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SURFACE WAVES AND SEISMIC RESPONSE OF LONG-PERIOD STRUCTURES

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ABSTRACT

During an earthquake, the presence of free surface generates waves, known as surface waves, which propagate along Earth's surface. In sedimentary basins, the conversion of seismic body waves at basin edges also generates surface waves, which travel across the basin. Surface waves are characterized by long-periods and much slower velocities than shear waves. Consequently, they are more visible in displacements than in accelerations, and show up much later in a record. In triggered seismic networks, the recorders are triggered on and off based on acceleration amplitudes. In most earthquakes, recorders are turned off before the arrival of surface waves, and the post-event memory is typically set too short to record them.

This paper investigates the effects of surface waves on structural response, and presents observational and analytical confirmations of their significance. Recent data from real-time monitored structures clearly show the importance of surface waves. Because their energy is concentrated at long periods, surface waves are particularly critical for long-period structures, such as tall buildings and base-isolated structures. Also, because of their long duration, surface waves can push a damaged structure into complete collapse because of the additional hysteretic deformation cycles that the structure goes through.

Surface waves control response spectra at long periods, and should be considered when designing and evaluating long-period structures for earthquakes, particularly when they are located in sedimentary basins.

Keywords: Surface waves, seismic response, long-period structures

INTRODUCTION

During an earthquake, the presence of free surface generates waves, known as surface waves, that propagate along Earth's surface. Surface waves differ from body waves in many respects – they are mainly concentrated near the surface and attenuate rapidly with depth, travel more slowly, their amplitudes do not decay with distance as much, and their velocities are strongly amplitude dependent (Shearer, 1999). There are two types of surface waves, Rayleigh waves and Love waves. Rayleigh waves exist at any free surface, whereas Love waves are generated only if there is a velocity gradient (i.e., a soil layer) near the surface. In sedimentary basins, the 2D and 3D geometry of the basin also creates surface waves. Seismic body waves convert into surface waves at basin edges and travel across the basin along the surface.

Because of their long period and long duration, surface waves are important for long-period structures, such as tall buildings and base-isolated structures, and for structures that are already damaged. The

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long period can cause resonant vibrations in flexible structures, whereas the long duration can push a damaged structure into complete collapse because of the additional hysteretic deformation cycles that the structure goes through. In a study of a base-isolated structure, Safak and Frankel (1996) have shown that base isolators, which are found to be beneficial for shear waves, can actually be detrimental for the structure when subjected to surface waves. Much of the damage in the Los Angeles basin during the 1994 Northridge earthquake was attributed to surface wave and basin edge effects (Somerville, 2004).

Current strong-motion networks do not adequately record surface waves, because the triggering mechanism on recorders is set to trigger based on acceleration amplitudes. Because of their long period, surface waves increase the amplitudes of displacements but not the amplitudes of accelerations. Also, because of their low velocity, they arrive much later than shear waves. In most cases, recorders are turned off before the arrival of surface waves, and the post-event memory is typically set too short to record them. It was only after the installation of real-time structural and ground motion monitoring networks the significance of surface waves has become more apparent.

In a benchmark paper, Joyner (2000) presented a rigorous study of the characteristics of surface waves in deep sedimentary basins, and introduced an empirical equation for the attenuation of surface wave amplitudes with magnitude, distance, and period. Although seismologists have long recognized the importance of surface waves, their significance on structural response and damage has not been adequately investigated. This paper aims to show the engineering significance of surface waves. It highlights the importance of surface waves by presenting observational, as well as analytical evidences of the contributions from surface waves to seismic response and damage.

SURFACE-WAVE-INDUCED VIBRATION RECORDS FROM STRUCTURES

Records from real-time monitored structures in sedimentary basins confirm the effects of surface waves. We will give an example by presenting the records from one such structure, the 17-story, steel-frame Health Sciences (Factor) Building at the University of California campus in Los Angeles. The building was densely instrumented by the USGS after the 1994 Northridge, California, earthquake by using 72 uniaxial accelerometers and four sets of digital recorders. The instrumentation includes four horizontal accelerometers at every floor, plus four vertical accelerometers at the two basement levels. More detail on the instrumentation can be found in Kohler et al. (2005).

The response of the building to the M=4.6 Yorba Linda, California earthquake of September 3, 2002, whose epicenter was approximately 35 km away, was recorded by the 24 of the 72 accelerometers that were operating in real-time at the time of the earthquake. Figures 1a and 1b show the recorded accelerations in the north-south and east-west principal directions of the building at the 3rd and 13th floors, and the corresponding displacements. Since these were real-time channels, we had the advantage of being able to investigate very long segments of data. The plots given in Figs. 1a and 1b show 240-sec. long segment of the response to the earthquake. The vertical lines around the 50-second mark on the 3rd floor acceleration plots depict the approximate record length that would have been available had the recording system not been in real-time (50 sec. was estimated by looking at the triggered records from the ground stations near the building). It is remarkable that the largest displacements in the N-S direction occur around the 100-second mark, which is approximately 80 seconds after the shear waves passed. This represents the surface wave effects on the response. If this were not a real-time recording we would not have observed such motions.

