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Effect of ground motion filtering on the dynamic response of a seismically isolated bridge with and without fault crossing considerations

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ABSTRACT

High-pass filtering not only removes the low-frequency noise from the near-fault ground motion records, but also eliminates the permanent ground displacement and reduces the dynamic ground displacement. This may considerably influence the calculated seismic response of a spatially extended engineering structure crossing a fault rupture zone. To demonstrate the importance of incorporating permanent ground displacements in the analysis and design of extended structures under specific fault crossing conditions, the dynamic response of a seismically isolated bridge located in the vicinity of a surface fault rupture (“Case A”) or crossing a fault rupture zone (“Case B”) is calculated by utilizing a near-fault ground motion record processed with and without a displacement offset. The seismically isolated bridge considered in this study is a 10-span continuous structure supported by 11 piers, resembling a typical segment of the 2.3 km long Bolu Viaduct 1 located in west-central Turkey. The Lucerne Valley record from the 1992 M_w 7.2 Landers earthquake, which preserves a permanent ground displacement in the fault-parallel direction and exhibits a large velocity pulse in the fault-normal direction, is used as the basis for investigating the effect of high-pass filtering on the dynamic response of the bridge. For the seismically isolated bridge located in the vicinity of the surface fault rupture (“Case A”), the utilization of the high-pass filtered ground motion leads to underestimating the demands of pier top, pier bottom and deck displacements. However, the demands of isolation displacement, isolation permanent displacement and pier drift are almost identical for both the unfiltered and filtered versions of the ground motion record. On the other hand, for the seismically isolated bridge traversed by a fault rupture zone (“Case B”), all response quantities are significantly underestimated when the high-pass filtered ground motion is used. These results, though limited to a single bridge structure and a single ground motion input, clearly indicate the importance of permanent ground displacement on the dynamic response of spatially extended engineering structures crossing fault rupture zones.

1. Introduction

Strong motion records are of fundamental importance in earthquake engineering design, but quite frequently they are contaminated by broadband noise limiting the frequency range over which useful data can be obtained. The influence of noise in strong motion records is most pronounced at high and low frequencies where the signal-to-noise ratio is typically low compared to that at the intermediate frequencies [1].

For analog accelerographs the high-frequency noise is primarily associated with the correction for instrument response, whereas for digital accelerographs the high-frequency noise is commonly related to the low resolution of the analog-to-digital converter, the effect of ambient, wind or wave sources at the location of the instrument, and the monoharmonic high-frequency noise caused by the proximity of the instrument to electrical generators or vibrating machinery [2]. The high-frequency noise is usually removed by applying a low-pass (high-cut) filter to the accelerogram, a correction that may not always be necessary depending on the intended use of the data and the particular characteristics of the high-frequency noise.

On the other hand, the low-frequency noise has been attributed to instrumental errors such as transducer misalignment and cross-axis sensitivity [3,4], mechanical or electrical hysteresis within the transducer system [5], and analog-to-digital conversion [6,7], as well as to natural distortions such as tilting and torsion of the ground in the vicinity of the instrument [8–12]. These instrumental errors and

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natural distortions generate small offsets in the baseline of the recorded ground accelerations, which in turn amplify upon integration resulting in significant drifts in the ground velocities and displacements, as well as in noticeable effects in the long-period range of the corresponding response spectra. The low-frequency noise is typically removed by high-pass (low-cut) filtering with corner frequencies often chosen based on the shape of the Fourier amplitude spectra and the signal-to-noise ratio.

Though high-pass filtering is effective in reducing the low-frequency noise in accelerograms, this may not always be the most desirable approach for processing near-fault records with a large permanent ground displacement interpreted as coseismic displacement of the ground due to slip on the fault. The reason is that high-pass filtering does not allow for displacement time series to have a static offset (corresponding to zero frequency), and therefore this lack of a permanent ground displacement in near-fault records may significantly affect the calculated seismic response of spatially extended engineering structures under specific fault crossing conditions. However, retrieving the true permanent ground displacement directly from an accelerogram is still an open problem in strong motion seismology as discussed in Section 2.

The main objective of this study is to demonstrate the importance of incorporating permanent ground displacements in the analysis and design of spatially extended engineering structures under specific fault crossing conditions. To achieve this objective, the dynamic response of a seismically isolated bridge located in the vicinity of a surface fault rupture ("Case A") or crossing a fault rupture zone ("Case B") is calculated by utilizing a near-fault ground motion record processed with and without a displacement offset.

