GROUND SURFACE AMPLIFICATION FOR CANYON TOPOGRAPHIES EXCITED WITH BI-DIRECTIONAL EARTHQUAKE RECORDS

Evangelia SKIADA1, Stavroula KONTOE1, Peter J. STAFFORD1, David M. POTT1

ABSTRACT

It is well established that topographic irregularities influence the surface ground motion. A number of case histories have shown aggravation of the ground motion in terms of amplitude, frequency content and elongation of the recorded duration in the vicinity of irregular topography. Several parametric studies have been performed on the subject, illustrating its importance and the main parameters that control the ground surface response based on different geometry configurations, ground stratigraphies and characteristics of the input motion. Most of the existing numerical studies focus on the impact of vertically propagating shear waves considering only one horizontal component of the ground motion. This paper considers the impact of both the horizontal and vertical components of the ground motion for the case of an empty canyon located in a soil layer above rigid bedrock. A parametric, time domain finite element (FE) study has been performed with the simultaneous imposition of the horizontal and the vertical components of 30 carefully selected earthquake records and wavelet pulses as input motions. The computed ground surface response is compared to the response obtained when considering only one component of the same suite of motions showing the impact of the bi-directional excitation.

Keywords: canyons; topography; 2D wave propagation; amplification; ground motion

1. INTRODUCTION

The impact of ground surface topography on the amplitude, duration and frequency content of the earthquake ground motion is well recognised. Effects related to topography have been manifested in several past earthquakes (i.e. Northridge 1994, Athens 1999, Haiti 2010 and Christchurch 2011) and are typically associated with convex features at the ground surface. Extensive parametric numerical studies have been performed on the subject, focusing mainly on single slope topographies above a half-space (Ashford et al. 1997, Bouckovalas and Papadimitriou 2005). Canyon topographic irregularities have been examined by Wong and Trifunac (1974) providing analytical relationships for the ground surface response around semi-elliptical and semi-cylindrical canyons. Due to the simplified assumptions of these studies, more recent studies focused on examining different canyon shapes, ground conditions and input motions in order to predict a more realistic ground surface response. Assimaki et al. (2005, 2007 and 2013) performed extensive studies on topographic amplification, examining different case histories after major events with altering ground conditions and input motions. Furthermore a number of recent studies (Tripe et al 2013, Rizzitano et al 2014) have shown that there is significant interaction between topographic aggravation and soil layer amplification and that the depth to bedrock is an important parameter.

The majority of existing numerical studies considered simplified excitations in the form of wavelets, while they examined only the horizontal component of the ground motion. A recent study by Skiada et al. (2017b) compared the horizontal ground surface response resulting from Ricker (1970) and Saragoni & Hart (1974) wavelet pulses to the one computed with 30 earthquake records examining only one component of the same suite of motions showing the impact of the bi-directional excitation.

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horizontal component of the ground motion. In this paper the work of Skiada et al (2017b) is extended using bi-directional analysis, considering both the horizontal and the vertical components of the ground motion for the same suites of motions. The aim of this paper is to examine the impact of bi-directional excitation on the predicted response and to further evaluate the use of wavelet pulses as a tool for simulating topography effects in a simplified and economical way.