ELASTIC AND INELASTIC RESPONSE SPECTRA FOR SURFACE WAVES

Since they dominate the long-period energy, surface waves have a significant influence on the seismic response of long-period structures. Long-period structures include tall buildings, long-span bridges, base-isolated structures, and most damaged structures. We will show the effects of surface waves on such structures by calculating the elastic and elasto-plastic response spectra for a ground record from the same Yorba Linda earthquake. The record is from the basement of the USGS Office building (a two-story wooden house) in Pasadena, California, identified as Station GSA in the Southern California's TriNet seismic network (http://www.trinet.org/). The north-south, east-west, and vertical accelerations recorded at the station, and the corresponding displacements are shown in Fig. 2. Note that although the accelerations attenuate quickly with time, the displacements do not because of the surface waves. In Fig. 3, we plot the close-up view of the east-west and vertical displacements for the surface-wave dominated portion of the record (i.e., beyond 27 sec.), and the corresponding particle motion in the vertical east-west plane. Note that the horizontal and vertical displacements are almost 90-degree out of phase and the particle motion has elliptical paths, which are characteristics of surface waves.

To show the effects of surface waves on structural response, we calculate and compare the pseudo-acceleration and displacement response spectra by considering two different record lengths, the first 20 seconds of the record (as marked in the acceleration plots in Fig. 2) and the entire record. The first 20-second segment is the strong-motion part dominated primarily by share waves. Beyond 20 seconds, the record is dominated by surface waves. The comparisons of response spectra for the two segments are given in Fig. 4. The figure shows, as expected, that the pseudo-acceleration response spectra are dominated by the first 20 seconds of the record. The remaining part beyond 20 seconds does not increase spectral amplitudes. For the displacement response spectra, however, there is a big increase in the amplitudes for periods above 1.0 second, when the entire record is considered. This is again due to the contributions made by the surface waves to the displacement response at long periods.

In order to see the contributions of surface waves to inelastic response, we calculated and compared the response time histories, as well as force deformation hysteresis loops, of a 2-second elasto-plastic oscillator for the two record lengths. The results are given in Fig. 5. The figure clearly shows that whether we consider the surface waves (i.e., use the entire record) or ignore them (i.e., use the first 20 seconds) makes a big difference in displacements and ductility demands. The maximum inelastic displacement and the ductility demand increase by a factor of 2.5 when the surface waves are included. This result has important consequences for structures that are already damaged, because a damaged structure can approximately be modeled as an elasto-plastic system. As stated earlier, the amplitudes of surface waves do not decay fast with distance, making them have long durations. The long duration forces a damaged structure to go through a large number of hyteresis cycles. Each additional cycle increases the inelastic displacement and ductility demand, particularly in structures with a deteriorating-type force-deformation hyteresis (e.g., unreinforced masonry structures). Such effects can easily push a damaged structure into total collapse.

ROTATIONAL BASE EXCITATIONS AND P-Δ EFFECTS

An important, but not well recognized, effect of surface waves on structures is that, in addition to horizontal and vertical excitations, surface waves also give rotational excitations to a structure. The rotational excitations are generated due to traveling vertical motions, as schematically shown in Fig. 6.

The traveling causes the curvature of a fixed point on the surface to change back-and-forth sinusoidally, giving the ground surface a rolling-type of motion. The foundation of a structure on the surface naturally wants to follow the ground curvature, which in turn causes rocking-type rotational excitations for the structure. The more firmly the foundation is in contact with the ground surface (e.g., a rigid mat foundation), the more significant such motions become.

Analytical equations for surface waves can be developed for simple cases, such as a homogenous half space or layered media (e.g., Ewing et. Al., 1957; Aki and Richards, 1980; Kramer, 1996). The equations for Rayleigh waves in a homogenous half space show that the vertical and horizontal motions are out of phase (i.e., when one is maximum or minimum the other one is zero), the horizontal and rotational motions are in phase, i.e., they both reach to a maximum or a minimum simultaneously. The latter observation has significant implications for structural response; it indicates that the rotational motions increase the horizontal displacements of the structure.

It is a common assumption for building structures that the vertical loads (i.e., those generated by the weight of the building and vertical ground accelerations) do not contribute to the horizontal response of the building. This implies that the horizontal displacements are so small that any overturning moments (commonly known as P-Δ effects) generated by the vertical misalignment in the building can be ignored. This may not be the case for surface-wave-induced motions, particularly in buildings with soft first stories. Because their horizontal and rotational components superimpose constructively, surface waves can cause such a large horizontal displacements that P-Δ effects cannot be ignored.

Surface-wave induced rotational motions and P-Δ effects are studied in more detail in Safak (2000, 2007).

