The effect of the extraction of the velocity pulse is unsatisfactory due to the large difference between the mother wavelet and the potential velocity pulse shape. Comparatively, the velocity pulse extracted by HHT-based method is relatively complete, and it can overcome the defect of imperfectly extracting the velocity pulse by the wavelet technology. The smaller the shape difference between the extracted velocity pulse and the wavelet mother wave, the more accurate the wavelet-based method is. On the contrary, the more complete the extracted velocity pulse is, the better recognition result can be obtained by using HHT-based method.

3. Identification of Ground Motion

The pulse-like ground motions extraction method proposed by Baker [18] is limited by the wavelet technology. Some obvious pulse-like ground motions cannot be identified. In this paper, the method for identifying the pulse-like ground motion by HHT is proposed. These two methods are used to divide the ground motions in the PEER database. The results of the calculation are listed in Table 2.

In Table 2, HHT and wavelet represent the pulse-like ground motions based on HHT method and wavelet method, respectively. No and Nbj are the sequence number and fault distance of pulse-like ground motions, respectively. Tp and PGV, respectively, indicate the period and PGV of the pulse-like ground motions. Orientation is the orientation of the velocity pulse, in degrees clockwise from north.

Among the 3066 ground motions numbered from 1 to 3155 in the PEER database, 150 pulse-like ground motions were identified by the wavelet-based method and 229 by the HHT-based. In the 229 pulse-like ground motions, 105 were also extracted by the wavelet-based method and 124 are newly identified. In the 150 pulse-like ground motions extracted by the wavelet-based method, 24 ground motions were not identified by the present HHT-based method. The main reason for these omissions is because the frequency of these pulses is too high, or the frequency of a part of the velocity pulse is too high, so that these signals are divided into high-frequency signals.
In order to confirm this reason, the No. 459 record which can be identified by wavelet-based method but not by HHT-based method will be analyzed. In this paper, the frequency threshold of low-frequency signal is 2 Hz. In order to discuss the influence of frequency threshold to the final recognition effect, the threshold is increased from 2 Hz to 4 Hz. That is to say, more signals are divided into low-frequency signals. After increasing the threshold, this pulse-like ground motion can be identified by the HHT-based method. When the threshold is set to 2 Hz, the low-frequency signal and the high-frequency signal are shown in Figure 14. When the threshold is set to 4 Hz, the low-frequency signal and the high-frequency signal are shown in Figure 15. It is obvious from these figures that the amplitude of the pulse increases obviously after the threshold is raised. The velocity pulse can be extracted in the low-frequency signal after increasing the threshold value, by the HHT-based method. However, this paper assumes that the frequency of velocity pulse is less than 2 Hz. Based on this assumption, signals higher than 2 Hz cannot be considered as low-frequency signals. It is also for this reason that this ground motion cannot be recognized as pulse-like ground motions. This strict implementation of frequency threshold ensures the accuracy of the HHT-based method.

The main function of the HHT-based method is to identify pulse-like ground motions with inconspicuous pulses. These velocity pulses are difficult to identify by wavelet-based method, and may be mistaken for nonpulse-like ground motions. Therefore, these four ground motions (No 776, 806, 1194, and 1499) which cannot be recognized by wavelet-based method, but can be recognized by HHT-based method, are taken as examples. The original record and the extracted velocity pulse are shown in Figures 16–19. Velocity pulse parameters are shown in Table 3.

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In Table 3, PGVr and PGVv, respectively, represent PGV of residual signal and velocity signal; ENr and ENv, respectively, represent the signal energy of residual signal and velocity signal.

In Figures 16–19, the original records used by the two extraction methods are not the same, because both extraction methods need to find the maximum pulse in all directions independently. Due to the difference of the
technology used, the maximum pulse direction obtained by the two methods may be different, which leads to the difference of the original record of the extracted pulse. It can be found from Figures 16 to 19 that the potential velocity pulse extracted by the HHT-based method is more complete than that extracted by the wavelet-based method. However, this improvement in completeness is often just a little. For example, ground motion No. 776—the ratio of PGV obtained by the two methods is basically the same, the difference is only 4.33%, but the energy ratio obtained by the HHT-based method is lower, which indicates that the energy residue of the HHT-based method is smaller, 10.70% lower than that of the wavelet-based method. This small difference will be amplified when calculating the pulse index, which leads to the recognition of pulse-like ground motion based on the HHT method and nonpulse-like ground motion based on the wavelet method. As a result, the HHT-based method and

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**Table 1: The velocity pulse index.**

| Tp (s) | PGV (cm/s) | Index  | A (rad) |
|--------|------------|--------|---------|
| HHT    | 2.0907     | 35.6323| 0.9903  | 0.1569  |
| Wavelet| 2.2330     | 32.4189| 0.7937  | 0.4572  |
**Table 2: Pulse-like ground motion table.**