2. METHODOLOGY

2.1 Numerical model description

Two-dimensional time-domain finite element analyses were performed, considering a canyon in a soil layer over rigid bedrock subjected to horizontal and vertical in-plane waves imposed simultaneously. The soil is treated as a homogeneous linearly elastic material, with properties listed in Table 1. The finite element (FE) model geometry consists of a canyon of height (H), slope inclination angle (i), crest-to-crest distance (L_{ctc}) and soil layer thickness (z), as presented in Figure 1. Parametric analyses focus on the impact of imposing simultaneously the horizontal and vertical component of 30 recorded earthquakes (bi-directional input motions) on the ground surface response. The basic set of analysis comprises of two fixed canyon geometries with an input of 30 earthquake motions corresponding to five earthquake scenarios. The FE mesh geometry was fixed for the current study, considering the slope height as H=50m, the crest-to-crest distance as L_{ctc}=280m, the depth to bedrock as z=125m and two slope inclination angles of i=45° and 90°. Ashford et al. (1997) and Bouckovalas and Papadimitriou (2005) show an increase of topographic amplification with slope angle. The same trend was observed by examining slope angles of 10°, 30°, 45°, 60°, 75° and 90° in the current research (not included in this paper). Although the angle of 90° corresponds to an unrealistic geometry in nature, it is mainly presented here as an upper bound of the expected aggravation and for comparison purposes to the more realistic scenario of 45°. The impact of the crest-to-crest distance was examined by Skiada et al. (2017a) showing that the interaction between the two slopes maximizes for L_{ctc}=280m. This distance is close to the wavelengths generated for the examined input motion frequency range, leading to resonance phenomena and is also presented in this study for illustrating the upper bound of the expected ground surface response.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
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<tbody>
<tr>
<td>Modulus of elasticity, E (MPa)</td>
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<tr>
<td>Mass density, ρ (Mg/m³)</td>
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</tr>
<tr>
<td>Poisson’s ratio, v (-)</td>
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</tr>
<tr>
<td>Horizontal coefficient of earth pressure, Ko (-)</td>
<td>1</td>
</tr>
<tr>
<td>Damping ratio, ξ (%)</td>
<td>5 (achieved by varying the Rayleigh damping parameters)</td>
</tr>
</tbody>
</table>

In addition to the base case analyses in which both horizontal and vertical motions were applied, three complementary sets of analyses were also performed as detailed in Table 2. The complementary analysis set 1 considers the horizontal component of the 30 records of the base case, while the analysis sets 2 and 3 were performed using a harmonic wavelet modulated by a temporal filter (Saragoni and Hart 1974) with different pulse periods (T_p) imposed either in the horizontal or vertical direction.

All numerical analyses were carried out with the Imperial College Finite Element Program, ICFEP (Potts and Zdravkovic 1999), employing the generalised-α time integration scheme (Chung and Hulbert 1993). This is an unconditionally stable implicit method with second order accuracy and controllable numerical
damping (Kontoe et al. 2008). For the wavelet analyses the time-step is taken as a fraction of the predominant period of the input motion (Δt=Τ_p/40). The largest element dimension, Δl, of the mesh follows the recommendation of Δl≤λ_{min}/10 (Kuhlemeyer and Lysmer 1973), where λ_{min} is the wavelength determined for the lowest wavelet motion period Τ_p. The same mesh and element dimensions were considered for the selected acceleration records.

Table 2. List of the presented numerical analysis

<table>
<thead>
<tr>
<th>Numerical run name</th>
<th>Input motion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base case analysis</td>
<td>30 selected records imposed in the horizontal and vertical direction</td>
</tr>
<tr>
<td>Bidirectional records</td>
<td>30 selected records imposed at the horizontal direction simultaneously</td>
</tr>
<tr>
<td>Complementary set 1</td>
<td>Saragoni and Hart (1974) wavelet imposed in the horizontal direction</td>
</tr>
<tr>
<td>Complementary set 2</td>
<td>Wavelet periods Τ_p=0.1,0.16,0.2,0.25,1/3,0.5,0.58,2/3,1 and 2secs</td>
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<tr>
<td>Complementary set 3</td>
<td>Saragoni and Hart (1974) wavelet imposed in the vertical direction</td>
</tr>
<tr>
<td>Vertical wavelet (vw)</td>
<td>Wavelet periods Τ_p=0.1,0.2,1/3,0.5,2/3,1 and 2secs</td>
</tr>
</tbody>
</table>

Figure 1. Geometry of the considered domain within the finite element analysis.

The distance of the lateral boundaries (L) of the FE mesh was specified, so that the numerical results obtained near the canyon are independent of the boundary conditions. The bottom boundary location is determined based on the bedrock location. The Domain Reduction Method was used to reduce the computational domain and to ensure that free-field conditions were obtained at the lateral boundaries of the FE mesh. This method is a two-step procedure for seismological applications which can be used to reduce the size of the domain to be analysed (Bielak et al. 2003 and Kontoe et al. 2009). During the first step (Step I), a simplified model is considered, with much smaller computational cost than analysing the whole domain. The second step (Step II) focuses on the reduced domain (area) of interest and an external region (Ω̂). Equivalent forces calculated from the displacement field computed during Step I, are implemented as an input along the line Γ in Step II (Figure 1). The perturbation of the external area is only outgoing and corresponds to the relative response between Steps I and II. Free-field conditions can be accurately represented in the numerical model of Step II by introducing the domain reduction method together with the standard viscous boundary at the lateral boundaries (Lysmer and Kuhlemeyer 1969). In Step I of the analysis, a soil column of thickness z was used and both a horizontal and a vertical acceleration time-history were applied at the base of the mesh, while tied degrees of freedom were used at the lateral boundaries in order to achieve same horizontal and vertical movements. In Step II, the standard viscous boundary was applied along the lateral boundaries and both horizontal and vertical displacements were restricted along the bottom boundary to represent the rigid bedrock assumption. The rigid bedrock assumption is considered realistic for high stiffness-contrast interfaces. The assumed boundary condition corresponds to an impedance ratio (defined as the ratio of the bedrock properties over the soil properties) equal to infinity, which results in zero transmission of energy in the bedrock.
and full trapping of energy in the soil domain. Based on wave propagation analysis for impedance ratio values greater than eight, the transmitted energy within the bedrock is nearly zero and most of the energy is reflected back into the soil domain, i.e. approaching the perfectly rigid bedrock assumption.

Topography effects are numerically assessed by de-coupling them from the soil layer effects. To achieve this decoupling, results from the 2D seismic response analyses, accounting for both topographic and soil layer amplification, are compared with 1D column analysis results which represent the free-field response and account only for the soil layer amplification. Acceleration time-histories at discrete points along the ground surface were obtained as the main output of the 2D analysis. The free-field motion corresponding to the crest stratigraphy was used for the Step I column analyses (i.e., the 1D model thickness for Step I was considered as z). The topographic amplification factor is usually determined as the ratio of 2D to 1D (column) peak ground acceleration values or as the ratio of 2D to 1D response spectra at the ground surface. For this study, the response spectra definition is employed with ratios of the horizontal and vertical spectral accelerations denoted as $S_{ah}$ and $S_{av}$ respectively.

### 2.2 Selection of the input ground motion

Both the base case analysis and the complementary set 1 (with the horizontal earthquake motion input) comprise of 30 records. To select the relevant records, a target response spectrum was defined using the Boore et al. (2014) ground-motion model. The scenario for which this target was established was a strike-slip rupture occurring with a rupture distance of 10km (in the present study this distance is not particularly important because the analyses are linear). The target spectrum is defined for a velocity horizon characterized by $V_{s0}=760$ m/s. Target spectra were computed for five magnitudes ($M=5.5, 6.0, 6.5, 7.0$ and $7.5$) so that the influence of spectral shape could be investigated. Six records for each magnitude were selected by finding those records within the PEER NGA West database that best matched the target spectra. Restrictions upon the scenario were imposed with records for each target spectra needing to have magnitudes within 0.25 units of the values noted above and distances less than 50km. The relatively relaxed distance range reflects the weak impact that distance has upon spectral shape. Individual components were assessed for their match to the target using an RMS measure computed on the logarithmic spectral ordinates. The selected records are listed in the Appendix. As shown in Skiada et al. (2017b), there is no trend between the earthquake magnitude and the amplification factors for the performed elastic analyses. The response within each magnitude bin varies significantly reflecting the record-to-record variability. For this reason, the 30 records are examined as a group with one mean value and one standard deviation of the response, regardless of the earthquake magnitude of the record. For the comparison between the different inputs in this study, only the mean value of the imposed 30 records is going to be presented.

As far as the wavelet analysis is concerned, harmonic wavelets with input period $T_p$ modulated by the Saragoni and Hart (1974) temporal filter are used in this study. Skiada et al (2017b) showed that this wavelet mimics better real earthquake motions than the widely used Ricker (1970) wavelet. The acceleration time history of the Saragoni and Hart (1974) wavelet is given by Equation 1:

$$a(t) = \sqrt{\beta} e^{-\beta t} \sin \left( \frac{2\pi t}{T_p} \right)$$

(1)

where $\alpha$ and $\gamma$ are constants controlling the shape of the acceleration-time history, $\beta$ is a constant controlling the amplitude, $T_p$ is the predominant period of the pulse and $t$ is time. For every considered period $T_p$, the values of $\alpha$, $\beta$ and $\gamma$ for the harmonic Saragoni and Hart (1974) wavelet were varied, so as to achieve a unit amplitude of the input excitation. The number of cycles of the Saragoni and Hart (1974) wavelet motion are kept constant and equal to 12 for all the examined input motion periods $T_p$. An illustration of the Saragoni and Hart (1974) harmonic motion with $T_p=0.5$ sec, $\alpha=4$, $\beta=50$ and $\gamma=5$ is presented in Figure 2. The different predominant periods $T_p$ considered for the wavelets imposed in the horizontal or the vertical direction analysis are presented in Table 2.
3. SPECTRAL RESPONSE AT THE SLOPE CREST AND TOE

Topographic amplification in spectral terms is firstly examined at the points of the irregularity where the diffracted wavefield is expected to result in large fluctuations in the computed surface response (i.e. the crest and the toe of the slope). The response of the points on the inclined slope surface for the case of \( i=45^\circ \) is not presented here.

The present investigation is part of a wider study which aims to incorporate topographic effects into Ground Motion Prediction Models (GMPEs). Topographic amplification resulting from all the numerical analyses are calculated for the same range of spectral periods with that used by Boore and Atkinson (2008) (i.e. \( T=0.01, 0.02, 0.03, 0.05, 0.075, 0.1, 0.15, 0.2, 0.25, 0.3, 0.4, 0.5, 0.75, 1.0, 1.5, 2.0, 3.0, 4.0, 5.0, 7.5 \) and 10secs). In more detail, for each examined location at the ground surface the calculated response spectral ordinates at the examined spectral periods are normalized with the corresponding 1D crest and toe spectral values at the same periods. As far as the wavelets are concerned, for each examined input wavelet period \( T_p \), the 2D spectral response at the canyon surface computed for spectral period equal to the pulse period \( T_p \), is similarly normalized to the corresponding 1D crest and toe spectral response.

The spectral amplification at the crest and toe points are presented for the horizontal and vertical directions in Figures 3 and 4 respectively. The mean value of the response for the 30 records imposed bi-directionally (base case) are shown in black color, while the mean response resulting from the 30 records imposed only horizontally (complementary set 1) is presented in grey color. The resulting horizontal surface spectral response from the base case has minor differences from the response of the complementary set 1 analyses both for the crest and the toe locations. This is reasonable because all analyses are linearly elastic so the response of a 1D soil column with simultaneous horizontal and vertical input (base case) is a superposition of the response resulting from the horizontal input (complementary set 1) and the response of the vertical input (is not shown here). The observed differences in the canyon case stem from the complicated scattered wavefield which develop in the 2D domain. Larger slope inclination (dashed lines) results in a larger amplitude of the response. This has been also shown by Ashford et al. (1997) and Bouckovalas and Papadimitriou (2005) and all the numerical results of this study confirm this conclusion.
Figure 3. Mean value of the horizontal spectral amplification at the crest - $x_{ct}=0\text{m}$ in Figure 1 (left) and toe – $x_{toe}=0\text{m}$ in Figure 1 (right) points with different input motions.

Horizontal response $\left(S_{ah}\right)$ resulting from the wavelets has the same shape as that obtained from the analyses using earthquake records when $T_p$ is equivalent to the spectral period. This shape is controlled by the fundamental wavelet period $T_p$. The response minimizes in cases of $T_p$ equal to the fundamental modes of the 1D crest (0.3sec and 1.0sec – Figure 3 left) and the 1D toe (0.2sec and 0.6sec – Figure 3 right). These minima result from the normalization of the response with the 1D crest and toe responses at these periods. The response maximises between these periods, because the 1D transfer function that the topographic amplification is normalised by has its minimum values in this range and therefore it is easier to observe the topographic effects (Skiada et al. 2016). In addition, the fundamental mode for this examined slope height appears to be 0.4sec ($T_p=4H/V_s$ with $H=50\text{m}$ and $V_s=500\text{m/s}$). Also, the examined crest-to-crest distance is $L_{ctc}=280\text{m}$ which resonates at input wavelengths around 250m (resulting from input $T_p=0.5\text{sec}$). Consequently, the maximum response is observed at the range of $T_p=0.4-0.5\text{sec}$ due to the input wavelengths being equal to the slope dimensions. Although, response amplitudes are larger for the wavelet pulses, the response shape is determined by the slope geometry and ground characteristics. The spectral topographic amplification shape for each input wavelet $T_p$ (and the equivalent spectral period) determined using the wavelet pulses is considered as adequate to describe the spectral amplification resulting from the records input. The wavelet pulses can be used as a prediction for the earthquakes response relating the pulse period $T_p$ to the spectral period of the records. For spectral periods smaller than 0.1sec and larger than 2secs the topographic effects are minimized due to the very high or very low frequency range of the input motion in comparison to the fundamental modes of vibration that affect the canyon response.