CONCLUSIONS

During an earthquake, the presence of free surface generates waves, known as surface waves, which propagate along Earth's surface. In sedimentary basins, the conversion of seismic body waves at basin edges also generates surface waves that travel across the basin. Because they are long-period and long duration, surface waves can be critical for long-period structures, such as tall buildings, long bridges, and base-isolated structures. Not only horizontal, but also vertical and rotational components of surface waves are important. Rotational and horizontal components are in phase, and superimpose constructively to increase horizontal response. In buildings with soft first stories, surface waves can create large P-Δ effects on the first story. Surface waves are also critical for damaged structures, because, in most cases, a damaged structure is a long-period structure. Moreover, since surface waves typically have long durations, they cause a damaged structure to go through a large number of cycles of hysteretic deformations, which can push a damaged structure into a total collapse. Surface waves are slow and typically arrive much later than shear waves in sedimentary basins. Also, since they are low frequency, surface waves do not increase accelerations but displacements. In triggered strong-motion networks, recorders typically trigger based on acceleration amplitudes. Data show that in most triggered strong motion networks, particularly those in structures, recorders shut off before surface waves arrive, missing a critical component of ground shaking. It is strongly recommended, especially in sedimentary basins, that the post-event memory of recorders be increased to several minutes to properly record surface waves.

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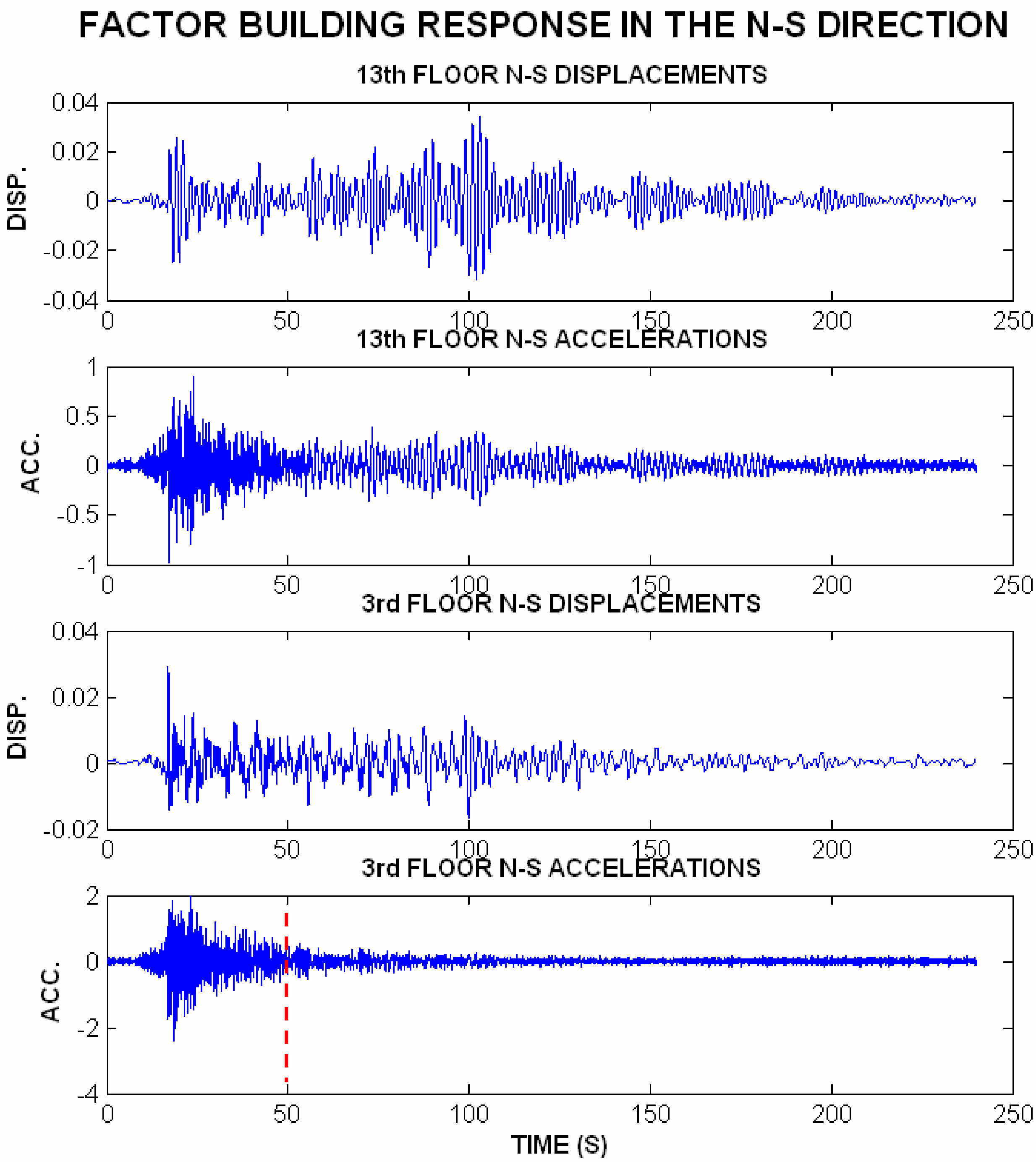

Figure 1*a*. Third floor and 13th floor accelerations and displacements in the N-S direction at Factor Building during the M=4.6 Yorba Linda, California earthquake of September 3, 2002.