| No. | Rjb (km) | Tp (s) | PGV (cm/s) | Orientation (rad) | Tp (s) | PGV (cm/s) | Orientation (rad) |
|-----|----------|--------|------------|-------------------|--------|------------|-------------------|
| 20  | 26.72    | 2.00   | 40.30      | 19.00             | 1.76   | 38.97      | 3.65              |
| 57  | 19.33    |        |            |                   | 0.85   | 25.61      | 1.22              |
| 68  | 22.77    | 2.43   | 18.81      | 2.55              |        |            |                   |
| 77  | 0.00     | 1.64   | 121.90     | 189.00            | 1.75   | 47.36      | 3.49              |
| 96  | 4.33     | 1.13   | 23.99      | 3.73              |        |            |                   |
| 139 | 0.00     | 2.04   | 18.23      | 3.65              |        |            |                   |
| 143 | 1.79     | 6.19   | 129.70     | 0.00              | 3.95   | 91.06      | 1.06              |
| 147 | 8.47     | 1.46   | 32.00      | 139.00            | 1.64   | 21.47      | 1.53              |
| 148 | 6.75     | 1.16   | 30.80      | 354.00            | 1.51   | 25.24      | 5.06              |
| 149 | 4.79     | 1.35   | 32.10      | 350.00            | 1.32   | 31.42      | 1.22              |
| 150 | 0.42     | 1.23   | 49.60      | 246.00            | 1.41   | 16.00      | 2.47              |
| 159 | 0.00     | 2.34   | 53.50      | 53.00             | 1.67   | 52.79      | 2.32              |
| 161 | 8.54     | 4.40   | 36.70      | 226.00            | 2.20   | 25.64      | 2.55              |
| 170 | 7.31     | 4.42   | 70.80      | 75.00             | 3.75   | 36.23      | 4.91              |
| 171 | 0.07     | 3.42   | 116.40     | 59.00             | 3.03   | 46.53      | 5.14              |
| 173 | 8.60     | 4.52   | 55.20      | 79.00             | 2.72   | 30.18      | 2.55              |
| 178 | 10.79    | 4.50   | 55.80      | 86.00             | 3.63   | 18.18      | 1.92              |
| 179 | 4.90     | 4.79   | 80.80      | 229.00            | 2.59   | 70.37      | 4.98              |
| 180 | 1.76     | 4.13   | 96.50      | 228.00            | 3.30   | 65.71      | 1.37              |
| 181 | 0.00     | 3.77   | 121.60     | 71.00             | 3.13   | 99.45      | 5.06              |
| 182 | 0.56     | 4.38   | 111.90     | 56.00             | 2.87   | 84.67      | 2.24              |
| 184 | 5.09     | 6.27   | 73.50      | 253.00            | 2.87   | 54.87      | 6.16              |
| 185 | 5.35     | 4.82   | 73.40      | 263.00            | 3.08   | 26.18      | 6.24              |
| 192 | 14.75    | 3.49   | 16.86      | 217.00            |        |            |                   |
| 204 | 7.40     | 0.69   | 26.00      | 217.00            | 1.24   | 17.51      | 6.08              |
| 223 | 14.31    |        |            |                   |        |            |                   |
| 230 | 1.10     |        |            |                   |        |            |                   |
| 250 | 9.65     | 1.01   | 43.30      | 65.00             | 1.01   | 27.00      | 0.98              |
| 265 | 13.80    |        |            |                   |        |            |                   |
| 285 | 8.14     | 1.71   | 38.10      | 72.00             | 1.65   | 38.96      | 5.06              |
| 292 | 6.78     | 3.27   | 71.10      | 87.00             | 2.97   | 59.15      | 1.45              |
| 300 | 8.81     |        |            |                   |        |            |                   |
| 316 | 16.54    | 4.39   | 60.80      | 204.00            | 4.31   | 52.10      | 5.69              |
| 319 | 6.18     | 1.22   | 52.90      | 56.00             | 2.00   | 29.03      | 0.04              |
| 341 | 37.92    |        |            |                   |        |            |                   |
| 345 | 29.91    |        |            |                   | 1.78   | 17.87      | 2.71              |
| 359 | 24.83    |        |            |                   | 1.48   | 23.87      | 3.79              |
Table 2: Continued.