2. Permanent ground displacement

Permanent ground displacement (also known as static displacement, residual displacement, displacement offset, permanent translation or fling step) is the flat level near the end of the baseline-corrected displacement time series derived from accelerograms at stations in the vicinity of a fault. The permanent ground displacement is interpreted as the coseismic deformation of the ground due to dislocation across the fault surfaces. The permanent ground displacement typically varies between a few centimeters to several meters depending on the local slip (i.e. slip on the immediate fault segment), the depth of burial of the fault, and the fault-to-station distance. An informative discussion on the characteristics of the permanent ground displacement in the vicinity of a fault for various types of movement (strike-slip, oblique, dip-slip), faulting depth (surface vs. buried), and slip distribution (uniform vs. variable) based on numerical simulations is presented by Dreger et al. [13]. The permanent ground displacement appears in the direction of the slip vector on the fault, and therefore manifests itself in the strike-parallel direction for strike-slip faults and in the strike-normal and vertical directions for dip-slip faults (e.g. [14,15]). It should also be noted that permanent translation along with forward rupture directivity are the two main causes of the pulse-like ground motions observed in the near-fault region (e.g. [14,15]) which have been identified as critical in the design of structures (e.g. [16–18]).

A considerable effort has been expended by seismologists and engineers over the last four decades to maximize the data return from accelerographs by retrieving the permanent ground displacement (e.g. [5,11,19–30]). These studies have proposed various processing schemes that involve, instead of high-pass filtering, baseline correction in an attempt to recover the permanent ground displacement directly from accelerograms. However, this problem has proved to be particularly challenging because the computed displacement offset may not be the true permanent ground displacement, but it may also incorporate the effects of natural distortions (such as tilting and torsion of the ground in the vicinity of the instrument) and instrumental errors (such as transducer misalignment and cross-axis sensitivity, mechanical or electrical hysteresis within the transducer system, and analog-to-digital conversion). These natural distortions and instrumental errors cause small offsets in the baseline of the accelerograms resulting in drifts in the velocity and displacement time series upon integration, making it difficult to fully understand the source of the baseline offsets for any given record and eventually recover the true permanent ground displacement. Evidently, these offsets cannot be removed by applying a high-pass filter to the accelerogram because such a procedure would preclude extracting the permanent ground displacement from the acceleration record.

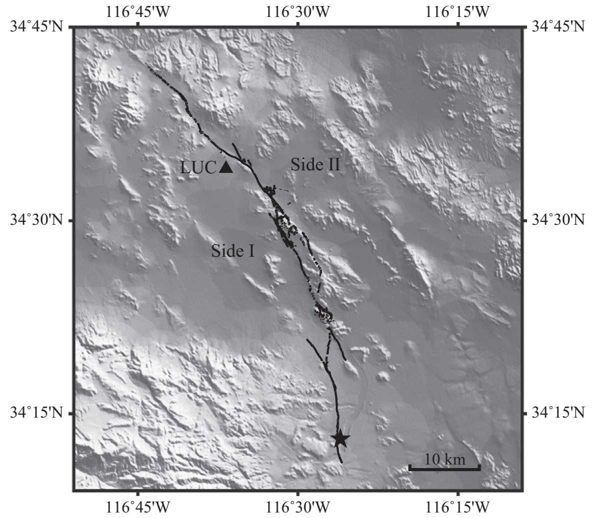

Fig. 1. Map view of the 1992 M_w 7.2 Landers earthquake illustrating the epicenter, the location of LUC station, and the fault trace.

Early studies indicated that permanent ground displacements derived directly from accelerograms using empirical baseline correction schemes are in most cases sensitive to the choice of the parameters for the baseline correction, and variations of these parameters may yield seemingly plausible displacement waveforms with very different offsets (e.g. [11,22]). To reduce this uncertainty, subsequent research studies focused on providing more robust guidelines for the selection of the parameters for baseline correction and then grid searching for displacement waveforms that most resemble a ramp or step function (e.g. [23,26,28]).

Independently determined geodetic data, such as Global Positioning System (GPS) measurements (preferably at stations collocated with accelerograph stations) and Interferometric Synthetic Aperture Radar (InSAR) observations, have also been used to assess the accuracy of baseline correction schemes in estimating the true permanent ground displacement (e.g. [11,22,23,28–30]). This presumes that the entire static displacement (obtained from static GPS measurements or InSAR observations) occurs during the earthquake with no postseismic deformation taking place in the averaging period following the event. These studies have shown that permanent ground displacements obtained from baseline correction schemes do not routinely converge to the correct value of the static displacement as inferred from static GPS measurements. Even the addition of static GPS data as a constraint to the baseline correction procedure does not necessarily guarantee convergence to the correct value of the static displacement, and even if the correct static offset is obtained the dynamic component of the displacement waveform may be in error by large amounts [30].

To overcome these limitations, recent studies have utilized high-rate GPS measurements (which provide accurate displacement data in a kinematic mode) as an additional constraint in the computation of the ground displacement time series during strong shaking and after strong shaking has ceased (e.g. [24,27,30]). This is achieved by combining high-rate GPS and accelerometer data to produce broad-