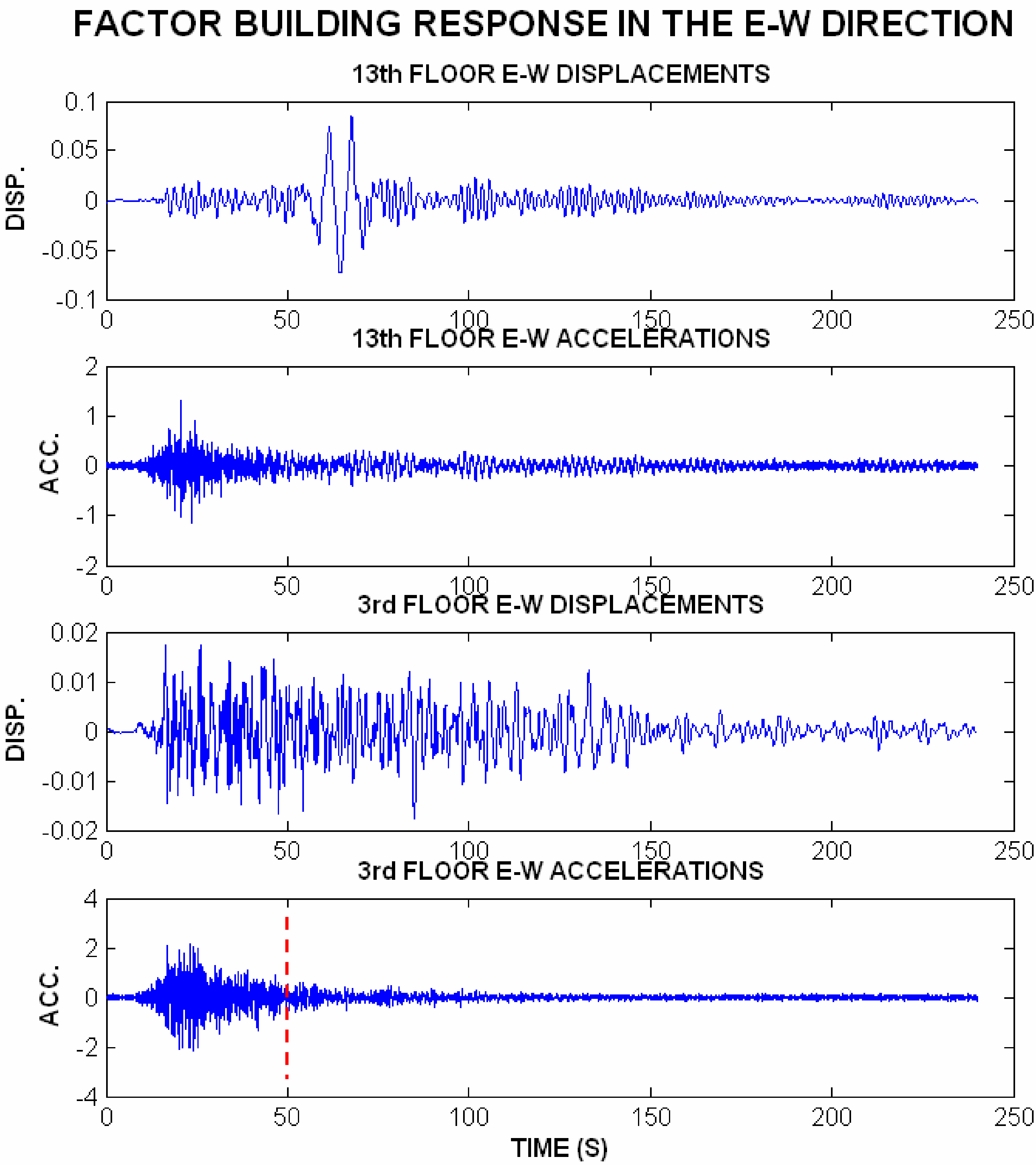

Figure 1*b*. Third floor and 13th floor accelerations and displacements in the E-W direction at Factor Building during the M=4.6 Yorba Linda, California earthquake of September 3, 2002.

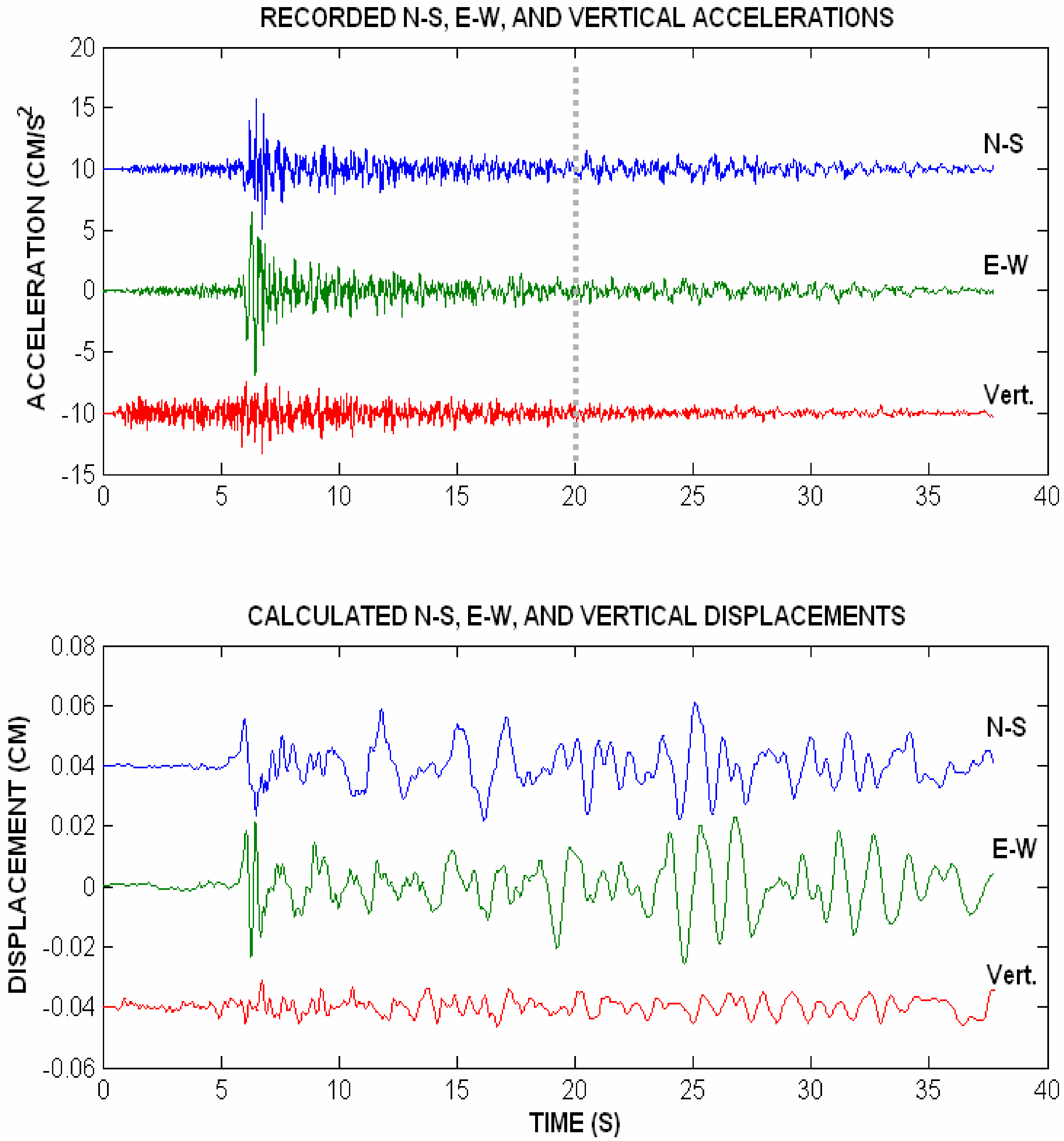

Figure 2. North-south, east-west, and vertical ground accelerations and displacements at Station GSA during the M=4.6 Yorba Linda, California earthquake of September 3, 2002.

