Simulation of Seismic-Wave Propagation through Geometrically Complex Basins: The Dead Sea Basin

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Prepared for the Steering Committee for Earthquake Readiness in Israel

Jerusalem, December 2012
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מניסיוני שטחנובו עמלות עלייה של שגיאה גיאולוגית זרה עמודים, שבנוסף מסלולים רכובים ביצות שוליות, תופעות מתארכות המתוחזקות בשיקור יניק. נוגם סדימנטרי עמודים לפגיו הולך קדם ממדיה אמיונית במדינת ישראל רשת סיסמית, ראשית: הוגדרו שתי מטרות, להימשך המלח כביש נוכחי, כמו יד, המלח ואזור התשתית בייב. אנו מתכנים את המלח ואזור התשתית, המשויכים לשתי תוכנות שפותחו בהדרכה של ד"ר מיכאל טסרסקי מאוניברסיטת הוקמה קבוצת מחקר בשיתוף פעולה עם נופים מנהליים מדיניות שונות במישר פיתוח תכנית והתאוששות מהפרisko הולך קדם ממדיה אמיונית במדינת ישראל רשת סיסמית, ראשית: הוגדרו שתי מטרות, להימשך המלח כביש נוכחי, כמו יד, המלח ואזור התשתית בייב. אנו מתכ纳米 את המלח ואזור התשתית, המשויכים לשתי תוכנות שפותחו בהדרכה של ד"ר מיכאל טסרסקי מאוניברסיטת הוקמה קבוצת מחקר בשיתוף פעולה עם נופים מנהליים מדיניות שונות במישר פיתוח תכנית והתאוששות מהפרisko הולך קדם ממדיה אמיונית במדינת ישראל רשת סיסמית, ראשית: הוגדרו две מטרות, להימשך המלח כביש נוכחי, כמו יד, המלח ואזור התשתית בייב. אנו מתכ纳米 את המלח ואזור התשתית, המשויכים לשתי תוכנות שפותחו בהדרכה של ד"ר מיכאל טסרסקי מאוניברסיטת הוקמה קבוצת מחקר בשיתוף פעולה עם נופים מנהליים מדיניות שונות במישר פיתוח תכנית והתאוששות מהפרisko הולך קדם ממדיה אמיונית במדינת ישראל רשת סיסמית, ראשית: הוגדרו две מטרות, להימשך המלח כביש נוכחי, כמו יד, המלח ואזור התשתית בייב. אנו מתכ纳米 את המלח ואזור התשתית, המשויכים לשתי תוכנות שפותחו בהדרכה של ד"ר מיכאל טסרסקי מאוניברסיטת הוקמה קבוצת מחקר בשיתוף פעולה עם נופים מנהליים מדיניות שונות במישר פיתוח תכנית והתאוששות מהפרisko הולך קדם ממדיה אמיונית במדינת ישראל רשת סיסמית, ראשית: הוגדרו две מטרות, להימשך המלח כביש נוכחי, כמו יד, המלח ואזור התשתית בייב. אנו מתכ纳米 את המלח ואזור התשתית, המשויכים לשתי תוכנות שפותחו בהדרכה של ד"ר מיכאל טסרסקי מאוניברסיטת הוקמה קבוצת מחקר בשיתוף פעולה עם נופים מנהליים מדיניות שונות במישר פיתוח תכנית והתאוששות מהפרisko הולך קדם ממדיה אמיונית במדינת ישראל רשת סיסמית, ראשית: הוגדרו две מטרות, להימשך המלח כביש נוכחי, כמו יד, המלח ואזור התשתית בייב. אנו מתכ纳米 את המלח ואזורהתשתית, המשויכים לשתי תוכנות שפותחו בהדרכה של ד"ר מיכאל טסרסקי מאוניברסיטת הוקמה קבוצת מחקר בשיתוף פעולה עם נופים מנהליים מדיניות שונות במישר פיתוח תכנית והתאוששות מהפרisko הולך קדם ממדיה אמיונית במדינת ישראל רשת סיסמית, ראשית: הוגדרו две מטרות, להימשך המלח כביש נוכחי, כמו יד, המלח ואזור התשתית בייב. אנו מתכ纳米 את המלח ואזור התשתית, המשויכים לשתי תוכנות שפותחו בהדרכה של ד"ר מיכאל טסרסקי מאוניברסיטת הוקמה קבוצת מחקר בשיתוף פעולה עם נופים מנהליים מדיניות שונות במישר פיתוח תכנית והתאוששות מהפרisko הולך קדם ממדיה אמיונית במדינת ישראל רשת סיסמית, ראשית: הוגדרו две מטרות, להימשך המלח כביש נוכחי, כמו יד, המלח ואזור התשתית בייב. אנו מתכ纳米 את המלח ואזור התשתית, המשויכים לשתי תוכנות שפותחו בהדרכה של ד"ר מיכאל טסרסקי מאוניברסיטת הוקמה קבוצת מחקר בשיתוף פעולה עם נופים מנהליים מדיניות שונות במישר פיתוח תכנית והתאוששות מהפרisko הולך קדם ממדיה אמיונית במדינת ישראל רשת סיסמית, ראשית: הוגדרו две מטרות, להימשך המלח כביש נוכחי, כמו יד, המלח ואזור התשתית בייב. אנו מתכ纳米 את המלח ואזור התשתית, המשויכים לשתי תוכנות שפותחו בהדרכה של ד"ר מיכאל טסרסקי מאוניברסיטת הוקמה קבוצת מחקר בשיתוף פעולה עם נופים מנהליים מדיניות שונות במישר פיתוח תכנית והתאוששות מהפרisko הולך קדם ממדיה אמיונית במדינת ישראל רשת סיסמית, ראשית: הוגדרו две מטרות, להימשך המלח כביש נוכחי, כמו יד, המלח ואזור התשתית בייב. אנו מתכ纳米 את המלח ואזור התשתית, המשויכים לשתי תוכנות שפותחו בהדרכה של ד"ר מיכאל טסרסקי מאוניברסיטת הוקמה קבוצת מחקר בשיתוף פעולה עם נופים מנהליים מדיניות שונות במישר פיתוח תכנית והתאוששות מהפרisko הולך קדם ממדיה אמיונית במדינת ישראל רשת סיסמית, ראשית: הוגדרו две מטרות, להימשך המלח כביש נוכחי, כמו יד, המלח ואזור התשתית בייב. אנו מתכ纳米 את המלח ואזור התשתית, המשויכים לשתי תוכנות שפותחו בהדרכה של ד"ר מיכאל טסרסקי מאוניברסיטת הוקמה קבוצת מחקר בשיתוף פעולה עם נופים מנהליים מדיניות שונות במישר פיתוח תכנית והתאוששות מהפרisko הולך קדם ממדיה אמיונית במדינת ישראל רשת סיסמית, ראשית: הוגדרו две מטרות, להימשך המלח כביש נוכחי, כמו יד, המלח ואזור התשתית בייב. אנו מתכ纳米 את המלח ואזור התשתית, המשויכים לשתי תוכנות שפותחו בהדרכה של ד"ר מיכאל טサー...
Simulation of Seismic-Wave Propagation through Geometrically Complex Basins: The Dead Sea Basin

by Shahar Shani-Kadmiel, Michael Tsesarsky, John N. Louie, and Zohar Gvirtzman

Abstract  The Dead Sea Transform (DST) is the source for some of the largest earthquakes in the eastern Mediterranean. The seismic hazard presented by the DST threatens the Israeli, Palestinian, and Jordanian populations alike. Several deep and structurally complex sedimentary basins are associated with the DST. These basins are up to 10 km deep and typically bounded by active fault zones.

The low seismicity of the DST, the sparse seismic network, and limited coverage of sedimentary basins result in a critical knowledge gap. Therefore, it is necessary to complement the limited instrumental data with synthetic data based on computational modeling, in order to study the effects of earthquake ground motion in these sedimentary basins.

In this research we performed a 2D ground-motion analysis in the Dead Sea Basin (DSB) using a finite-difference code. Cross sections transecting the DSB were compiled for wave propagation simulations. Results indicate a complex pattern of ground-motion amplification affected by the geometric features in the basin.

To distinguish between the individual contributions of each geometrical feature in the basin, we developed a semiquantitative decomposition approach. This approach enabled us to interpret the DSB results as follows: (1) Ground-motion amplification as a result of resonance occurs basin-wide due to a high impedance contrast at the base of the uppermost layer; (2) Steep faults generate a strong edge-effect that further amplifies ground motions; (3) Sub-basins cause geometrical focusing that may significantly amplify ground motions; and (4) Salt diapirs diverge seismic energy and cause a decrease in ground-motion amplitude.

Introduction

Sedimentary basins are known to amplify ground motions and to prolong the shaking by trapping seismic energy (Anderson et al., 1986; Joyner, 2000; Boore, 2004). The outcome of this phenomenon was observed in Mexico City (Singh, Mena, and Castro, 1988), the Los Angeles basin (Graves, Pitarka, and Somerville, 1998), and Kobe, Japan (Pitarka et al., 1998), among other places. The Dead Sea Basin (DSB) is a unique sedimentary basin due to its extreme depth, nearly 10 km, subvertical boundary faults, and complex geometry formed by convex salt diapirs and concave sub-basins. Several active faults within the basin provide internal seismic sources in addition to external sources from neighboring basins and the Dead Sea Transform (DST) itself. These circumstances provide an opportunity to study the influence of different intrabasin features on earthquake ground motion. Our primary goal in this study is to develop a semiquantitative methodology for decomposing a complex basin effect to individual contributions derived from specific geometrical features. Such an analysis enables better understanding of the integrated seismic phenomenon and allows generalizations of semiquantitative rules, useful for other basins around the world.

The second goal of this study is to model earthquake ground motion in the DSB, which hosts important industrial and tourist facilities in Israel, Jordan, and the Palestinian Authority. The lack of seismic recordings in the basin, due to relatively low seismicity of the region and relatively sparse national seismic network, produces the need for synthetic data in order to supplement the instrumental data. This study explores principally the basin effects on earthquake ground motion.

Geological Setting

The DST is one of the largest active strike-slip faults of the world, connecting the east Anatolian fault in the north to the extensional zone of the Red Sea in the south (Fig. 1a; Garfunkel, Zak, and Freund, 1981). It defines the active boundary between the Arabian and the African plates with an estimated ongoing slip rate of ~3 to ~5 mm/year (Wdowinski et al., 1997).
The ∼105 km of left-lateral motion along the DST since its formation in the Early to Middle Miocene (Quennell, 1956; Freund, Zak, and Garfunkel, 1968) has created several pull-apart basins, the largest being the DSB, 100 km × 20 km in size (Fig. 1b).

This study focuses on the DSB, which is bounded by active normal step faults, filled with ∼10 km of soft sediments and penetrated by large salt diapirs. It is generally accepted that both eastern and western boundary faults (Fig. 1b) and the normal step faults Sedom and Ghor-Safi are active (Aldersons et al., 2003; Hofstetter et al., 2007; Data and Resources).

Seismicity

Moderate and strong earthquakes associated with the DST are evident in geological, historical, and archaeological records. However, due to long return periods, the instrumental

Figure 1. (a) Overview map of the DST, compiled after Garfunkel, 1981. Arrows indicate directions of relative motion at faults. Epicenters of the 1927 Jericho earthquake and 1995 Gulf of Aqaba earthquake marked by gray filled circles. (b) Shaded relief map based on the DTM of Hall, 2008, overlaid by major faults and significant populated settlements, industrial facilities and tourist resorts. Modeled cross sections and simulated sources are denoted by straight solid lines and stars, respectively. Faults modified after Bartov and Sagy, 1999; Smit et al., 2008. Abbreviations: CGF, Carmel-Gilboa fault; DST, Dead Sea Transform; AF, Arava fault; JV, Jordan Valley; TLV, Tel-Aviv; JLM, Jerusalem; AMN, Amman; BS, Beer-Sheva; ELT, Elat; NBA, Nuweiba; DSI, Dead Sea Industries. The color version of this figure is available only in the electronic edition.
record is rather limited. To date, the strongest earthquake ever recorded in Israel was the 1995 $M_w$ 7.2 Gulf of Aqaba earthquake (Fig. 1a), with its epicenter located ~80 km south of Elat, the southernmost city of the country (Hofstetter, 2003). Prior to that, the largest earthquake felt in the country was the 1927 Jericho earthquake (Fig. 1a), later estimated from damage reports as an $M_w$ 6.2 (Garfunkel et al., 1981; Shapira, Avni, and Nur, 1993; Avni et al., 2002).

For seismic hazard assessment it has been suggested that the DST is capable of producing earthquakes with magnitudes up to 7.5. Return periods for $7.5 \geq M \geq 5$ were estimated as 50 years in the Elat area, 30 years in the Arava and Dead Sea area, and 25 years in the Jordan Valley (Fig. 1a; Shapira et al., 2007). However, because these estimates strongly depend on the sparse historical record, much research was invested in the unique paleoseismic record of the Dead Sea lacustrine sediments.

Breccia beds in the Lisan formation formed during the last 60,000 years were interpreted as seismites (Seilacher, 1984), induced by $M > 5.5$ earthquakes (Marco and Agnon, 1995; Marco et al., 1996; Marco and Agnon, 2005; Hamiel et al., 2009). Marco et al. (1996) presented columnar sections of the Lisan formation from the Massada plain and Amiaz plain (Fig. 1b), exhibiting some 30 seismites that were formed by the same set of earthquakes. The seismites found within the Amiaz plain (Fig. 1b) are consistently thicker than those found in the Massada plain, even though according to Begin et al. (2005), 11 strong earthquakes from the recorded set occurred just north of Massada, which is farther from the Amiaz plain. Another indication of strong ground motion in the Amiaz plain is presented by Levi et al. (2008), who studied the development of clastic dykes found in the Amiaz plain and showed that they are seismically induced. According to Levi’s models, a threshold value of $M \geq 6.5$ earthquake at close proximity is needed in order to achieve the injection velocities. Alternatively, the simulations presented here raise the possibility that dyke injection as well as other seismites at the Amiaz plain may be explained by exceptionally strong ground-motion amplification.

The paleoseismic record of the Lisan formation shows little evidence of surface ruptures that can be directly linked with seismic activity on the boundary faults. Some superficial faulting is documented (Marco and Agnon, 1995; Marco and Agnon, 2005) within the ductile sediments of the formation, however, these are localized features that have no continuous spatial distribution.

Simulation Methods

Model Setup

Two geological cross sections were simulated in this study (locations in Fig. 1b): cross-section A transects the basin east of Mount Massada, a UNESCO world heritage site (Fig. 2a); cross-section B transects Mount Sedom and the Amiaz plain near the Ein-Bokek Hotel complexes and the industrial facility of the Dead Sea Industries (Fig. 2b). The cross sections were constructed based on a compilation of available geological data, borehole data, for example, Sedom deep 1 (Baker, 1994), and geophysical data, mainly seismic and gravimetry surveys (ten Brink et al., 1993; Al-Zoubi and ten Brink, 2001). For cross-section A, we used structural maps of the top and bottom of the Sedom formation salt unit (Al-Zoubi and ten Brink, 2001) and a generalized north–south cross section of the entire basin (Sagy, 2009) and used it for correlation with cross-section B. Cross-section B was compiled based on structure from seismic surveys and supplemented by borehole data for mechanical properties, specifically, pressure-wave velocity and density (Frieslander, 1993; Baker, 1994; Al-Zoubi, Shulman, and Ben-Avraham, 2002). Mechanical properties such as shear-wave velocity and quality factors were derived using empirical relations presented in Brocher (2008). The salt diapir in section B protrudes through the uppermost Lisan formation and gives rise to Mount Sedom, rising ~225 m above the Dead Sea and ~100 m above the Amiaz plain. Thus, the Amiaz plain is bounded by the western boundary fault in the west and Mount Sedom in the east and is actually a sub-basin within the DSB.

To simplify the numerical calculations in E3D, the topography of the cross section was flattened; the top surface of the
resulting model conforms to the average elevation of the exposed Lisan formation along the transecting line. The Lisan formation is the topmost sediment filling the basin and is at an average elevation of \(-370\) m (below sea level) along cross-section A and \(-260\) m along cross-section B. The water of the Dead Sea and the air surrounding it was replaced with Lisan formation sediments to fill the missing topography. Mount Sedom above the Sedom Salt diapir (\(-180\) m) was totally removed, as well as the slopes of the Judea Mountains and the Moab Mountains to the west and east of the Dead Sea, respectively (Fig. 1b). Therefore, the results of our simulations should only be applied to the basin itself and not to its unreal boundaries, which might have a topographic effect that was not considered. Water effects within the lake, such as water-bottom multiple reflections, were also ignored.

As part of the simulation preprocessing, the geological cross sections were spatially discretized into the intended grid spacing, depending on the modeled frequencies. Simulation

Figure 2. Dead Sea Basin simulation results: Left panel cross-section A (Massada) and Right panel cross-section B (Amiaz). (a, f) Horizontal PGV. (b, g) Amplification ratio relative to a reference model. (c, h) Shear-wave velocity model of the modeled cross section. (d, i) Time-distance plot of horizontal velocity from surface cells. Gray is no ground motion, black is positive (east) ground motion, and white is negative (west) ground motion. Scale saturates at 0.1 m/s for clarity. (e, j) Frequency-distance plot, computed as the Fourier spectra of the synthetic seismograms presented in (d, i). The scale saturates at 0.4 m/s for clarity. Abbreviations: WBF, western boundary fault; EBF, eastern boundary fault; SF, Sedom fault; GSF, Ghor-Safi fault; SSD, Sedom Salt diapir; LSD, Lisan Salt diapir. The color version of this figure is available only in the electronic edition.
parameters and mechanical properties of the geological units are summarized in Tables 1 and 2, respectively.

The simulated scenario presented here (Fig. 2) is a normal-slip rupture initiating at a depth of 13 km on Sedom fault near the lower limit of the seismogenic zone in the region (Aldersons et al., 2003; Ambraseys, 2006). In our simulations the source is described in terms of a finite-length fault with uniform moment. The modeled hypocenter is denoted by a star and paired arrows pointing in the slip direction. The ruptured fault plane of the finite source extends 3.5 km in the up-dip direction, and rupture initiates near the bottom (of the fault plane). For our parametric study of basin effects we kept simple ruptures entirely within high velocity rocks below the basin. The normal-faulting double-couple rupture front propagates radially from the hypocenter along the fault plane, at a constant rupture velocity of 2.8 km/s (Scholz, 2002). All the 2D elements on the fault plane were given identical moment and a Gaussian source time function with frequency content between 0.1 and 10 Hz. Note that the size of the source (i.e., its moment) is not important in this 2D analysis content between 0.1 and 10 Hz. Note that the size of the source is described in terms of a finite-length fault with uniform moment. The modeled hypocenter is denoted by a star and paired arrows pointing in the slip direction. The ruptured fault plane of the finite source extends 3.5 km in the up-dip direction, and rupture initiates near the bottom (of the observed section the absolute ground motion. Therefore, we only analyze the relative amplification and derive no conclusions from the absolute ground motion.

Simulation Results

Simulation results of the modeled cross-sections A and B are summarized and visualized in Figure 2a–j by panels for each cross section. From top to bottom they present:

Figure 2a,f: Horizontal peak ground velocity (PGV) across the modeled section sampled at model resolution (absolute value).

Figure 2b,g: Amplification ratio across the modeled section computed relative to a reference model, which is a homogeneous medium with properties of the surrounding rocks. Note that this presentation of amplification following Gvirtzman and Louie (2010), differs from the common way of presenting amplification relative to reference stations on hard rock at the basin edges.

Figure 2c,h: The modeled cross section, shaded according to shear-wave velocities (listed in Table 2).

Figure 2d,i: Time-distance plot of horizontal velocity synthetic seismograms sampled at the surface cells. Gray is no ground motion, black is positive (east) ground motion, and white is negative (west) ground motion. Although PGVs reached values of nearly 1 m/s, the scale saturates at 0.1 m/s for clarity.

Figure 2e,j: Frequency-distance plot, computed as the Fourier spectra of the synthetic seismograms presented in Figure 2d,i. The scale saturates at 0.4 m/s for clarity.

Table 1
Dead Sea Basin, 2D Simulation Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model dimensions (km; grid cells)</td>
<td>26.74 × 15; 5348 × 3000</td>
</tr>
<tr>
<td>Spatial discretization (km)</td>
<td>0.005</td>
</tr>
<tr>
<td>Time steps (#)</td>
<td>40,000</td>
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<tr>
<td>Time step interval (s)</td>
<td>0.0005</td>
</tr>
<tr>
<td>Modeled time (s)</td>
<td>20.0</td>
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<tr>
<td>Simulation processor time (hours)</td>
<td>~30</td>
</tr>
<tr>
<td>Minimum; maximum $V_p$ (km/s)</td>
<td>1.35; 5.94</td>
</tr>
<tr>
<td>Minimum; maximum $V_S$ (km/s)</td>
<td>0.41; 3.55</td>
</tr>
<tr>
<td>Minimum; maximum density (g/cm³)</td>
<td>1.74; 2.70</td>
</tr>
<tr>
<td>Minimum; maximum $Q_P$</td>
<td>46; 806</td>
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<tr>
<td>Minimum; maximum $Q_S$</td>
<td>23; 403</td>
</tr>
</tbody>
</table>

Table 2
Velocity, Density, and $Q$ Properties of the Dead Sea Basin Formations*

<table>
<thead>
<tr>
<th>Geological Unit</th>
<th>$V_p$, km/s</th>
<th>$V_S$, km/s</th>
<th>$\rho$, g/cm³</th>
<th>$Q_P$</th>
<th>$Q_S$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lisan &amp; Samra formations—Pleistocene</td>
<td>1.35</td>
<td>0.41</td>
<td>1.74</td>
<td>46</td>
<td>23</td>
</tr>
<tr>
<td>Amora formation (upper)—Pleistocene</td>
<td>3.75</td>
<td>2.20</td>
<td>2.25</td>
<td>356</td>
<td>178</td>
</tr>
<tr>
<td>Amora formation (lower)—Pleistocene</td>
<td>4.04</td>
<td>2.44</td>
<td>2.28</td>
<td>414</td>
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<td>2.70</td>
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* $V_p$ and $\rho$ were measured in Sedom deep 1 borehole, $V_S$, $Q_P$ and $Q_S$ were calculated using empirical relations (Frieslander, 1995; Baker, 1994; Brocher, 2008).
accl units.

Table 3 summarizes the simulation parameters.

Figure 3 shows the step-by-step evolution of the six models used as simulation input. The following is a short description of the different models:

Figure 3a, reference: A reference model with a single homogeneous medium.

Figure 3b, layers: A series of horizontal sedimentary layers with mechanical properties of the DSB geological units.

Figure 3c, faults: A series of layers as in (b) bounded by two near-vertical faults.

Figure 3d, diapir: A series of layers as in (b) with a dome-shaped intrusion (diapir), near the surface.

Figure 3e, basin: A series of layers as in (b) with a deep sub-basin near the surface.

Figure 3f, combined: A model combining all of the features in Figure 3a–e.

The mechanical properties of the individual units are summarized in Table 2. The modeled earthquake hypocenter is fixed at the same location in all simulations (see Fig. 3). Fault plane of the finite source extends 3.0 km in the upward direction. The normal-faulting double-couple rupture front propagates radially from the hypocenter along the fault plane, at a constant rupture velocity of 2.8 km/s (Scholz, 2002). All the 2D elements on the fault plane were given identical moment and a Gaussian source time function. Table 3 summarizes the simulation parameters.

Decomposition Results

The PGV signature of the reference model is straightforward. Strongest ground motions above the source and a gradual decrease with distance (observation 1 in Fig. 3a). The layers model produces a ground-motion amplification above the source (observation 1 in Fig. 3b) and the amplification signature follows a trend similar to that presented in Figure 2 (observation 2 in Fig. 3b). At a distance of approximately 15 km a local minimum appears, substantiating that this phenomenon is independent of intrabasin features, that is, faults and diapirs which are absent from this model (observation 3).

In the faults model, ground-motion amplification increases near the basin boundary faults or edges (observations 4 and 5 in Fig. 3c). The asymmetry between the two edge-effects in opposite sides of the basin is probably related to the general trend of the ground-motion amplification that increases toward the right side of the basin (observation 2). The PGV signature produced by the diapir model resembles that of the Layers model except for a small depression directly above the diapir (observation 6 in Fig. 3d). The basin model produces three distinct peaks above the sub-basin, observations 7, 8, and 9 in Figure 3e. Combining all the geometrical features into a single model, the resulting signal contains the individual signature of each feature (Fig. 3f).

Interpretation

Our decomposition technique revealed that the general trend (observation 2) of the ground-motion amplification and the local minimum (observation 3) are both independent of intrabasin features. The general trend in the amplification ratio reflects the fact that PGV of the reference model decays over a much shorter distance compared with that of the layers model. While in the reference model PGV at a distance of more than 15 km from the epicenter decays to nearly zero, in the layers model energy is trapped in the uppermost layer and PGV remains approximately constant (Fig. 3b).

Entrapment of seismic energy in a soft layer on top of a hard substrate is a well-known phenomenon, visualized by the wave-field snapshots in Figure 4. This effect is caused by interference of seismic waves in several different manners: (1) Body waves reflected from the surface interfere with body waves reflected from the base of the uppermost layer causing vertical resonance; (2) Body and surface waves interaction caused when body waves reflected from the base of the uppermost layer interfere with surface waves traveling across the basin; and (3) Surface-surface waves interaction caused when left-traveling surface waves interfere with right-traveling surface waves. The net result of the previously described processes is significant ground motion for prolonged duration.

The local minimum within the generally increasing amplification trend is related to the source radiation pattern. It resides roughly on a plane rotated at 45° to the nodal planes and is visible in the time-distance plots in Figures 2 and 3b (observation 3) as the first motion of shear-waves transform from left to right.