| No. | Rjb (km) | Wavelet Tp (s) | PGV (cm/s) | Orientation (rad) | HHT Tp (s) | PGV (cm/s) | Orientation (rad) |
|-----|----------|---------------|------------|-------------------|------------|------------|-------------------|
| 372 | 1.41     | 0.26          | 26.30      | 322.00            | 373        | 1.41       | 311.00            |
| 407 | 1.99     | 0.91          | 26.93      | 3.81              | 409        | 1.53       | 18.85             | 5.22              |
| 412 | 13.16    | 1.95          | 16.28      | 0.27              | 415        | 1.33       | 50.86             | 5.69              |
| 418 | 7.31     | 0.44          | 32.80      | 284.00            | 448        | 1.52       | 18.05             | 1.28              |
| 459 | 9.85     | 1.23          | 37.30      | 78.00             | 496        | 1.92       | 15.73             | 5.06              |
| 503 | 58.69    | 1.57          | 34.80      | 117.00            | 504        | 1.68       | 18.49             | 2.79              |
| 505 | 55.96    | 1.39          | 36.90      | 104.00            | 506        | 1.39       | 25.97             | 6.01              |
| 507 | 58.88    | 1.57          | 32.90      | 113.00            | 508        | 1.61       | 26.51             | 6.08              |
| 509 | 58.48    | 1.67          | 34.00      | 113.00            | 510        | 1.77       | 24.81             | 6.24              |
| 517 | 0.99     | 2.16          | 39.40      | 121.00            | 527        | 2.07       | 32.93             | 4.98              |
| 540 | 0.00     | 1.72          | 18.58      | 2.63              | 558        | 1.30       | 22.14             | 2.47              |
| 566 | 4.00     | 0.79          | 27.00      | 75.00             | 568        | 1.32       | 12.60             | 4.97              |
| 569 | 3.71     | 1.13          | 92.20      | 231.00            | 573        | 1.32       | 57.93             | 1.45              |
| 574 | 56.18    | 2.75          | 21.63      | 0.96              | 577        | 2.71       | 20.01             | 0.98              |
| 575 | 55.82    | 3.35          | 20.91      | 0.98              | 576        | 2.34       | 20.30             | 1.22              |
| 579 | 55.11    | 2.51          | 20.90      | 0.98              | 583        | 2.20       | 17.27             | 5.30              |
| 588 | 56.94    | 3.99          | 17.14      | 3.49              | 589        | 1.26       | 17.78             | 5.61              |
| 595 | 10.31    | 0.82          | 30.00      | 133.00            | 611        | 1.97       | 18.00             | 3.46              |
| 614 | 14.90    | 0.86          | 40.10      | 176.00            | 615        | 1.92       | 18.04             | 4.98              |
| 615 | 14.95    | 0.88          | 33.10      | 207.00            | 645        | 1.53       | 18.71             | 2.84              |
| 668 | 14.37    | 0.90          | 28.00      | 162.00            | 690        | 0.99       | 17.45             | 2.49              |
| 692 | 11.47    | 0.81          | 44.30      | 74.00             | 721        | 2.70       | 26.88             | 5.14              |
| 722 | 18.48    | 2.13          | 33.10      | 321.00            | 723        | 1.91       | 17.83             | 1.22              |
| 725 | 11.16    | 2.87          | 42.10      | 319.00            | 732        | 1.72       | 17.67             | 3.76              |
| 736 | 40.85    | 2.77          | 16.39      | 3.79              | 738        | 2.41       | 30.37             | 1.30              |
| 744 | 50.71    | 1.89          | 20.29      | 3.73              | 753        | 0.98       | 27.15             | 2.52              |
| 754 | 20.44    | 2.22          | 19.26      | 4.98              | 755        | 1.16       | 22.81             | 4.44              |
| 758 | 19.97    | 1.16          | 22.81      | 4.44              | 764        | 2.01       | 36.16             | 2.39              |
| 766 | 10.27    | 1.64          | 43.60      | 147.00            | 767        | 1.77       | 28.34             | 4.75              |
| 768 | 13.81    | 1.93          | 25.86      | 4.04              | 776        | 2.33       | 33.70             | 6.08              |
Table 2: Continued.

| No. | Rjb (km) | Wavelet | HHT |
|-----|----------|---------|-----|
|     |          | Tp (s)  | PGV (cm/s) | Orientation (rad) | Tp (s)  | PGV (cm/s) | Orientation (rad) |
| 777 | 27.33    |         | 1.91 | 37.33 | 1.30 |
| 778 | 24.52    |         | 2.53 | 33.05 | 0.04 |
| 779 | 0.00     |         | 1.70 | 92.87 | 4.04 |
| 783 | 74.16    | 1.83    | 48.20 | 37.00 | 1.50 |
| 784 | 72.09    | 1.39    | 36.30 | 261.00 | 1.72 |
| 786 | 30.56    |         | 0.00 | 17.10 | 3.81 |
| 787 | 30.62    | 2.47    | 34.41 | 0.04 |
| 796 | 77.34    | 1.32    | 32.90 | 68.00 | 1.73 |
| 799 | 58.52    |         | 1.23 | 17.10 | 3.81 |
| 802 | 7.58     | 4.57    | 53.50 | 70.00 | 1.11 |
| 803 | 8.48     | 5.65    | 62.00 | 280.00 | 2.91 |
| 806 | 23.92    |         | 2.00 | 12.51 | 6.24 |
| 808 | 77.32    | 2.08    | 33.40 | 67.00 | 2.00 |
| 825 | 0.00     | 4.84    | 124.10 | 2.00 | 2.59 |
| 826 | 40.23    |         | 1.81 | 26.77 | 5.06 |
| 827 | 15.97    |         | 2.79 | 16.05 | 2.47 |
| 828 | 0.00     | 3.00    | 96.70 | 287.00 | 1.91 |
| 838 | 34.86    | 9.13    | 28.80 | 47.00 | 3.03 |
| 864 | 11.03    |         | 1.85 | 21.81 | 2.55 |
| 879 | 2.19     | 5.12    | 132.30 | 270.00 | 3.94 |
| 900 | 23.62    | 7.50    | 55.80 | 238.00 | 4.88 |
| 949 | 3.30     |         | 2.00 | 12.51 | 6.24 |
| 960 | 11.39    |         | 2.22 | 24.27 | 6.24 |
| 963 | 20.11    |         | 1.48 | 44.66 | 3.81 |
| 982 | 0.00     | 3.16    | 101.50 | 49.00 | 1.76 |
| 983 | 0.00     | 3.54    | 66.10 | 34.00 | 2.68 |
| 987 | 20.36    |         | 1.54 | 15.65 | 5.01 |
| 1003| 21.17    | 0.98    | 41.60 | 87.00 | 1.32 |
| 1004| 0.00     | 0.93    | 77.90 | 271.00 | 1.64 |
| 1013| 0.00     | 1.62    | 86.30 | 31.00 | 2.10 |
| 1044| 3.16     | 1.37    | 116.10 | 21.00 | 2.37 |
| 1045| 2.11     | 2.98    | 118.30 | 34.00 | 2.37 |
| 1050| 4.92     | 0.59    | 50.20 | 205.00 | 1.74 |
| 1051| 4.92     | 0.84    | 106.10 | 41.00 | 1.50 |
| 1052| 5.26     | 0.73    | 56.80 | 33.00 | 1.81 |
| 1054| 5.54     | 1.23    | 76.30 | 199.00 | 1.76 |
| 1063| 0.00     | 1.25    | 149.10 | 209.00 | 2.06 |
| 1084| 0.00     | 2.98    | 106.30 | 63.00 | 1.58 |
| 1085| 0.00     | 3.53    | 114.00 | 37.00 | 2.12 |
| 1086| 1.74     | 2.44    | 130.60 | 20.00 | 1.36 |
| 1106| 0.94     | 1.09    | 105.60 | 318.00 | 1.66 |
| 1114| 3.31     | 2.83    | 103.00 | 332.00 | 1.94 |
| 1119| 0.00     | 1.81    | 95.60 | 301.00 | 1.70 |
| 1120| 1.46     | 1.55    | 153.20 | 318.00 | 1.70 |
| 1148| 10.56    | 7.79    | 40.30 | 80.00 | 7.23 |
| 1158| 13.60    |         | 1.83 | 22.77 | 5.06 |
| 1161| 7.57     | 5.99    | 53.00 | 33.00 | 4.90 |
| 1165| 3.62     | 5.37    | 38.10 | 265.00 | 2.22 |
| 1166| 30.73    |         | 2.78 | 22.59 | 5.30 |
| 1176| 1.38     | 4.95    | 90.60 | 25.00 | 3.45 |
| 1182| 9.76     | 2.57    | 58.30 | 291.00 | 1.73 |
| 1193| 9.62     | 6.65    | 61.60 | 144.00 | 3.72 |
| 1194| 19.07    |         | 5.55 | 26.73 | 4.98 |
| 1197| 3.12     |         | 1.37 | 66.40 | 5.77 |
| 1201| 14.82    |         | 2.48 | 29.51 | 5.30 |
| 1208| 24.10    |         | 2.41 | 20.29 | 0.04 |
| 1209| 24.13    |         | 3.11 | 23.85 | 5.22 |
| 1231| 0.11     |         | 2.82 | 28.92 | 5.06 |
| 1244| 9.94     | 5.34    | 108.90 | 6.00 | 4.01 |