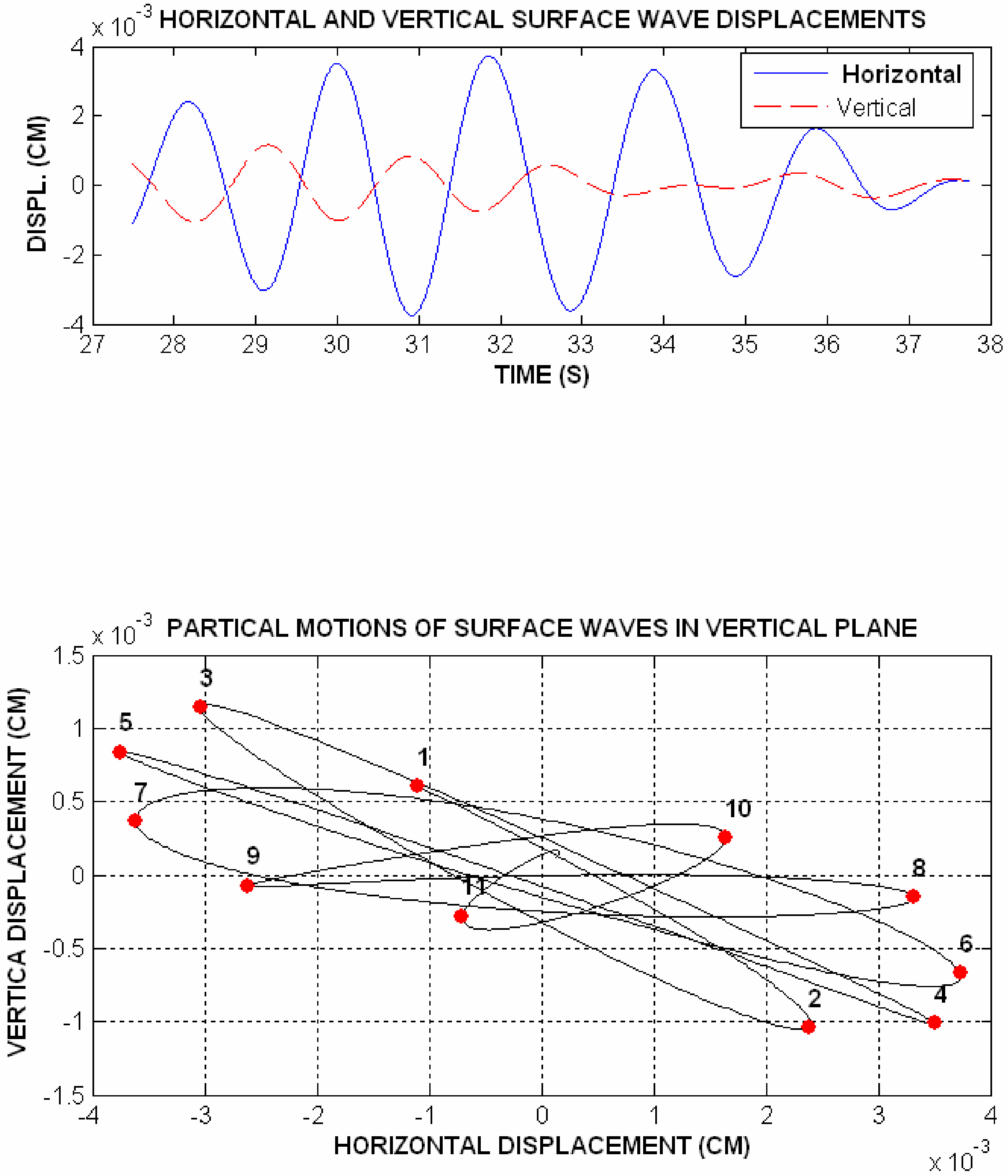

Figure 3. Close-up view of the east-west and vertical displacements for the surface-wave dominated portion of the record, and corresponding particle motion in the vertical east-west plane.

