Unearthing Clues to Reduce the Devastating Effects of Earthquakes: The Hilbert-Huang Transform

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Abstract: In this paper the use of the energy-time-frequency representation, the Hilbert-Huang Transform (HHT), for the decomposition and characterization of seismic ground response signals, is discussed. The HHT, integrated by the Empirical Mode Decomposition (EMD) and the Hilbert Transformation (HT), enables engineers to analyze non-stationary oscillation systems and to obtain more detailed intensity descriptions on time-varying frequency diagrams. The advantage of the HHT over other representations is its sharp intensity-localization properties in the time-frequency plane. This paper first provides the fundamentals of the HHT method, and then uses them to analyze recordings of Mexico City soft-soil deposits, indicating that the HHT method is able to extract some motion characteristics useful in studies of seismology and geotechnical engineering, which might not be exposed effectively and efficiently by other conventional data processing techniques.

Key-Words: - Hilbert-Huang Transform, Seismic recordings, Site effects, Time Series Analysis

1 Introduction
Earthquakes represent the single largest potential cause of damage (from natural hazard) facing many countries in the world. The severity of the impact is a direct function of the performance of structures during strong earthquake. Although damaging earthquakes are infrequent, their consequences can be immense. According to recent studies of Federal Emergency Management Agency (USA), damages and losses from earthquakes have steadily increased in recent years. Population growth, urbanization, and the expansion of the built environment, all contribute to this trend. Decisive action is necessary to counter this trend of increasing losses; improved engineering design must part of that action.

Proper data analysis methods for the extraction of the temporal-frequency-energy distribution of motion recordings (ground acceleration) can help to explain earthquake phenomena, to understand important seismic issues (source mechanism, directivity influence, and soil dynamic nonlinearity) and to improve our knowledge of the underlying physical process the data expose.

A recently developed method, the Hilbert–Huang Transform (HHT) (Huang et al. 1999) seems to be able to meet some of these challenges. This study seeks to use the Hilbert-Huang transform to analyze dynamic and earthquake motion recordings and to examine the rationale of the HHT for studies of engineering and seismology. The objective of the analysis is to reveal useful information from motion recordings that might be either hidden or distorted by conventional data-analysis approaches. The examples are not exhaustively described but they are listed in the hope of attracting the attention of the geotechnical, seismic and engineering societies to this interesting, challenging and critical research area.

2 The Hilbert-Huang Transform
The HHT was proposed by Huang et al. (1998) and consists of two parts: i) Empirical Mode Decomposition EMD, and ii) Hilbert Spectral Analysis HAS (Hilbert transformation). With EMD any data set can be decomposed into a finite number of intrinsic mode functions IMFs. An IMF is described as a function satisfying the following conditions: i) the number of extrema and the number of zero-crossings must either equal or differ at most by one; and ii) at any point, the mean value of the envelope defined by the local maxima and the envelope defined by the local minima is zero. An IMF admits well-behaved Hilbert transforms (Hongzhi and Chen, 1998). For an arbitrary function $X(t)$ in linear programming-class (Titchmarsh, 1948), its Hilbert transform $Y(t)$, is defined as,

$$Y(t) = \frac{1}{\pi} P \int_{-\infty}^{\infty} \frac{X(t')}{{t-t'}} \, dt'$$

(1)
where \( P \) indicates the Cauchy principal value. Consequently an analytical signal \( Z(t) \), can be produced by,

\[
Z(t) = X + iY(t) = a(t)e^{i\theta(t)} \tag{2}
\]

where \( a(t) = [X^2(t) + Y^2(t)]^{1/2} \), and \( \theta(t) = \arctan \frac{Y(t)}{X(t)} \) are the instantaneous amplitude and phase of \( X(t) \), respectively. Since Hilbert transform \( Y(t) \) is defined as the convolution of \( X(t) \) and \( 1/t \) by Eq. (1), it emphasizes the local properties of \( X(t) \) even though the transform is global. Using \( a(t) \) and \( \theta(t) \) expressions, the instantaneous frequency of \( X(t) \) is defined as,

\[
\omega(t) = \frac{d\theta(t)}{dt} \tag{3}
\]

However, there is still considerable controversy on this definition. A detailed discussion and justification can be found in (Huang et al., 1998). EMD is a necessary pre-processing of the data before the Hilbert transform is applied. It reduces the data into a collection of IMFs and each IMF, which represents a simple oscillatory mode, is a counterpart to a simple harmonic function, but is much more general. We will not describe EMD algorithm here due to the limitation of the length of the paper. The readers are referred to (Huang et al., 1998) for details.