The ground-motion amplification that occurs near the boundary faults of the basin is caused by the interference of surface waves and body waves to create an edge-effect (Kawase, 1996; Graves et al., 1998; Pitarka et al., 1998). At
Figure 3. Simulation results from six models: (a) reference, (b) layers, (c) faults, (d) diapir, (e) basin, and (f) combined. The presentation scheme follows that of Figure 2. Time-distance plot scale saturates at 0.1 m/s, and the frequency-distance plot scale saturates at 0.8 m/s for clarity. Abbreviations: PGV, peak ground velocity; Amp., amplification; Freq., frequency; BW, body wave; SW, surface wave; RW, reflected wave. The color version of this figure is available only in the electronic edition.
the near fault (the fault nearest the source), seismic waves propagate upward on both sides of the fault, the faster traveling body waves on the left side of the fault reach the surface before the slower body waves propagating on the right side of the fault. Surface waves formed at the basin edge propagate into the basin and interfere with later arriving body waves (Gvirtzman and Louie, 2010). The development of this near-fault edge-effect (observation 4) is visualized in the time-distance plot of the faults model in Figure 3c (body waves, BW; surface waves, SW). At the far fault (on the right side of the basin), seismic waves reflected by the fault interfere with seismic waves trapped in the uppermost layer resulting in a similar edge-effect (observation 5 in Fig. 3c). The time-distance plot of the faults model shows the development in time of the far-fault edge-effect (reflected waves, RW).

The diapir, an upward convex structure with shear-wave velocity higher than its surroundings, leads to a decrease in ground-motion amplification (observation 6 in Fig. 3d). We propose that this convex body scatters body waves that are reflected downward from the surface thus, preventing vertical resonance.

The two peaks above the edges of the sub-basin in Figure 3e marked as observations 7 and 9 are near and far edge-effects, respectively, caused by the subvertical walls bounding the sub-basin. The central peak, observation 8, is caused by a geometrical convergence of the seismic waves by the concave structure of the sub-basin (Graves et al., 1998; Semblat et al., 2002). We term this type of convergence “geometrical focusing”.

Figure 5 presents PGV curves (Fig. 5a) and amplification ratios (Fig. 5b) from all six simulations plotted together above the combined model (Fig. 5d) for comparison. After analyzing the individual signatures of the geometrical features, we are able to quantify their relative contribution. In particular, we distinguish between ground-motion amplification related to material properties such as that illustrated by the layers model, and ground-motion amplification related to geometrical features such as that illustrated by the faults, diapir, and sub-basin models.

To accomplish this, the amplification ratio for the combined model is computed relative to the layers model and presented in Figure 5c. This exercise demonstrates that material related ground-motion amplification is perturbed by geometrical effects. Fault-related edge effect amplifies ground motion by 30% (observations 4 and 5); geometrical focusing in sub-basins amplifies ground motion by 30% (observation 8); and divergence of seismic waves by diapirs deamplifies ground motion by 50% (observation 6). As some of the seismic energy is trapped in the sub-basins, ground motion between the sub-basin and the far-fault is deamplified by 30% (observation 10).

Discussion

The decomposition process presented here not only enables us to identify the individual contribution of various intrabasin features to the ground-motion amplification, it also allows us to reexamine the complex results of the DSB simulations.

Material related ground-motion amplification occurs throughout the entire basin due to resonance developed within the Pleistocene lacustrine sediments of the Samra and Lisan formations (unified in our models). This effect is caused by the impedance ratio across the interface between the Samra–Lisan formation and the sediments of the Pleistocene Amora formation and the Pliocene Sedom salt, which are 3.5 and 4, respectively. Material related ground-motion amplification is illustrated by the simulation results of the layers model (Fig. 3b), of which material properties follow those of the geological units of the DSB cross sections. Figure 6a presents synthetic seismograms sampled from the reference and the layers models (see Fig. 3a,b for location). The Fourier spectra of these seismograms (Fig. 6b) and the spectral amplification ratio (Fig. 6c), reveal amplification

<table>
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<th>Table 3</th>
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<td>Model dimensions (km; grid cells)</td>
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<tr>
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<td>Minimum; maximum Qp</td>
<td>46; 806</td>
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**Figure 4.** Wave-field snapshots of modeled cross-section B. White is motion east; black is motion west. Time in seconds is displayed at the bottom right corner of each snapshot. The color version of this figure is available only in the electronic edition.
at the fundamental frequency of 0.2 Hz, and at its overtones 0.6, 1.0, and 1.4 Hz.

Comparing the synthetic seismogram from the idealized layers model with that from the Amiaz plain in cross-section B of the DSB simulations (see Fig. 2b for location) shows that the typical resonance pattern of mode 1, 2, 3 is distorted by ground-motion amplification at other frequencies as well (labeled in Fig. 7 with a question mark). Specifically, note the prominent peak found between the fundamental frequency, 0.3 Hz, and the first overtone, 0.9 Hz. We suggest that these amplified frequencies are contributed by the basin deeper structure.