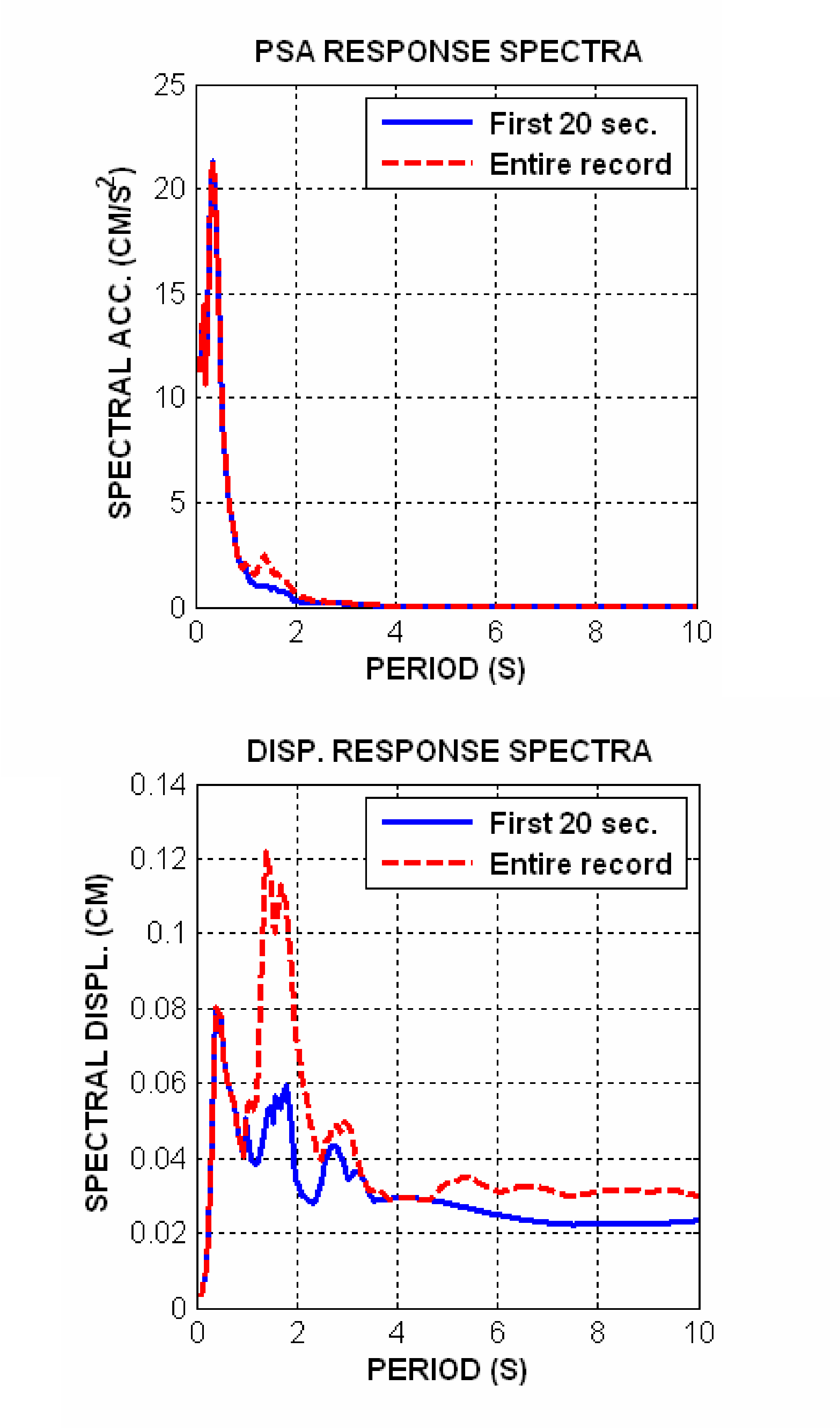

Figure 4. Comparison of pseudo-acceleration and displacement response spectra for the first 20 seconds (as marked in the acceleration plots in Fig. 2) and the entire record.