Shock and Vibration
| No. | Rjb (km) | Tp (s) | PGV (cm/s) | Orientation (rad) | Tp (s) | PGV (cm/s) | Orientation (rad) |
|-----|----------|--------|------------|------------------|--------|------------|------------------|
| 1246 | 18.02 | 6.00 | 41.74 | 1.06 |
| 1257 | 52.46 | 2.30 | 14.97 | 3.81 |
| 1262 | 49.29 | 3.36 | 15.51 | 5.32 |
| 1264 | 50.50 | 2.74 | 21.65 | 5.22 |
| 1265 | 51.49 | 2.73 | 26.11 | 4.75 |
| 1295 | 46.65 | 3.03 | 17.27 | 4.04 |
| 1310 | 86.61 | 8.54 | 31.11 | 3.89 |
| 1311 | 84.88 | 3.81 | 20.13 | 2.24 |
| 1329 | 81.69 | 2.40 | 28.53 | 4.67 |
| 1342 | 88.05 | 6.73 | 22.35 | 6.24 |
| 1402 | 38.36 | 7.88 | 32.30 | 48.00 |
| 1410 | 101.27 | 2.56 | 28.00 | 2.47 |
| 1415 | 99.89 | 2.82 | 17.13 | 1.27 |
| 1421 | 99.54 | 2.25 | 25.23 | 1.30 |
| 1430 | 105.49 | 2.60 | 20.16 | 2.55 |
| 1433 | 83.57 | 7.81 | 13.13 | 3.81 |
| 1435 | 102.46 | 2.87 | 17.76 | 2.32 |
| 1454 | 103.65 | 2.04 | 16.13 | 5.06 |
| 1463 | 86.57 | 8.09 | 28.72 | 3.73 |
| 1464 | 72.52 | 10.88 | 35.80 | 76.00 |
| 1465 | 87.63 | 5.96 | 20.21 | 3.81 |
| 1466 | 84.95 | 5.48 | 23.09 | 3.73 |
| 1468 | 82.23 | 6.96 | 26.29 | 3.73 |
| 1470 | 92.26 | 10.37 | 27.20 | 80.00 |
| 1471 | 49.81 | 9.11 | 44.00 | 68.00 |
| 1472 | 54.28 | 8.67 | 47.50 | 59.00 |
| 1473 | 66.25 | 10.23 | 42.70 | 69.00 |
| 1475 | 56.03 | 8.37 | 45.70 | 57.00 |
| 1476 | 28.04 | 5.29 | 62.70 | 155.00 |
| 1477 | 30.17 | 5.93 | 63.30 | 123.00 |
| 1478 | 40.88 | 8.97 | 41.70 | 71.00 |
| 1479 | 35.68 | 8.87 | 45.20 | 72.00 |
| 1480 | 19.83 | 5.38 | 63.20 | 131.00 |
| 1481 | 25.42 | 9.58 | 54.90 | 70.00 |
| 1482 | 19.89 | 9.33 | 57.80 | 94.00 |
| 1483 | 22.06 | 6.43 | 47.60 | 162.00 |
| 1485 | 26.00 | 9.34 | 43.70 | 75.00 |
| 1486 | 16.74 | 8.04 | 31.30 | 112.00 |
| 1487 | 35.00 | 12.31 | 44.40 | 55.00 |
| 1489 | 3.76 | 10.22 | 56.50 | 76.00 |
| 1490 | 9.49 | 8.18 | 31.36 | 0.06 |
| 1491 | 7.64 | 10.38 | 52.80 | 100.00 |
| 1492 | 0.00 | 11.96 | 209.10 | 142.00 |
| 1493 | 5.95 | 13.12 | 37.10 | 83.00 |
| 1496 | 10.48 | 8.94 | 45.30 | 77.00 |
| 1498 | 17.11 | 7.78 | 64.10 | 45.00 |
| 1499 | 8.51 | 5.90 | 30.88 | 6.24 |
| 1501 | 9.78 | 6.55 | 78.90 | 136.00 |
| 1502 | 16.59 | 8.46 | 52.30 | 34.00 |
| 1503 | 0.57 | 5.74 | 136.50 | 113.00 |
| 1504 | 0.62 | 3.88 | 38.48 | 2.55 |
| 1505 | 0.00 | 12.29 | 342.10 | 144.00 |
| 1508 | 0.00 | 5.81 | 37.50 | 2.24 |
| 1510 | 0.89 | 5.00 | 104.90 | 109.00 |
| 1511 | 2.74 | 4.73 | 71.20 | 125.00 |
| 1514 | 55.48 | 9.38 | 42.50 | 65.00 |
| 1515 | 5.16 | 8.10 | 56.20 | 85.00 |
| 1516 | 80.18 | 5.30 | 23.02 | 3.81 |
| 1519 | 6.98 | 10.40 | 45.50 | 91.00 |
4. Evaluation of Pulse-Like Ground Motions