For the vertical spectral topographic amplification $\left(S_{av}\right)$, the results are not presented for the record input in the horizontal direction because the resulting vertical response at the ground surface is of parasitic nature and cannot be directly compared to the vertical response due to the bi-directional earthquake input motion. The bi-directional vertical surface response (black lines of Figure 4) in this case is compared to the resulting vertical response considering input harmonic wavelets with Saragoni and Hart (1974) temporal filter imposed in the vertical direction (complementary set 3-red lines of Figure 4). In this case, the same shape of the response is observed, but it is shifted to $T_v$ values half of those for which the maxima and minima were observed for the horizontal response. This is because the fundamental modes are computed from a P wave velocity (equal to $V_p=1000\text{m/s}$ in this case due to Poisson’s ratio $v=1/3$ so $V_s/V_p=0.5$). Based on these results the wavelets’ response can be considered as adequate in predicting the shape of the response resulting from the bi-directional earthquake input. The response amplitude, however, is underestimated particularly for the crest point and the 90º slope configuration if wavelets are used for its prediction.
4. SPECTRAL RESPONSE ALONG THE CANYON SURFACE

Aiming to evaluate the use of wavelets for predictions of the bi-directional input response, spectral response comparisons for all the points at the canyon surface using different input motions are performed. Examining only the response close to the irregularity may be misleading, especially for very large slope angles. The response away from the crest and the toe is an oscillation around the free field response with decaying amplitude controlled by the $T_p$ value. Taking into account this dependence, the distances away from the crest ($x>0$ refers to $x_{cr}>0$ in Figure 1) and away from the toe ($x>0$ refers to $x_{toe}>0$ in Figure 1) are normalised with the input motion wavelength $\lambda_p$. For the wavelet analysis, the values of $\lambda_p$ correspond to the examined wavelet period $T_p$ (equal also to the spectral period of interest), while for the earthquake record analysis, the $\lambda_p$ corresponds to the spectral period of interest ($T$). Horizontal and vertical spectral amplification is only presented for three spectral periods ($T=0.3$sec, 0.5sec and 1sec) in the range of 0.1sec to 2.0sec in the following figures, where the maxima and minima of the response are expected.

The distribution of the horizontal response across the crest points (Figure 5 left) indicates that there is negligible difference between the bi-directional response and the records input in the horizontal direction, as expected. However, larger differences exist at the toe area (Figure 5 right), especially for the period $T=0.3$sec. Crest response is generally found to be less sensitive to the input motion and the dimensions of the irregularity, while the toe is more sensitive due to the resonance phenomena in the canyon for certain input motion periods (motions with predominant wavelengths or periods comparable to the slope height, the canyon width and the 1D crest and toe fundamental modes).

Differences due to the slope angle variation are mainly concentrated in close proximity to the crest ($x/\lambda_p\leq1$). These amplitude differences appear small for most periods, but are larger for the shorter period range (around $T=0.1$sec), where there is much more fluctuation of the response close to the irregularity. The variation of the topographic amplification with normalised distance indicates that wavelets are capturing the fluctuation of the response and the right curvature across the surface points. However, the magnitude difference especially at the toe area indicates that using the wavelets as a prediction tool may overestimate the expected response, especially at the fundamental modes of the crest ($T=0.3$sec and $T=1$sec). The curves being presented are the mean values of the response while there is record-to-record variability around these that must be accounted for in design. Wavelets can be used to give some reasonable approximation to the overall distribution of the response.
Figure 5. Mean value of the horizontal spectral amplification at the crest area (left) - $x_{cr}>0m$ in Figure 1 and the toe area (right) - $x_{toe}>0m$ in Figure 1 with different input motions.
Similarly, comparison of the vertical spectral response resulting from the bi-directional input and the wavelet input in the vertical direction are presented in Figure 6 for the same spectral periods of the response at the crest (left) and the toe (right) areas respectively. The wavelet pulses are considered as adequate to capture the response at the crest and toe areas. Differences in the response are mainly observed for the slope angle of 90° and very close to the irregularity. The slope angle of 90° is an extreme slope geometry which introduces a singularity in response and an increased sensitivity to the different input motions.

5. CONCLUSIONS

Topographic amplification has been extensively examined in the literature, especially for valleys and single slopes. For canyon topographies, it has been observed that the ground surface response is greatly affected by the 1D crest and toe fundamental modes and by input motion wavelengths that are comparable to the dimensions of the irregularity, i.e. the slope height (H) and the canyon width or crest-to-crest distance (L_{ctc}). Limited literature research from previous numerical studies using either wavelet input motions or complicated earthquake records illustrate how input motion characteristics effect the topographic amplification variation across the ground surface.

Taking these into consideration, an extensive numerical study has been performed for many canyon geometries. Two of these cases have been presented here, focusing on different input motion scenarios, considering mainly a suite of recorded earthquake motions imposed simultaneously in both the horizontal and the vertical directions. The aim was to identify trends in the ground surface response and to investigate the use of simple input motions in the form of wavelets to predict the spectral topographic amplification resulting from the bi-directional record input for several spectral periods. The resulting response at the ground surface has been examined in two ways, firstly focusing on the response close to the topographic irregularity and examining its dependence on the input motion characteristics and secondly focusing on the distribution of the ground response from the irregularity to the free-field and how this changes for several spectral periods.

The response at the topographic irregularity is mainly affected by the wavelet input motion period T_p or the spectral period of interest for earthquake records input. For input periods T_p or for spectral response periods equal to the fundamental modes of the crest or the toe, the topographic response minimises because the soil layer amplification dominates the response. Due to the definition of the topographic amplification, its resulting values are very small at these periods. For any other period intermediate to the crest or toe fundamental modes, the soil layer amplification is small enough for the topographic phenomena to be observed and the topographic response maximises. Considering that both the slope height and the canyon width fundamental modes fall in this intermediate range, it is reasonable to observe the topographic response maxima there. For design purposes, the response resulting from the wavelet pulses with an input period T_p equal to the spectral period of interest produces the same fluctuations of topographic amplification with spectral period. The response shape away from the irregularity fluctuates as a function of the input motion wavelength \(\lambda_p\). The area close to the irregularity that is strongly affected by topography is located at maximum distances of \(x/\lambda_p=2\). Overall it is concluded that the wavelet analysis can generally produce a response very close to the bi-directional records response, considering a wavelet with T_p equal to the spectral period of interest.
Figure 6. Mean value of the vertical spectral amplification at the crest area (left) - $x_{cr}>0m$ in Figure 1 and the toe area (right) - $x_{ttoe}>0m$ in Figure 1 with different input motions.
6. ACKNOWLEDGMENTS

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7. REFERENCES


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Greece.


## APPENDIX

<table>
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<tr>
<th>Magnitude</th>
<th>ID</th>
<th>Earthquake record description</th>
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</thead>
<tbody>
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<td>Imperial Valley, 10/16/79, 0658, Westmoreland Fire 360 (CDMG STATION 5169)</td>
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<td>Loma Prieta 10/18/89 00:05, Coyote Lake Dam Downstream, 285 (CDMG STATION 57521)</td>
</tr>
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<td>00755L</td>
<td>Loma Prieta 10/18/89 00:05, Coyote Lake Dam DAM SW Abutment, 195 (CDMG STATION 57521)</td>
</tr>
<tr>
<td><strong>M = 7.5</strong></td>
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<td>00139L</td>
<td>Tabas, Iran, 09/16/78, Dayhook, LN</td>
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<td>00848L</td>
<td>Landers 7/23/92 18:49, Coolwater, LN (SCE STATION 23)</td>
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<td>Kocaeli 08/17/99, Izmit, 090 (ERD)</td>
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<td>Chi-Chi 09/20/99, NST, E</td>
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<td>Chi-Chi 09/20/99, TCU049, E</td>
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