In light of these results we suggest an explanation to the abundance of clastic dykes injected into the Lisan formation in the Amiaz plain (Levi et al., 2008). Whereas seismites, that is, breccia, liquefied layers, and slumps, have been observed throughout the Lisan formation, the clastic dykes are confined to the Amiaz plain above the Amiaz sub-basin. Emplacement of clastic dykes compared with other seismites requires a higher energy threshold. We attribute the localization of clastic dykes to the previously described geometrical effect of the Amiaz sub-basin.

The topographic effect on ground-motion amplification was not accounted for in our simulations; however, with the results of Boore (1972) this effect can be readily estimated. Mount Sedom, with a cross-sectional wavelength of 4 km and a shear-wave velocity of 2.54 km/s. Because topography can have significant effects on seismic waves when the incident wavelength is comparable to the size of the topographic feature, amplification would be expected at ~0.6 Hz (Boore, 1972). The steep shoulders of the DSB rise 400 to 500 m above the basin with shear-wave velocity ranging from 2.95 to 3.37 km/s. To assess the topographic effect of these features, we follow the method presented by

![Figure 5](image)

**Figure 5.** PGV data from all six simulations plotted together: (a) PGV across the modeled section. (b) Amplification ratio relative to the reference model. (c) Amplification ratio of the combined model relative to the layers model. (d) Shear velocity model of the combined model. Line thickness varies so that overlapped lines remain visible. The color version of this figure is available only in the electronic edition.

![Figure 6](image)

**Figure 6.** (a) Synthetic seismograms of horizontal ground velocity sampled from the reference model and the layers model (see Fig. 4a,b for location). (b) Fourier spectrum of each of the synthetic seismograms. (c) Spectral amplification ratio.

![Figure 7](image)

**Figure 7.** (a) Synthetic seismograms of horizontal ground velocity sampled from the cross-section A and its reference model (see Fig. 2b for location). (b) Fourier spectrum of each of the synthetic seismograms. (c) Spectral amplification ratio.
Ashford et al. (1997), yielding topographic amplification at ~0.65 Hz. Our study explores the ground-motion effects of basin structure between 0.1 and 7 Hz, hence, our results are limited at the lower end of this frequency band, where topographic effects are expected to occur.

Water-bottom multiple reflections in the Dead Sea would be expected to affect the vertical resonance discussed previously. The density of the briny Dead Sea water is ~1.2 g/cm³, hence, pressure-wave velocity is slightly higher than 1.5 km/s, and the fundamental resonant frequency for a water column of 200 m is on the order of 1.9 Hz. Our models, which substitute shallow sediments for lake water, do not show this pressure-wave resonance.

Summary and Conclusions

The dimensions of the Dead Sea Basin (DSB), 10 km deep × 20 km wide × 100 km long, its steep boundary faults and salt diapir intrusions result in a complex geometry. Due to the low seismicity of the Dead Sea Transform (DST) combined with limited instrumental coverage of the DSB, there is a critical knowledge gap in terms of expected ground motions during a strong earthquake. However, moderate and large seismic events from instrumental (Data and Resources), archaeological and historical (Ellenblum et al., 1998), and geological (Marco et al., 1996; Levi et al., 2008) records are well documented. In this research we performed a 2D numerical ground-motion analysis of the DSB with particular consideration of the geometrical complexity. Specifically, we studied the individual contribution of each geometrical feature in the basin to surface ground motion.

We show that via a semiquantitative decomposition approach, the contribution of the individual intrabasin features to ground motion can be identified in an otherwise complex signal. This process not only allows identification of the individual signature of each feature, but also conveys a physical understanding of how these signatures interact to form the complete signal. Ground-motion amplification in geometrically complex sedimentary basins occurs (1) basin-wide due to resonance and anelastic effects, (2) above steep structures, that is, faults and diapir flanks due to an edge-effect, and (3) above sub-basins due to localized geometrical focusing. Narrow and upward convex bodies with a relatively high seismic-wave velocity, such as salt diapirs and magmatic intrusions, may cancel ground-motion amplification.

Data and Resources


Acknowledgments

This research was partially funded by the Ministry of National Infrastructures of the State of Israel, Grant #210-17-001, and by the Geological Survey of Israel as part of a project assessing the instability factors in the Dead Sea Infrastructure.

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Manuscript received 8 September 2011