In order to evaluate the identification quality of the pulse-like ground motion, the velocity response and acceleration response of nonpulse-like and pulse-like ground motions are calculated, respectively. A very important feature of the pulse-like ground motion is that its response spectrum gets larger values at the frequency of the velocity pulse [31] than other frequency area. The velocity and acceleration responses of a pulse-like ground motion are calculated at its own velocity pulse frequency and the damping ratio is 0.05. In order to compare with the nonpulse-like ground motion, the velocity and acceleration responses of the nonpulse-like ground motion are also calculated. Since there is no near-fault velocity pulse in nonpulse-like ground motion, the near-fault velocity pulse can only be replaced by the maximum velocity pulse, and the velocity and acceleration responses of nonpulse-like ground motion can be obtained by using the frequency at the maximum velocity pulse. The velocity and acceleration responses of the ground motion are shown in Table 4.

The wavelet-based method differ in identifying some ground motions. Similar phenomena can also be found in other ground motions in Figures 16–19. Therefore, it is very important to extract the velocity pulse more completely, as even a little difference will lead to a huge deviation of the results. In this paper, the improvement of wavelet-based method is expected to extract more accurate velocity pulses, so as to reduce the misidentification of pulse-like ground motions.

| No. | Rjb (km) | Wavelet Tp (s) | PGV (cm/s) | Orientation (rad) | HHT Tp (s) | PGV (cm/s) | Orientation (rad) |
|-----|---------|---------------|------------|-------------------|------------|------------|-------------------|
| 1520 | 4.67    | 11.14         | 35.50      | 5.00              | 10.35      | 18.30       | 3.49              |
| 1522 | 87.67   |               |            |                   |            |            |                   |
| 1523 | 54.50   | 8.30          | 39.60      | 66.00             | 6.85       | 32.19       | 3.73              |
| 1524 | 45.15   | 7.67          | 42.80      | 63.00             |            |            |                   |
| 1525 | 54.45   | 9.46          | 40.70      | 60.00             | 5.83       | 38.47       | 0.04              |
| 1526 | 47.67   | 9.28          | 46.80      | 63.00             | 6.08       | 45.76       | 0.27              |
| 1528 | 2.11    | 10.32         | 76.70      | 70.00             | 6.79       | 41.53       | 0.27              |
| 1529 | 1.49    | 9.63          | 104.80     | 76.00             | 4.26       | 57.01       | 0.12              |
| 1530 | 6.08    | 8.69          | 67.10      | 75.00             | 5.59       | 61.05       | 3.65              |
| 1531 | 12.87   | 7.19          | 56.10      | 34.00             | 7.70       | 43.95       | 3.81              |
| 1532 | 17.16   |               |            |                   | 6.01       | 26.20       | 3.81              |
| 1533 | 22.12   |               |            |                   | 5.03       | 58.00       | 6.08              |
| 1534 | 31.05   |               |            |                   | 4.86       | 23.15       | 2.47              |
| 1535 | 12.38   |               |            |                   | 3.72       | 29.24       | 1.22              |
| 1536 | 9.34    |               |            |                   | 3.66       | 28.96       | 4.40              |
| 1537 | 13.13   | 9.02          | 60.70      | 84.00             | 5.82       | 52.45       | 6.24              |
| 1538 | 1.83    |               |            |                   | 4.77       | 14.84       | 2.55              |
| 1539 | 8.27    | 8.88          | 61.50      | 49.00             | 6.23       | 62.17       | 2.47              |
| 1540 | 70.61   |               |            |                   | 7.53       | 26.59       | 0.04              |
| 1541 | 12.02   | 0.88          | 65.80      | 88.00             | 1.35       | 54.91       | 5.06              |
| 1542 | 0.00    |               |            |                   | 1.81       | 15.05       | 4.98              |
| 1543 | 93.30   |               |            |                   | 1.04       | 17.69       | 2.55              |
| 1544 | 6.68    |               |            |                   |            |            |                   |
| 1545 | 9.98    | 1.09          | 34.60      | 85.00             |            |            |                   |
| 1546 | 10.35   |               |            |                   | 1.61       | 44.76       | 5.06              |
| 1547 | 31.06   |               |            |                   | 1.49       | 6.31        | 1.25              |
| 1548 | 8.48    | 0.73          | 42.40      | 66.00             | 1.47       | 17.38       | 0.35              |
| 1549 | 0.18    | 3.16          | 121.40     | 56.00             | 3.85       | 51.09       | 5.06              |
| 1550 | 18.47   | 3.19          | 32.70      | 274.00            | 5.73       | 15.44       | 4.04              |
| 1551 | 33.86   | 1.06          | 30.10      | 74.00             |            |            |                   |
| 1552 | 35.78   |               |            |                   | 4.94       | 17.12       | 0.29              |
| 1553 | 21.34   | 1.38          | 69.80      | 272.00            |            |            |                   |
| 1554 | 24.40   |               |            |                   | 5.07       | 25.38       | 6.16              |
| 1555 | 25.17   | 1.53          | 35.40      | 305.00            |            |            |                   |
| 1556 | 13.04   | 0.92          | 61.50      | 280.00            |            |            |                   |
| 1557 | 0.00    | 3.86          | 56.30      | 280.00            | 3.01       | 16.47       | 2.63              |
| 1558 | 21.09   |               |            |                   | 2.66       | 17.81       | 2.55              |
| 1559 | 18.10   |               |            |                   | 3.65       | 27.51       | 1.84              |
| 1560 | 30.81   |               |            |                   | 6.35       | 18.59       | 0.04              |
| 1561 | 21.62   |               |            |                   | 4.71       | 15.90       | 2.47              |
Figure 14: 2 Hz frequency threshold. (a) The low-frequency signal. (b) The high-frequency signal.

Figure 15: 4 Hz frequency threshold. (a) The low-frequency signal. (b) The high-frequency signal.

Figure 16: No. 776 ground motion. (a) The extracted pulse based on HHT. (b) The extracted pulse based on wavelet.
In Table 4, NF represents pulse-like ground motions and NNF represents nonpulse-like ground motions. HHT indicates pulse-like ground motions identified by the HHT-based method (the HHT group), and wavelet indicates pulse-like ground motions identified by the wavelet-based method (the wavelet group). PSA and PSV, respectively, denote the Pseudo-Response Spectrum Acceleration and Velocity. E and SD represent mean and standard deviation, respectively.

It can be found from Table 4 that the velocity and acceleration responses of the pulse-like ground motion are far greater than those of the nonpulse-like ground motion. This indicates that the extracted velocity pulse is obvious and can significantly increase the velocity and acceleration responses around its own frequency. Because of the limitation of the wavelet-based method, the wavelet-based method can only extract very obvious velocity pulses, which leads to the larger PSA and PSV values. The purpose of the HHT-based method is to extract those velocity pulses which are difficult to be recognized by the wavelet-based method, and the PSA and PSV of this part of velocity pulses are relatively small. Affected by this part of the ground motion, the PSA and PSV of pulse-like ground motion based on HHT identification are smaller than those from wavelet identification. However, because the PSA and PSV of pulse-like ground motions are much larger than those of nonpulse-like ground motions, it can be shown that there are obvious differences between pulse-like ground motions and nonpulse-like ground motions. It can be proved that the pulse-like ground motions

![Figure 17: No. 806 ground motion. (a) The extracted pulse based on HHT. (b) The extracted pulse based on wavelet.](image)

![Figure 18: No. 1194 ground motion. (a) The extracted pulse based on HHT. (b) The extracted pulse based on wavelet.](image)
CSV is an important index to describe the energy of the velocity pulse; the CSV values of various components are calculated and listed in Table 5. In Table 5, \( E_v, E_p, \) and \( E_r \), respectively, represent the mean of CSV of velocity signal, the velocity pulse signal, and residual signal; \( SD_v, SD_p, \) and \( SD_r \), respectively, represent the standard deviation of CSV of the velocity signal, the velocity pulse signal, and residual signal. The velocity signal is equal to the velocity pulse plus the residual signal. Correspondingly, \( E = E_v + E_r \). HHT and wavelet have the same meaning as in Table 4.

Statistical analysis of CSV and fault distance shows that pulse-like ground motions identified by these two methods are mostly recorded in high-magnitude earthquakes. By comparing the number of pulse-like ground motions obtained by the two methods, it can be found that HHT-based method can identify more pulse-like ground motions in high magnitude ground motions. This is mainly due to the larger energy released by high magnitude earthquakes, resulting in sharp peaks in velocity time history. The waveforms of velocity pulse and wavelet mother wave are quite different and difficult to be recognized.

It can be found from Table 5 that the CSV of each component of the wavelet group is larger than that of the HHT group, which means that the velocity pulse energy extracted by the wavelet group is very high. This can also explain the phenomenon that the acceleration and velocity responses of the wavelet group extraction are better than those of the HHT group, because the wavelet group can only extract the high energy and very obvious velocity pulse. The rate of pulse CSV extracted from the HHT group accounted for 70% in the total signal CSV, which was higher than 58% for the wavelet group. This indicates that the pulses extracted by the HHT method are more complete. Combining the

| No.  | 776 |  | 806 |  | 1194 |  | 1499 |  |
|------|-----|---|-----|---|-----|---|-----|---|
| Method | HHT | Wavelet | HHT | Wavelet | HHT | Wavelet | HHT | Wavelet |
| PGVr (cm/s) | 37.04 | 31.89 | 29.28 | 51.94 | 21.46 | 34.88 | 22.98 | 39.94 |
| PGVv (cm/s) | 62.35 | 57.90 | 41.79 | 51.94 | 37.64 | 53.52 | 33.90 | 40.00 |
| PGV ratio (%) | 59.40 | 55.07 | 70.07 | 100.00 | 57.01 | 65.17 | 67.80 | 99.84 |
| ENr (cm²/s²) | 7.02E+05 | 1.16E+06 | 5.86E+05 | 9.92E+05 | 6.86E+05 | 1.83E+06 | 1.36E+05 | 1.11E+06 |
| ENv (cm²/s²) | 1.12E+06 | 1.58E+06 | 1.30E+06 | 1.28E+06 | 1.25E+06 | 2.52E+06 | 8.80E+05 | 2.09E+06 |
| Energy ratio | 62.50% | 73.26% | 45.04% | 77.63% | 54.99% | 72.64% | 41.24% | 53.04% |
| Index | 0.86 | 0.56 | 0.98 | 0.00 | 0.98 | 0.25 | 0.99 | 0.10 |
| \( t_{20\%\text{ orig}} \) (s) | 7.61 | 7.90 | 12.71 | 12.62 | 40.00 | 35.93 | 31.29 | 36.91 |
| \( t_{10\%\text{ pul}} \) (s) | 7.01 | 8.00 | 12.34 | 12.53 | 36.46 | 35.20 | 30.63 | 34.58 |

Table 4: The velocity and acceleration response.

| Method | HHT | Wavelet |
|--------|-----|---------|
| PSA (cm/s²) | 85.9310 | 58.9505 | 116.4102 | 64.8269 |
| NNF | 11.9143 | 18.9083 | 13.2829 | 19.7373 |
| PSV (cm/s) | 58.1894 | 57.6377 | 82.4328 | 91.6787 |
| NNF | 6.5630 | 13.1217 | 7.2636 | 14.1058 |

Figure 19: No. 1499 ground motion. (a) The extracted pulse based on HHT. (b) The extracted pulse based on wavelet.
Table 5: The CSV table.

| Magnitude | $E_v$ (cm$^2$/s) | SD$E_v$ (cm$^2$/s) | $E_p$ (cm$^2$/s) | SD$E_p$ (cm$^2$/s) | $E_r$ (cm$^2$/s) | SD$E_r$ (cm$^2$/s) | Nu | $R$ (%) |
|-----------|------------------|---------------------|------------------|---------------------|------------------|---------------------|----|---------|
| **HHT**   |                  |                     |                  |                     |                  |                     |     |         |
| 8-7       | $1.01E + 04$     | $2.59E + 04$        | $7.45E + 03$     | $2.36E + 04$        | $2.49E + 03$     | $3.19E + 03$        | 106 | 74.15   |
| 7-6       | $3.35E + 03$     | $3.60E + 03$        | $2.22E + 03$     | $2.96E + 03$        | $1.05E + 03$     | $1.06E + 03$        | 99  | 66.20   |
| 6-5       | $8.44E + 02$     | $9.66E + 02$        | $5.94E + 02$     | $8.00E + 02$        | $2.18E + 02$     | $1.83E + 02$        | 23  | 70.44   |
| 5-4       | $5.38E + 02$     | $0.00E + 00$        | $3.52E + 02$     | $0.00E + 00$        | $1.27E + 02$     | $0.00E + 00$        | 1   | 65.38   |
| **Wavelet** |                |                     |                  |                     |                  |                     |     |         |
| 8-7       | $1.72E + 04$     | $4.44E + 04$        | $1.19E + 04$     | $3.01E + 04$        | $3.50E + 03$     | $1.07E + 04$        | 60  | 69.12   |
| 7-6       | $5.52E + 03$     | $6.87E + 03$        | $2.73E + 03$     | $4.49E + 03$        | $2.33E + 03$     | $4.26E + 03$        | 67  | 49.34   |
| 6-5       | $9.70E + 02$     | $1.47E + 03$        | $5.27E + 02$     | $9.69E + 02$        | $3.97E + 02$     | $5.15E + 02$        | 22  | 54.35   |
| 5-4       | $6.43E + 02$     | $0.00E + 00$        | $3.50E + 02$     | $0.00E + 00$        | $2.31E + 02$     | $0.00E + 00$        | 1   | 54.49   |

Figure 20: Comparison of extracted pulses. (a) No. 68 ground motion. (b) No. 96 ground motion. (c) No. 139 ground motion. (d) No. 407 ground motion.
Table 6: The CSV table.

| No. | Magnitude | Distance (km) | V30 (m/s) | Mechanism   | CSV_{V} (cm²/s) | CSV_{p} (cm²/s) | CSV_{T} (%) | CSV_{V} (cm²/s) | CSV_{p} (cm²/s) | CSV_{T} (%) |
|-----|-----------|---------------|-----------|-------------|-----------------|-----------------|-------------|-----------------|-----------------|-------------|
| 68  | 6.61      | 22.77         | 316.46    | Reverse     | 1155.97         | 646.80          | 55.95       | 1319.28         | 762.41          | 57.79       |
| 96  | 5.20      | 4.33          | 288.77    | Strike-slip | 305.59          | 208.86          | 68.35       | 483.45          | 275.75          | 57.04       |
| 139 | 7.35      | 0.00          | 471.53    | Reverse     | 1097.73         | 342.37          | 31.19       | 1052.92         | 334.43          | 31.76       |
| 407 | 5.77      | 1.99          | 398.49    | Reverse     | 497.49          | 231.45          | 46.52       | 873.20          | 397.85          | 45.56       |

Figure 21: Distribution of velocity pulse period. (a) HHT1. (b) Wavelet1. (c) HHT2. (d) Wavelet2. (e) HHT3.
above two phenomena, it can be concluded that the HHT-based method has better recognition ability for lower energy velocity pulses.

The first four velocity pulses which were recognized by the HHT-based method but not by the wavelet-based method are shown in Figure 20. The velocity pulses are evaluated by CSV, and the main parameters are listed in Table 6.

In Table 6, CSVv and CSVp, respectively, represent the CSV of velocity signal and the velocity pulse; CSVr is the ratio of CSVp to CSVv. From these four examples, it can be found that the HHT-based method is much better than the wavelet-based method in extracting the velocity pulse because the more complete velocity pulse can be extracted by the HHT-based method. Based on the same mother wave, the basic mode of velocity pulse extracted by the wavelet-based method will not change. If the potential velocity pulse differs too much from the mode of the mother wave, the extraction rate of the velocity pulse will be very low and the near-fault velocity pulse cannot be recognized. The HHT-based method does not have such problems, and can improve the recognition of velocity pulses. Table 6 can quantitatively support the above conclusions. It shows that the CSV value of the velocity pulses identified by the HHT-based method is much higher than that of the wavelet-based method by 12% on average. Through the above analysis, it can be concluded that the difference between mother wave mode and potential velocity pulse is the main reason for the unsatisfactory recognition effect of velocity pulse by the wavelet-based method.

The period distribution of velocity pulses of pulse-like ground motions identified by two methods is shown in Figures 21 and 22 and listed in Table 7.

In Figure 21 and Table 7, HHT1 and Wavelet1 represent periods of the velocity pulses identified by the HHT-based method and the wavelet-based method, respectively; HHT2 and Wavelet2 represent the periods of common pulses obtained by the HHT-based method and wavelet-based method, respectively, and these common pulses can be identified by both methods; HHT3 represents the period of velocity pulses that can only be identified by the HHT method.

Several conclusions can be drawn from Figure 21 and Table 6. (a) More high-frequency velocity pulses can be identified by the HHT-based method. (b) There is no obvious difference between the two methods in identifying the common velocity pulse period.

Several conclusions can be drawn from the evaluation of the above four indicators. Firstly, the pulse-like ground motions obtained by the two identification methods are obvious, and the pulse-like ground motions have obvious near-fault characteristics. Secondly, the HHT-based method is more complete in recognizing velocity pulses, and can identify pulse-like ground motions which are difficult to recognize by the wavelet-based method. Third, the reason for incomplete recognition of the wavelet-based method is that the difference between the mother wave and the potential velocity pulse is too large.

5. Conclusion

In this paper, a HHT-based pulse-like ground motion identification method is improved upon. The HHT method is used to decompose the ground motion signal into low frequency component and high frequency component, and Baker criterion is used to identify the pulse in the low frequency component. Compared with the method of fitting the velocity pulse with a single waveform and the method of extracting the pulse with wavelet, this method can identify the pulses with different shapes, which increases the recognition range of velocity pulse. In order to verify the effect of the proposed method, 3066 ground motions selected from the PEER database are carried out. The main conclusions are as follows:

(1) The near fault velocity pulse is extracted more completely by this method. HHT is used instead of wavelet to analyze the ground motions, which overcomes the dependence of wavelet analysis on the selection of the mother wave, so that pulse-like ground motions can be identified more comprehensively. According to the analysis of four typical complex pulse-like ground motions, it can be found that the energy and amplitude of velocity pulse extracted by HHT are higher, and the average pulse index is 72.5% higher.

(2) In order to evaluate the effectiveness of HHT-based method in a large number of ground motions, the HHT-based method and wavelet-based method are used to identify 3066 ground motions in the PEER database. In these ground motions, 150 pulse-like
ground motions are identified by the wavelet-based method, while 229 are identified by the HHT-based method. 105 of the 229 HHT-identified ground motions are also identified by the wavelet-based identification method. In order to evaluate the pulse-like ground motion quality extracted by the present HHT-based method, acceleration response, velocity response fault distance, and CSV are calculated. By comparing these parameters of the HHT-based method and the wavelet-based method, it is found that the pulse-like ground motions obtained by the two methods have strong near-fault characteristics, and the near-fault velocity pulse energy extracted by the HHT-based method is more thorough.

(3) Although the HHT-based method solves the problem of the selection of the mother wave in wavelet technology, only 229 pulse-like ground motions are extracted from the PEER database, which is far less than the actual number of pulse-like ground motions in this database. Among these 3066 ground motions, 419 of them have fault distance less than 20 km, and most of them are pulse-like ground motions. Because of the inevitable mode aliasing in HHT, some near-fault pulses are difficult to be identified by the HHT-based method. A better way to solve these problems may be to introduce the artificial neural network into the identification of pulse-like ground motion, and use it to judge a variety of characteristic information of ground motion, so as to give the pulse-like ground motion.

Data Availability
The data used to support the findings of this study have been deposited in the PEER database repository.

Conflicts of Interest
The authors declare that they have no conflicts of interest.

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