By EMD, any signal \( X(t) \) can be decomposed into finite IMFs, \( imf_j(t)(j = 1,...,n) \), and a residue \( r(t) \), where \( n \) is nonnegative integer depending on \( X(t) \), i.e.,

\[
X(t) = \sum_{j=1}^{n} imf_j(t) + r(t) \tag{4}
\]

For each \( imf_j \), let \( X_j(t) = imf_j(t) \), its corresponding instantaneous amplitude, \( a_j(t) \), and instantaneous frequency, \( \omega_j(t) \), can be computed with Eqs. (2) and (3). By (3) \( imf_j \) can be expressed as the real part \( RP \) in the following form,

\[
imf_j(t)RP[a_j(t)\exp(i\int w_j(t)dt)] \tag{5}
\]

Therefore, by Eqs. (4) and (5), \( X(t) \) can be expressed as the IMF expansion as follows,

\[
X(t) = RP \sum a_j(t)\exp(i\int \omega_j(t)dt) + r(t)
\]

which generalize the following Fourier expansion

\[
X(t) = \sum_{j=1}^{\infty} a_j e^{i\omega_j t}
\]

by admitting variable amplitudes and frequencies. Consequently, its main advantage over Fourier expansion is that it accommodates nonlinear and nonstationary data perfectly. Eq. (6) enables us to represent the amplitude and the instantaneous frequency as functions of time in a three-dimensional plot, in which the amplitude is contoured on the time-frequency plane. The time-frequency distribution of amplitude is designated as the HAS or simply Hilbert spectrum, denoted by \( H(\omega, t) \). For a comprehensive illustration of the HHT-seismic approach, Garcia et al., (2006) is suggested.

3 HHT for Earthquake Geotechnical Analyses

Earthquake-resistant design is the first line of defense in improving structural safety and reducing losses from earthquakes. Structural engineers must take into account two fundamental characteristics of earthquake shaking: 1) how ground shaking propagates through the Earth (especially near the surface) –site effects–, and 2) how buildings respond to this ground motion. Currently neither characteristic is sufficiently well understood.

Presently recordings of ground motion in urban areas seemed to be insufficient to adequately characterize this phenomenon. Despite of the great efforts to improve the earthquake ground motion data (access, size and quality) there are no significant advances in reducing the dangerous difference between what is measured and predicted.

The intention of this work is point out a possible reason for this situation: the useful information from motion recordings is being either hidden or distorted by conventional data-analysis approaches.
3.1 HHT seismic interpretation

As an example of the Hilbert amplitude spectra HAS applied to earthquake recordings (obtained from the IMFs), the E-W accelerograms of the October 9th 1995 earthquake recorded in CDAO site (soft soils) is shown in Figure 1. HAS in Figure 1b shows two sets of strong-ground motion in the time intervals 90-110 and 120-140 s. Based on the HAS observation the first arrival consists of low frequency signals, while the later one contains low and high-frequency signals. Figure 1c (inset in Figure 1b) shows the Fourier amplitude spectrum of the acceleration time series. The Fourier spectrum does not provide information that is specific to the localized low-frequency signals or to time-dependent or evolutionary frequency content.

A revision of the Fourier spectra indicates that the frequency content of the waves is spread out with the maximum spectral amplitude (~250 cm/s) at 0.3 Hz. The HAS in Figure 1b shows quantitatively the temporal-frequency distribution of vibration characteristics in the ground-motion recording: two sets of strong-ground motion in the time intervals 90–110 and 120–140s consisting of low-frequency signals between 0.35 to 0.70 Hz with intensities around 24 and 20 cm/s², respectively. The highest intensity (I_{max}~24 cm/s²) at 0.5 Hz is surrounded by an important zone (iso-acceleration curves ~ 20 cm/s²) on a wider frequency band (from 0.4 to 0.6 Hz). The second wave train arrival, with accelerations on the middle of the intensity-scale registered, covers frequencies up to 1.0 Hz.

Fig. 1 A HAS example: accelerograms recorded in CDAO, a soft-soils station
3.2 Soil amplification: a HHT reinterpretation of Site Effects

Site effects play a very important role in characterizing ground motions because they may strongly amplify (or deamplify) seismic arrivals at the last moment just before reaching the surface of the ground or the basement of man-made structures. For much of the history of seismological research, site effects of the effects of the surface geology have received much less attention than they should, with the exception of Japan, where they have been well recognized through pioneering work by Sezawa and Ishimoto as early as the 1930’s (Kawase and Aki, 1989). The situation was drastically changed by the catastrophic disaster in Mexico City during the Michoacan, Mexico earthquake of 1985, in which strong amplification due to extremely soft clay layers caused many high-rise buildings to collapse despite their long distance from the source. The real cause of the observed long duration of shaking during the earthquake is not well resolved yet however, there is no room for doubt that the primary cause of the large amplitude of strong motions in the soft soil (lakebed) zone relative to those in the hill zone is a simple one-dimensional (1D) site effect of these soft layers.