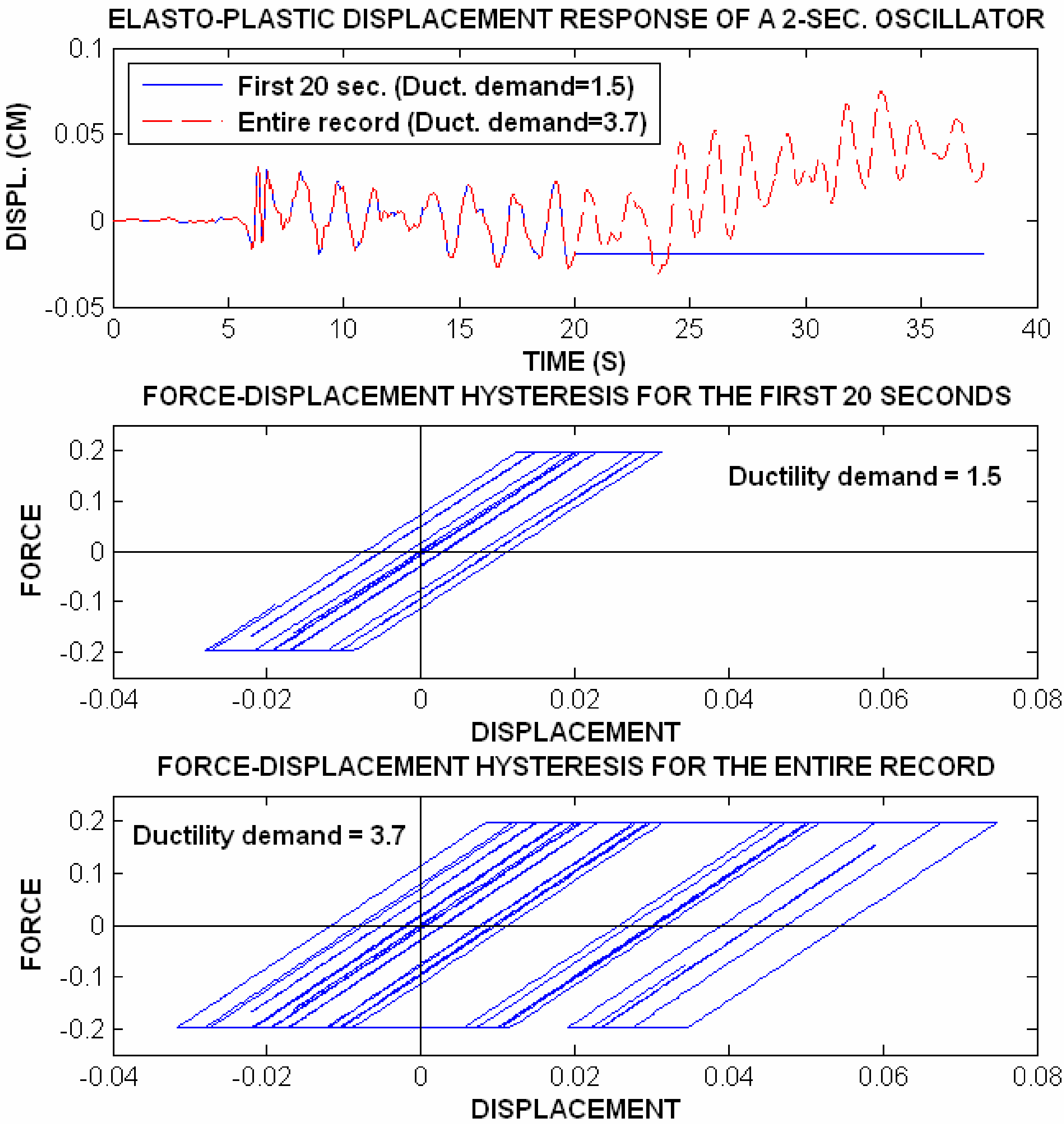

Figure 5. Comparison of elasto-plastic responses, ductility demands, and force-deformation hysteresis loops of a 2-second elasto-plastic oscillator corresponding to the first 20 seconds (as marked in the acceleration plots in Fig. 2) and the entire record.

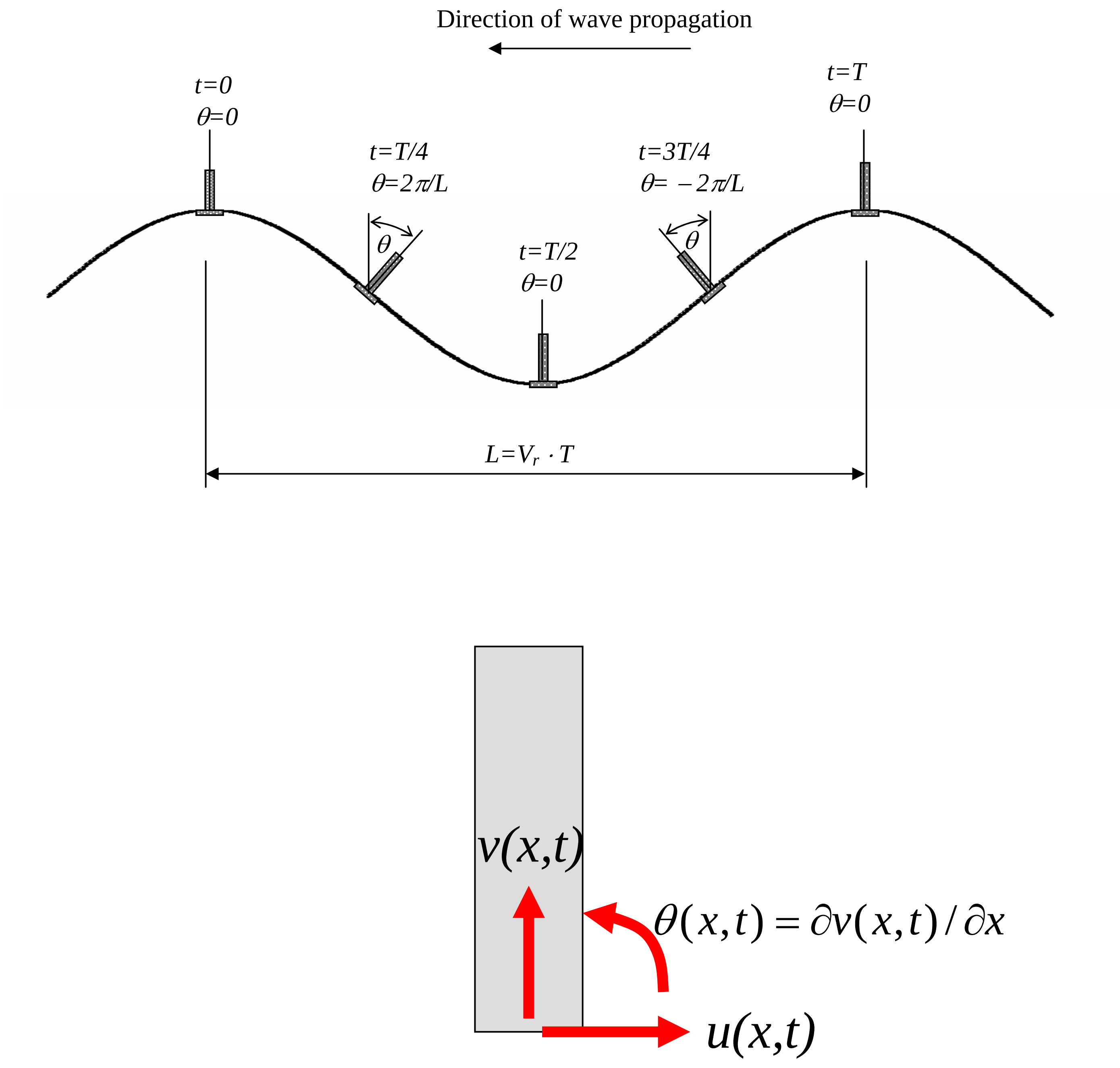

Figure 6. Schematic representation of rotational motions generated by traveling vertical motions (top), and surface-wave-induced excitations acting on a structure (bottom).