There are plenty of ways to estimate site effects. An empirical approach is to obtain site amplification factors in the frequency domain directly from the observed records. The observed ground motions itself is the final product of the source, path and site effects, so we need a way to extract only the site effects from data. A basic but effective approach is to take spectral ratios of two adjacent records with different soil conditions. An ideal case is a free-field site on an intact hard rock outcrop next to a site on soft sedimentary layers. If we install borehole stations just beneath the surface station, i.e. conduct downhole measurements, then we can directly observe wave propagation phenomena between these stations. A M_c=7.5, strong earthquake, recorded at CDAO site, was used to calculate spectral ratios from bedrock (CU station) to 60, 30, 12 and 0 m stations (Figure 2a).

From the Fourier spectra ratios (Figure 2b) it is noted that the strong-motion amplification was significant in a wide frequency band (0.2 to 1 Hz) with the most pronounced resonance slightly shifted to the left. Noticeable differences in amplification are detected in 60 m and 30 m responses, while the spectrum at 12 m is equivalent to the surface spectrum implying that this upper layer does not amplify the motions (under strong and weak shakings).
Using the spectral ratios in Figure 2b three behavior-bands can be observed: the lowest frequency-band, a central band (where \( f_0 \) is localized) and the high frequency band. On the basis of these results, it may be argued that the existence of specific frequency ranges where the responses cannot be predicted from simple quantitative reasoning through Fourier spectra.

The HAS (Figure 2c) permit to outline the differences between responses and to mark the effects of the input characteristics on the amplification ratios. Comparisons between 60 m (the “real” input that affect the soil column) and CU (the outcropping used as seismic excitation) spectra alert about the impact of the reference site-selection on the amplification ratios and soil-nonlinearity conclusions.

Despite of the similar intensity in both HAS (60 and CU), the time interval and frequencies where maximum accelerations are developed has a profound influence on the determination of soil amplification: the material between 60-30 m amplifies more than those between 30-12 m. Frequencies activated (and used to calculate the amplification ratios) are very different: wide range activated in the 30m-HAS and considerable intensities (spectral ordinates) below 0.5 Hz for CU. This kind of characteristic cannot be deduced from Fourier analysis.

HHT analysis depicts a deamplification from 12 to 0 m (more energy is dissipated during the strong event) and because of the modification of the frequency content this superior layer can be considered as a low-pass filter. This is not observed in the Fourier spectra, only the HAS analysis permits seeing that response is due to a collection of acceleration spikes of low frequency from bedrock and crossing the materials until the second measurement station the strong shaking starts mobilizing a broader intensity-frequency range (higher harmonics are generated increasing strong-motion amplitudes). Comparing the different results exposed by Fourier and HHT, it seems inappropriate to relate coordinates (frequency, spectral amplitude) for describing a phenomenon that is clearly time dependent.

![Fig. 2b Fourier interpretation of site-effects](image-url)
Fig. 2c HHT interpretation of site-effects
The above arguments indicate that the HHT allows a more precise characterization of the layers behavior as linear or nonlinear and demonstrates that Fourier analysis is not able to reveal effectively the responses characteristics dealing with nonstationary time histories.

4 Conclusion

HHT offers an important next step in a long-term effort to reduce earthquake losses through improved structural and ground-based earthquake strong motion recordings. The dangers of unsafe “underbuilding” and costly “overbuilding” for earthquakes can only be dealt with by the capture of vital information when earthquakes occur.

For seismic processes (nonstationary) the Fourier-based spectral analyses are not adequate because they are based on linear and stationary assumptions. In this short paper we have addressed the possibility of characterizing natural systems (soil deposits) by the time-frequency variations of system signals (accelerograms that represent the systems dynamics). The objective of describing data from engineering perspectives (time-frequency-intensity domain) for finding specific and indicative behavior patterns reducing the error mechanisms is addressed applying the HHT to the seismic information. Our analysis is of a preliminary nature and many issues have to be investigated rigorously but the HHT seems to have much potential for this approach. If new alternatives for analyze the sets of strong motion recordings are not applied on engineer fields by the time of the next damaging earthquake, a great opportunity to understand and to mitigate the effects of such natural disasters will be lost.

References: