Reviewer #1

We thank the reviewer for pointing out many importing issues. In order to be clear, the response structure is in the prescribed sequence:

- (1) Comments from Referee
- (2) Author's response
- (3) Author's changes in the manuscript
- (1) One major question that arises from this manuscript is what is the contribution of the new GMPE? Can this GMPE be used for intensity prediction in the future?
- (2) We thank the reviewer for pointing this out. The new GMPE is essential to emphasize how shear wave measurements are important in Israel and also in every modern GMPE. This work is preliminary. Therefore, the main contribution will be after collecting more data regarding additional earthquakes. For now, according to the new equation, 11 sites, which constitute 58% of our measured samples, move into the 60% prediction boundary. This suggests that the prediction boundary actually encompasses over 80% of the macroseismic observations. Hence, on the one hand, statistically, this new GMPE can be used. But on the other hand, in order to be a part of any standard, it should base on more data and also includes additional terms and not only a site condition term.
- (3) We added a sentence in the conclusion section to clarify these points
- (1) No sensitivity analyses were performed.
- (2) We thank the reviewer for the point and we include the sensitivity tests in the new version.
- (3) See page 8 (section 4.2). Also, fig11
- (1) No validations of the GMPE were performed.
- (2) At the moment a moderate earthquake will occur in the area we will be able to validate the GMPE.
- (1) Can the authors compare macro-seismic data from other historical and perhaps instrumental earthquakes to their GMPE and discuss the results?
- (2) This work focuses on the 1927 event and it is part of wider research which extends to additional potentially earthquakes. Certainly, comparing macro-seismic data from other historical events will enhance the attenuation relation and that is the future plan. Please keep in mind though that 1927 was the only destructive earthquake for which we have relatively reliable data.
- (1) The authors took a formerly derived GMPE, with its regression and constants, and simply added another term, regressing only for its constant. Such an action means the authors think that the magnitude, attenuation, geometrical spreading and site response are all independent. That is not fundamentally wrong, but should be stated.

- (3) Had been stated in the new manuscript.
- (1) The authors adopt 760m/s as the Vs reference for their new GMPE, although this value is probably not suitable for Israel, as the Judean group is close to the surface in many regions, and its shear wave velocity is higher.
- (2) We thank the reviewer for this point.
- (3) This part had been corrected.
- (1) After developing their own site term, the authors try to explain why 8 points did not "converge into the prediction boundary" of their equation. They explain that Boore et al.'s GMPE is constrained to a distance of 70 km, and some their data is further away. This argument is weak, as they did not adopt Boore et al.'s equation, but Hough and Avni's intensity equation, and only Boore's site term, therefore using their distance constraint does not seem to explain the misfit. Also – 5 sites beyond 70 km did converge to their GMPE.
- (2) You are definitely right about using Boore et al.'s equation.
- (3) We dropped out this explanation from the new manuscript.
- (1) The authors fail to discuss or at least mention other research regarding this exact earthquake, such as Kadmiel et al. (2015, SCEC). I think it would be interesting if the authors try to use the data from Zohar and Marco (2011), which attempted to correct the intensities of the 1927 EQ to site conditions, such as surface geology, slope and construction. Zohar and Marco's work should at least be mentioned, as they did try to deal with the site response biasing the intensity reports.
- (2) We mentioned the significant work of Zohar and Marco (2012 instead of 2011) and used their modern epicenter location for our calculation.
- (3) We added a comment about Kadmiel work.
- (1) The manuscript should be English and grammar proofed before re-submitted.
- (2) The original manuscript was English and grammar proofed
- (3) The new manuscript is English and grammar proofed
- (1) The magnitude of the earthquake in the abstract and in the Introduction is different. Although the difference is small- please pick one.
- (3) Had been corrected in the new manuscript.
- (1) In the abstract and several more instances MASW is explained as Multi Analysis of Surface Waves.
- (2) Some of the authors use it.
- (3) Had been corrected in the new manuscript.

- (1) In the abstract and in several more instances the authors state that (line 15-16) "based on 1927 macroseismic data integrated with modern measurements". This phrasing is somewhat misleading, since it hints that new seismic data is being used, where I believe the authors are referring to the velocity profile measurements they performed.
- (2) Comment accepted.
- (3) We redefined it in the new manuscript.
- (1) Abstract line 25 –seismic hazard and not risk.
- (2) Comment accepted.
- (3) Had been corrected in the new manuscript.
- (1) Introduction some opening paragraph is missing.
- (2) Comment accepted.
- (3) We added an intro section to the manuscript
- (1) Page 2 line 3 how about source distance?
- (2) Comment accepted.
- (3) Had been corrected in the new manuscript.
- (1) Page 2 line 10 that is one definition of what amplification is, I think the authors should mention the other, common definition, relative to a near rock outcrop.
- (2) Comment accepted.
- (3) Had been changed in the new manuscript.
- (1) Page 2 lines 10-11 site amplification can be attributed to many factors, such as basin effect, focusing effects, topography and on and on, and not only due to "reverberation of the seismic waves in the upper layers according to acoustic impedance differences". The decrease in shear wave velocity when getting closer to the surface is alone a reason for amplification of magnitudes, without any resonance in the upper layers.
- (2) Comment accepted.
- (3) Had been changed in the new manuscript.
- (1) Figure 1 is somewhat "overcrowded".
- (2) Comment accepted.
- (3) Had been changed in the new manuscript.
- (1) Page 2 lines 17-20 this should come earlier in this section.
- (2) Comment accepted.

- (3) Had been changed in the new manuscript.
- (1) Page 2 lines 26-27 several claims were made as to how is Vs30 suitable for Israel (i.e. Zaslavsky et al. 2012, Natural Science).
- (2) Although Zaslavsky et al. (2012) claimed that the use of Vs30 is a simplification that cannot be justified in the complex geological conditions as in Israel, no alternatives were proposed. Therefore, in this scenario, the Israel Standards Institute still adopts the Vs30 parameter.
- (3) We clarified this adding a statement to the manuscript.
- (1) Where is the Hough and Avni (2011) reference in the list?
- (2) Comment accepted.
- (3) Had been changed in the new manuscript.
- (1) Vs30 notation is not consistent throughout the manuscript.
- (2) Comment accepted.
- (3) Had been changed in the new manuscript.
- (1) Is the equation of Hough and Avni based on Bakun (2006) (page 3 line 28) or Bakun and Wentworth (1999) (page 5 line 2-3) or both, and where are these references in the list?
- (2) The equation is based on Bakun and Wentworth (1997).
- (3) References had been updated to the new manuscript.
- (1) Page 50 line 6 what do the authors mean by 60% prediction boundary? Is that the boundary for which 60% of the data is included within? Unclear.
- (2) Exactly
- (3) We redefined it in the new manuscript.
- (1) I'm not sure that section 4.1-4.2 belong in the discussion section. They seem to be more suitable in the methods section, since they are part of the modeling method.
- (2) We agree about that.
- (3) We moved this section to the proper section in the new manuscript.
- (1) Page 5 lines 17-18 what kind of data from the GII was yours compared to? This is very unclear. Is it borehole data? Refraction? HVSR? Is there a reference to the data?
- (2) The GII report (Aksinenko and Hofstetter, 2012) present all available geological, topographical, geophysical, geotechnical and borehole information to identify site-specific characteristics. This includes refraction and borehole.

- (1) Figure 10 -for which site are these results?
- (2) This figure refers to Beit Alfa site.
- (3) We clarified it in the new manuscript.
- (1) Page 7 line 3 Hough's name is spelled wrong. Also the citing is not complete.
- (2) Comment accepted.
- (3) Had been corrected in the new manuscript.
- (1) Page 7 line 9 Boore's equation is equation (4) and not (2). Also citing not complete.
- (2) Comment accepted.
- (3) Had been corrected in the new manuscript.
- (1) Figure 11 the legend is not clear does the curve represent the new GMPE, with the site term? Also I believe there is no need to use different symbols for amplified and de-amplified, they can be put in the same category as "MMI before site correction" or similar. Same goes for figure 7 there is no need to use different colors for the symbols, and the use of the term "amplified" or "de-amplified" is not accurate amplification is relative to reference rock conditions, and here I believe you mean the sites were "amplified" comparing to the GMPE.
- (2) Comment accepted.
- (3) Had been changed in the new manuscript.
- (1) Page 7 line 15 again Boore's equation is #4.
- (2) Comment accepted.
- (3) Had been corrected in the new manuscript.
- (1) It would seem to be useful if the authors use index numbers to identify their measurement locations in the figures, as they are numbered in table 1.
- (2) We thought over this but unfortunately, this leads to "overcrowded" figures.
- (1) In table 1 include the epicentral distance of the measurements. This will allow the reader to understand the statements they make regarding the misfit of the different locations.
- (2) Comment accepted.
- (3) Had been added in the new manuscript.

Reviewer #2

We thank the reviewer for pointing out many importing issues. In order to be clear, the response structure is in the prescribed sequence:

- (1) Comments from Referee
- (2) Author's response
- (3) Author's changes in the manuscript
- (1) Data are not shown in Chapter 3, and also the derivation of results and uncertainties are not given. This needs to be provided to the reader. As given here, one is not convinced.
- (2) Comment accepted.
- (3) We add a whole part of supplementary material which include all the MASW reports.
- (1) The optimization of the constant (p.7, line 6) is only mentioned but not explained.
- (2) C4 is optimized by the Least Squares Fitting (LSF) A mathematical procedure for finding the best-fitting curve to a given set of points by minimizing the sum of the squares of the offsets ("the residuals") of the points from the curve.
- (3) We added a brief explanation to the new manuscript.
- (1) A discussion of the directivity of amplification in entirely missing.
- (2) The data and analyses for 1927 are rudimentary, and we feel that for such a moderate event (M6.2) it is premature to include directivity.
- (3) We mention directivity it in the new manuscript.
- (1) General language: in parts very colloquial and not scientific/precise enough. Phrasing like somewhat, incomplete referencing, mentioning of authors without year of publication etc. might give an impression of rushed writing, that must be thoroughly revised.
- (2) We accept this comment.
- (3) Care is taken to avoid colloquial language and to properly reference sources in new manuscript.
- (1) Abstract: be more precise, what are specific results? This is rather an intro plus technical description.
- (2) We thank the reviewer for pointing this out.
- (3) Had been changed in the new manuscript.

- (1) Introduction: description of formula 1 is incomplete in text.
- (2) We thought the description of the formula is sufficient and we give the classical reference of Aki and Richards, 2002. Yet, we accept the comment.
- (3) We added an explanation on the actual behavior of the amplification as reflected on the formula.
- (1) Methods: it is not clear if the term offset is used properly. It rather seems to mean profile distance in meters?
- (2) In surface seismic acquisition, the horizontal distance from source to the first geophone defined as offset as we mentioned in our manuscript.
- (1) Results: this chapter is completely inappropriate, because no data is introduced, nothing described, and no workflow given to the reader. Thereby, it is not possible to judge quality of results and be confidential in the outcome.
- (2) A simple workflow is given in the method section. Regarding the data see item (3)
- (3) Data will be accessible at the supplementary material within the new manuscript.
- (1) Discussion: The remaining discussion should also include a discussion of comparing achieved results here with other authors methods and workflows, not for the region alone but especially seen in worldwide literature.
- (2) We consider our work as pioneering one with no parallels elsewhere. Yet we compared several sites from the GII's report (Aksinenko and Hofstetter, 2012) and had other relevant data been accessible for us we would certainly expand the comparison.
- (3) The first passage of the revised discussion addresses the reviewer's concern. In addition clarify in the new manuscript some issues in this regard (see also response to comment concerning Figure 9).
- (1) Most of the figures are only mentioned in the text but need proper description there, too.
- (2) We accept this comment.
- (3) Had been corrected in the new manuscript.
- (1) Figure 1: could be less scetchy.
- (2) We accept this comment.
- (3) Had been changed in the new manuscript.

- (1) Figure 2: map made by JKH -> give proper reference or include him as author, if considerable work was done.
- (2) We accept this comment.
- (3) Had been corrected in the new manuscript.
- (1) Figure 8+9: correct legend spelling.
- (2) Thanks for identifying this.
- (3) Had been corrected in the new manuscript.
- (1) Figure 9: what is second measurement? This is unexplained and not understandable.
- (2) Comment accepted.
- (3) We redefined it in the new manuscript.
- (1) Figure 11: incomplete references in legend, caption: dots mark suspected.....
- (2) Comment accepted.
- (3) Had been corrected in the new manuscript.

Calibrating a New Attenuation Curve for the Dead Sea Region Using Surface Wave Dispersion Surveys in Sites Damaged by the 1927 Jericho Earthquake

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Abstract. Strong motion data is not common around the Dead Sea region. Therefore, calibrating a new attenuation equation is a considerable challenge. However, the Holy Land has a remarkable historical archive, attesting to numerous regional and local earthquakes. Combining the historical record with <u>modern-new seismic</u> measurements will enhance the regional equation.

On 11 July 1927, a crustal rupture generated a moderate $6.25M_L$ earthquake around the northern part of the Dead Sea. Up to five hundred people were killed and extensive destruction was recorded, even at places as far as 150 kilometers from the focus. We consider local near-surface properties, in particular, the shear-wave velocity, as an amplification factor. Where the shear-wave velocity is low, the seismic intensity at places far from the focus would likely be greater than expected from a standard attenuation curve. In this work, we used the Multi-Multichannel Analysis of Surface Waves (MASW) method to estimate seismic wave velocity at anomalous sites in Israel in order to calibrate a new attenuation equation for the Dead Sea region, based on 1927 macroseismic data integrated with modern measurements.

Our new attenuation equation contains a term which quantifies solely only lithological effects, whilst while factors such as building quality, foundation depth, topography, earthquake directivity, type of fault, etc., remained out of the equationour scope. Nonetheless, about 60% of the measured anomalous sites fit expectations; therefore, this new GMPE is statistically better than old ones and better fitting is achieved compared to other relevant attenuation equations.

From a local point of view, this is the first time that an integration between of historical data and modern shear-wave velocity profileseismic measurements improves the attenuation relation for the Dead Sea region. In the wider context, regions of low-to-moderate seismicity should use macroseismic historical earthquake data, together with modern measurements, in order to better estimate the peak ground acceleration or the seismic intensities caused by future earthquakes. This integration will conceivably lead to a better mitigation of damage from understanding of future earthquakes and improve maps of seismic hazardrisk.

1 Introduction

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Generating a modern and applicable attenuation equation is one of applied seismologists main interests. Considering the Dead Sea area, for which instrumental strong motion data are not available, this task is particularly challenging. Using the Holy Land's historically rich database, researchers had defined seismic intensities and estimated earthquake locations. Investigating anomalous sites, with seismic intensities higher or lower than predicted from the basic regional attenuation

relation, may lead to a better attenuation equation. The local geological conditions can strongly influence the nature and severity of shaking at a given site. Assessing the local geological conditions by geophysical techniques at these anomalous sites, and adding a logarithmic term to a basic attenuation equation, should improve the equation.

 This work focuses on the 1927 event, but it is part of wider research which extends to additional earthquakes. The 1927

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 event was chosen as it is the only devastating one recorded during the instrumented period.

Our main goal in this research is a tighter constraint on the attenuation equation derived from this event. This should allowus to examine whether this preliminary work coincides with our expectations of site amplification and de-amplification due to the lithology.

1.1 Site Response

15 Ground motion is controlled by a number of variables, including source characteristics, <u>source distance</u>, propagation directivity, near-surface geology, etc. <u>Elastic-The elastic</u> properties of near-surface materials, and their effects on seismic wave propagation, are crucial <u>for to</u> earthquake and civil engineering, and in environmental and earth science studies.

Seismic <u>surface</u> waves are <u>initiated generated</u> at the moment that <u>an-the</u> earthquake <u>wave front impinges on the</u> <u>surfaceoccurs</u>. These waves <u>spread out</u>, and the surface shakes are traveling and shaking the surface as they pass. <u>SurfaceThe</u>

- 20 wave amplitude at the surface is <u>controlledaffected</u> by the mechanical properties of the rocks below. These <u>rocks</u>-often consist of <u>low velocity</u> weathered rock over bedrock with_<u>a</u>_much higher <u>seismic velocityvelocities</u>. When seismic waves pass from a high-velocity layer to a low-velocity layer, their amplitudes and duration <u>typicallycan</u> increase. <u>The phenomena</u> of site amplification, as a result of soft sediments overlying hard bedrock, is well known since the early days of seismology (Milne, 1898). Site-effects are also well known and were investigated after several major earthquakes: Mexico City 1985
- 25 (Singh et al., 1988), Yerevan 1989 (Borcherdt et al., 1989), San Francisco 1989 (Hough et al., 1990), Los Angeles 1994 (Hall et al., 1994) and Kobe, 1995 (Aguirre and Irikura, 1997). Therefore, local lithology is a crucial factor for estimating site amplification, defined as the amplitude ratio between the surface layer and the underlying bedrock. Site amplification at a specific site can be attributed to many factors, such as basin effects, focusing effects, topography, and reverberation of the seismic waves in the upper layers due to acoustic impedance differences (Figure 1).

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Therefore, lithology is a crucial factor for estimating site amplification, defined as the amplitude ratio between the surface layer and the underlying bedrock. Site amplification is due reverberation of the seismic waves in the upper layers according to acoustic impedance differences (Figure 1). The amplification, *A*, is proportional to the reciprocal square root of the product of the shear-wave velocity, *Vs*. (Eq. (1)) (Aki and Richards, 2002):

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$$A \propto \frac{1}{\sqrt{V_{\text{s}}...}}$$
,

(1)

where is the density of the investigated soil. As shear-wave velocity decreases by a given fraction the amplification increases by half that fraction (for a constant density). Since density plays a minor role (Moro, 2015; Xia et al., 1999) the V_s value can be used to represent site conditions.

The phenomena of site amplification as a result of soft sediments on top of hard bedrock is well known since the early days of seismology (Milne, 1898). Also, site-effects are well known and were investigated based on several major earthquakes: Mexico City 1985 (Singh et al., 1988), Armenia 1989 (Borcherdt et al., 1989), San Francisco 1989 (Hough et al., 1990), Los Angeles 1994 (Hall et al., 1994) and Kobe (Japan) 1995 (Aguirre and Irikura, 1997).

The most widely used <u>index parameter</u> in the classification of the soil response is the average shear-wave velocity in the uppermost 30 meters of sediment, the Vs_{30} . This <u>index parameter</u> was accepted for site classification in the USA – National

15 Earthquake Hazards Reduction Program – NEHRP(National Earthquake Hazards Reduction Program – NEHRP), (Building Seismic Safety Council, 2001), also iIn Europe by the new provisions of Eurocode 8 (BSI, 2011), and in Israel it is accepted by the design provisions for earthquake resistance of structures - SI 413 (The Standards Institution of Israel, 2013). Standards Institute (The Standards Institution of Israel, 2013). The value of 30 meters comes from the USA and European building codes, where it was found empirically that this depth is directly proportional to

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comes nom the OSX and European building codes, where it was round empirically that this depth is directly proportional to deeper and shallower values (Boore et al., 2011). Zaslavsky et al. (2012) argued that the use of V_{320} is a simplification that cannot be justified in the complex geological conditions in Israel, yet no alternatives have thus far been proposed. Therefore, in this scenario, the Israel Standards Institute still adopts the V_{320} index. In Israel, there is not much data for this kind of correlation. Therefore, in this scenario, the Israel Standards Institute adopts the V_{320} parameter.

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In modern attenuation equations, also known as ground motion prediction equations (GMPE), coefficients are <u>derived set</u> from strong motion data, namely ground acceleration measurements. In the past, and in areas lacking the technology to record earthquakes, it is impossible to <u>measure the peak ground acceleration (PGA) directly directly measure the peak</u> ground acceleration (PGA). Therefore, it is common to categorize historical earthquakes with seismic intensity scales that describe the damage at each site or area (Ambraseys, 2009; Guidoboni and Comastri, 2005).

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1.2 The M6.2 1927 Jericho 1927 earthquake

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The left-lateral Dead Sea transform separates the Sinai-Levant Block from the Arabian Plate (Figure 2). The 6.2M_L July 11, 1927 Jericho earthquake (Ben-Menahem et al., 1976; Shapira, 1979) was the strongest and most destructive earthquake to hit the Holy Land during the past and current centuriescentury. Furthermore, it was the first to be instrumentally recorded by seismographs. Furthermore, for the first time an earthquake with epicenter in the Holy Land was recorded by seismographs.

- The epicentral location was <u>originally</u> estimated at a few kilometers south of the Damia Bridge, which is 30 kilometers north of Jericho (International Seismological Summary ISS Bulletin of 1927). <u>In the following A few</u>-decades-later, new estimates have been <u>published</u> calculated: Shapira et al (1993) calculate the epicenter to be near Mitzpe Shalem. Zohar & Marco (2012) estimated the epicenter to be near the Almog settlement, about 30 kilometers north of Shapira's epicenter, and
- Kagan et al (2011), surmised that the source was somewhere on the Kalia fault, which is located in the northern part of the Dead Sea graben, perpendicular to the main Dead Sea fault (Figure 2).
 The damage from the earthquake was heavy, especially in places near the source, but not only there: In Nablus, located 70
- km from the epicenter (Figure 2), 60 people were killed, 474 were injured, and more than 700 structures were destroyed, most of which were built on soft sediments (Blankenhorn, 1927; Willis, 1928). By comparison, Jerusalem is only about 30
 kilometers from the source and the damage there was much smaller, especially in property. However, in Mount Scopus and the Mount of Olives (eastern neighborhoods in Jerusalem), the damage exceeded that in other parts of Jerusalem (Abel, 1927; Brawer, 1928). Other cities also suffered from this earthquake: Tens of people were injured and even died, and
- hundreds of houses were ruined in Ramleh and Lod (Brawer, 1928). In addition, Jericho in the Jordan Valley also suffered significant damage, especially in terms of buildings collapsing (Figure 3). The total number of victims was about 350-500
 (Ambraseys and Melville, 1988; Amiran, 1951; Arieh, 1967; Ben-Menahem, 1991). Beyond the casualties, several environmental effects were reported: The Jordan river flow ceased near the Damia bridge for about 21.5 hours (Willis, 1928) and a one-one-meter seiche wave was observed in the Dead Sea (Abel, 1927; Blankenhorn, 1927). Some evidence suggests
- that the earthquake was felt up to 700 kilometers from the epicenter (Ben-Menahem, 1991), although a different interpretation suggests this distance was only 300 kilometers (Ambraseys and Melville, 1988).
 Compiling historical evidence, Avni (1999) estimated the seismic intensities (MSK scale) at 133 different locations around
- Israel, Palestine, Jordan, Lebanon, Syria, and Egypt (Figure 4 and supplementary). Avni's (1999) basic attenuation equation yields an R² of about 0.26. Based on the methodology proposed by Bakun and Wentworth (1997), Hough & Avni (2011) revised the attenuation equation for the Dead Sea region based on Bakun (2006):

 $MMI(M,d) = -0.64 + 1.7M - 0.00448d - 1.67\log(d)$

(2)

30 where *MMI* is Modified Mercalli Intensity (assumed to be equivalent to MSK), *M* is the magnitude and *d* is the distance from the epicenter.

Raphael and Agnon (2018) note that damage from the 1927 Jericho earthquake was higher east of the transform (on the Arabian Plate) than on the west (Sinai-Levant Block). This observation, consistent with their archaeoseismic findings for earthquakes in antiquity, requires further study. Our main goal in this research is a tighter constraint on the attenuation equation for this event. This should allow us to examine whether this preliminary work coincides with our expectations of site amplifications and de-amplifications due to the lithology.

2 Methods - <u>Multichannel Multi</u> Analysis of Surface Waves (MASW)

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The MASW method is environmentally friendly, non-invasive, low-cost, rapid, robust, and provides reliable Vs_{30} data. (Miller et al., 2002). Multichannel records make it possible to separate different wavefields in the frequency and velocity domains. Fundamental and higher modes can be analyzed simultaneously, but generally, only the fundamental mode is used because among all the wave types it has the highest energy among all the wave types (Park et al., 1998).

The MASW method <u>consists of can be subdivided into</u> three main steps: (A) Acquisition of experimental data, (B) signal processing to obtain the experimental dispersion curve, and (C) inversion to estimate Vs_{30} (Figure 5). The inverse problem consists of estimating a set of parameters that describe the soil deposit, based on an experimental dispersion curve. Inversion problems based on wave propagation theory cannot be solved in a direct way due to their non-linearity. Thus, iterative

- 15 methods must be used where a theoretical dispersion curve is determined for a given layer model and compared to the previously obtained experimental dispersion curve (Ryden et al., 2004). $VS_{307}Vs_{30}$ typically does not converge to one stable value. In other words, for the same dispersion curve, one will get slightly different Vs_{30} depending on the initial model. Yet, the ensuing uncertainty is of little consequence since Vs_{30} enters logarithmically into the attenuation equation (see below).
- We carried out the surveys with an array of 24 vertical geophones (R.T. Clark's geophones of natural frequency of 4.5 Hz) at equal intervals of 2-3 meters over a total length of 46-69 meters. For the survey sound sourceIn order to initiate the system, we used a five-kilogram sledgehammer pounding a twenty centimeter square aluminum plate at variable offsets of 5, 10, 15, 20, 25 and 30 meters (both forward and reversed). The seismic data were recorded on a Geometrics Geode seismograph at a sampling rate mostly of 8 kHz for 0.5-2 seconds (Table 1). For an acceptable Signal to Noise Ratio (SNR), we used the so-called "vertical stacking" approach, which is a summation of multiple synchronized repetitions of the test (usually five times).

Rayleigh wave dispersion curves are obtained by the MASW module of the RadExPro® software, whose calculation procedure is based on a paper by Park et al. (1998), and also by the WinMASW® software. From all the dispersion images that we calculated from each offset shot (Figure 6), we choose the smoothest and clearest one (Figure 6) to compute the site's Vs_{30} profile. An inversion process then finds the shear-wave velocity profile whose theoretical dispersion curve is as close as possible to the experimental curve (Figure 6). The data and coefficients are automatically inverted via genetic algorithms

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which represent an optimization procedure belonging to the classification of global-search methods. Genetic algorithms are commonly used to generate high-quality solutions to optimization and search problems by relying on bio-inspired operators such as mutation, crossover and selection Compared to traditional linear inversion methods based on gradient methods (Jacobian matrix) these inversion techniques produce a very reliable result in terms of precision and completeness (Moro et al., 2007).

Rayleigh wave dispersion curves were obtained by the MASW module of the RadExPro software in which the calculation procedure is based on a paper by Park et al. (1998). From all the dispersion curves that we picked for each site (Figure 6A), we chose the smoothest and clearest dispersion image (Figure 6B) to compute the site's Vs₃₀ profile (Figure 6D). An inversion process then finds that shear wave velocity profile whose theoretical dispersion curve is as close as possible to the experimental curve (Figure 6C). This procedure is done by Occam's inversion which is part of the MASW module of the RadExPro software. During this process, the Root Mean Square (RMS) error between the curves is minimized while

2.2 Velocity model

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All models were considered to be a stack of homogeneous linear elastic layers, neglecting lateral variations in soil properties. The number of unknowns for a layered model, when considering only shear-wave velocity, is three for each layer: density, thickness, and one elastic constant. Therefore, the number of unknowns is 3*n*-1 (where *n* represents the number of layers). The change in density with depth is usually small in comparison to the change in shear modulus and is normally neglected (Park et al., 1997).

2.3 Number of layers & layer thicknesses

maintaining the maximum model smoothness (Constable et al., 1987).

- 20 The resolution of surface wave surveys decreases with depth. Thin layers are well resolved when they are close to the surface, whereas at great depth, the resolution is limited and only large changes can be detected (Foti et al., 2014). Regardless of the number of the layers of the site, *Vs₃₀* is almost the same in each case (Error! Reference source not found.Figure 7). For those reasons, as well as the lack of density information, we did not restrict each model to a specific number of layers. Without boreholes and lithostratigraphic data, which is the case in our work, a useful rule of thumb is to
- 25 assume layer thicknesses increasing with depth, to compensate for the decreased resolution with depth, an intrinsic shortcoming of surface wave testing (Foti et al., 2014).

2.4 Depth of investigation

We used a five-kilogram sledgehammer and summed up five strikes. For some sites, this type of source is insufficient to determinate a shear-wave profile down to 30 meters. In addition, at some sites, we were not able to spread the geophones at intervals of more than two meters, which limited the length of the seismic line. This length probably excludes longer

wavelengths which limits the depth of investigation. Lastly, as the shear-wave velocity of the lowest frequency is higher more data is available for deeper layers. Therefore, the penetration depth will decrease in areas with low shear-wave velocity. For instance, if we can clearly detect a phase velocity of about 300 m/sec at 5 Hz, we can roughly estimate a depth of investigation of approximately 20-30 meters according to the following equation:

$$= \frac{\left(\frac{Velocity_{f_{\min}}}{f_{\min}}\right)}{\left(\frac{f_{\min}}{f_{\min}}\right)}$$

п where n equals 2-3 (Foti et al., 2014; Moro, 2015). In other words, this equation emphasizes that the depth of investigation is about a half to a third of the largest wavelength observed.

3 Results

Ζ 5

Zohar and Marco (2012) relocated the epicenter to a point near the Almog settlement. We used this most recently published 10 epicenter for calculating the new epicentral distances, d. Figure 7Figure 8 shows a scatter plot of MMI vs. d for their 133 sites. Hough and Avni (2011) fit this data with a curve which best describes the attenuation relation for this event. Using the mathemathical form of their curve, we calculated upper and lower limits such that 60% of the points are enclosed. This we call the 60% prediction boundary. We consider that the lithological effects probably account for much of the scatter beyond this boundry, due to amplification and de-amplification.

Avni's (1999) original attenuation equation yields a R² of 0.26. Hough & Avni's (2011) revised equation, based on Bakun 15 and Wentworth (1997), yields the same fit. Identifying the Kalia fault as the source location (Kagan et al., 2011) in Eq. (2) yields a fit of 0.35. The best fit of 0.38 is obtained using the Almog settlement as the epicenter (Zohar and Marco, 2012). Accordingly, our analysis is based on this epicenter location. A scatter diagram of the distribution of all 133 sites for which Avni (1999) estimated seismic intensity, together with a prediction boundary of 60% from Eq.(2), highlight the sites that 20 were amplified and de-amplified (Figure 7).

3.1 MASW surveys

From these 24 surveys, we succeeded in extracting Vs30 for 19 of 20 sites (the Hartuv data were too noisy for interpretation) (Table 2).

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4 Discussion

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A number of researchers have studied the 1927 event. Avni (1999) tried to reduce the impact of local geology and attempted to generate basic attenuation curves for specific azimuths. Zohar and Marco (2012) relocated the source position while Shani-Kadmie et al. (2016) studied directivity of the source pattern. None of these publications address the Vs_{30} measurements. An attenuation equation with a term that depends on the Vs_{30} index should lead to a better understanding of past events, and to more useful predictions of future earthquakes.

4.1 Survey locations and validation

The decision as to where exactly each survey <u>should would</u> take place was based on Avni's thesis (Avni, 1999). <u>WhereIf</u> the location was not sufficiently <u>clear-known</u>, we <u>re</u>checked the reference given by Avni. In most cases, there was evidence of specific damaged buildings. We tried to locate <u>those-these</u> buildings <u>while looking aton</u> historical maps (1927-1945). Unfortunately, most sites were located inside urban areas, where we could not <u>execute-carry out</u> the seismic surveys. Therefore, we surveyed in <u>nearby</u> open areas as <u>near-close</u> as possible to the referenced damage zones.

To validate our results, we compared them with a summary of thousands of seismic evaluations around Israel carried out over the years by the Geophysical Institute of Israel (GII), and compiled in a report by (Aksinenko and Hofstetter, 2012).

These evaluations were based upon refraction and borehole velocity measurements yielding *Vs* and/or *Vp* values, as well as the effects of topography and geology. The spacing of their data was such that often a number of GII sites had to be averaged to provide a value within several kilometers for comparison with our MASW values. However, Figure 9 shows that the GII-based values are in consistent agreement with those of the MASW. However, this comparison is a bit tricky because *Vs*₃₀ results for two sites 5 km or much less distant could be significantly different, as shown in Figure 9Figure 10. Remembering that *Vs*₃₀ enters a logarithmic term, we find our approach potentially useful.

To validate our results, we compared them with the nearest (up to three kilometers distance) data from The Geophysical Institute of Israel (GII) and a reasonable fit was achieved (Figure 8). However, this comparison is a bit tricky because Vs₃₀ results for two sites distant three kilometers or much less could be significantly different, as shown in Figure 9. Remembering that Vs₃₀ enters a logarithmic term, we find our approach potentially useful.

25 4.2 A new attenuation equation

In the present case of the 1927 earthquake, the sources of the data are mostly historical documents and not strong data measurements. This makes it difficult to quantify site response into a single equation. In the practical modern attenuation relationship, Vs_{30} is a crucial index. A term that depends on Vs_{30} has previously been constrained for several large data sets (Abrahamson et al., 2014; Boore et al., 1997; Campbell and Bozorgnia, 2008). We chose the Boore et al. (1997) attenuation

30 equation (Eq. (4)) in order to emphasize site response.

 $\ln Y = b_1 + b_2(M - 6) + b_3(M - 6)^2 + b_5 \ln(r) + b_v \ln\left(\frac{Vs}{V_A}\right)$

where Y is the ground-motion variable (peak horizontal acceleration or pseudo-acceleration response in g), M is the moment magnitude, r is the epicentral distance in kilometers, V_{A_a} and all b terms are frequency dependent coefficients to be determined. By adding Boore et al.'s (1997) Vs term to Hough and Avni (2011) attenuation equation (Eq. (2)), we suggest a new equation for the region:

$$MMI = -0.64 + 1.7M - 0.00448d - 1.67\log(d) + C_4 \ln\left(\frac{Vs_{30}}{V_A}\right)$$

where V_A and C_d are adjustable coefficients. The first four coefficients remain the same as we assert that the magnitude, attenuation, geometrical spreading and site response are all independent. We adopt the value of V_A from Boore's (1987) equation (Eq. (4)), as it represents a single value independent of the frequency. We took formerly derived GMPE, with its coefficients, and added another term, by regressing only for the new coefficient, then optimizing C_d and V_A by Least Squares Fitting (LSF), as shown in **Error! Reference source not found.**Figure 11 we get the final equation:

$$MMI = -0.64 + 1.7M - 0.00448d - 1.67\log(d) - 2.1\ln\left(\frac{Vs_{30}}{655}\right)$$

4.2 Velocity model

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All models were considered as a stack of homogeneous linear elastic layers, neglecting lateral variations in soil properties. The number of unknowns for a layered model, when considering only shear wave velocity, is three for each layer: density, thickness, and one elastic constant. Therefore, the number of unknowns is 3n-1 (where n represents the number of layers). The change in density with depth is usually small in comparison to the change in shear modulus and is normally neglected (Park et al., 1997). Therefore we set the density to 2000 [kg/m³] for all layers in all our sites and thus the number of unknowns decreases to 2n-1.

20 4.2.1 Number of layers & layer thicknesses

The resolution of surface wave surveys decreases with depth. Thin layers are well resolved when they are close to the surface, whereas at great depth, the resolution is limited and only large changes can be detected. The reduction of the sensitivity with depth results in a loss of resolution, or in the ability to identify the properties of thin layers. Thus, these features cannot be accurately resolved (Foti et al., 2014). Regardless of the number of the layers of the site, Vs_{30} is almost the same in each case (Figure 10). For those reasons, as well as the lack of density information, we did not restrict each model to a specific number of layers. Without boreholes and lithostratigraphic data, which is the case in our work, a good

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rule of thumb is to assume layer thicknesses increasing with depth, to compensate for the decreased resolution with depth, which is an intrinsic shortcoming of surface wave testing (Foti et al., 2014).

4.2.2 Depth of investigation

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We used a five-kilogram sledgehammer and summed up five strikes. In some sites this type of source is insufficient to determinate a shear-wave profile down to 30 meters. In addition, at some sites we were not able to spread the geophones at intervals of more than two meters which limited the length of the seismic line. This length probably excludes longer wavelengths which limits the depth of investigation. Lastly, as the shear-wave velocity of the lowest frequency is higher – more data is available for deeper layers. Therefore, the penetration depth will decrease in areas with low shear-wave velocity. For instance, if we can clearly detect a phase velocity of about 200-300 m/sec at 5 Hz, we can roughly estimate a depth of investigation of approximately 12-20 meters according to the following equation:

$$\frac{\frac{\left(\frac{Velocity_{f_{\min}}}{f_{\min}}\right)}{Z = \frac{n}{n}},$$

where *n* equals 2-3 (Foti et al., 2014; Moro, 2015). In other words, this equation emphasizes that the depth of investigation is about a half to a third of the largest wavelength observed.

(3)

4.3 The performance of the new attenuation equation

- With these coefficients, 58% or 11 of 19 sites, were amplified or de-amplified as we expected. For the entire distance range (up to 250 km) the Vs₃₀ corrections leave 42% sites out of the prediction boundary (eight of nineteen sites). Seismic intensities at all these eight sites are overpredicted by the attenuation equation (Eq. (2)) (Figure 11Figure 12). We expect that Vs₃₀ at these sites will be higher than 655 m/sec in order to obtain de-amplification. However, our results show the opposite effect these eight sites are characterized by lower Vs₃₀ which drives amplification. This can be caused by the fact that measurements were taken over agricultural fields, of which the upper layers (the first few meters) are characterized by low
- shear-wave velocity, decreasing the average Vs. Another reasonable explanation is that we did not succeed in extracting the average shear-wave velocity down to 30 meters and perhaps we missed some high-velocity shear-wave layers at deeper layers. In such cases, we constrain the last layer to be thicker in order to estimate Vs_{30} for all our surveys.

4.3 A new attenuation equation

25 In the present case of the 1927 earthquake, the sources of the data are mostly historical documents and not measurements. This makes it difficult to quantify site response into a single equation. In the practical modern attenuation relation, $V_{s_{30}}$ is a crucial index. A term that depends on $V_{s_{30}}$ has been constrained for several large data sets (Abrahamson et al., 2014; Boore et al., 1997; Campbell and Bozorgnia, 2008). We chose the Boore et al. (1997) attenuation equation (Eq. (4)) in order to emphasize site response.

$$\ln Y = b_1 + b_2 (M - 6) + b_3 (M - 6)^2 + b_5 \ln(\mathbf{r}) + b_\nu \ln\left(\frac{Vs}{V_A}\right), \tag{4}$$

where *Y* is the ground-motion variable (peak horizontal acceleration or pseudo-acceleration response in g), *M* is the moment magnitude, *r* is the epicentral distance in kilometers, V_{A_r} and all *b* are frequency dependent coefficients to be determined. By adding Boore et al.'s Vs term to Hoguh and Avni's attenuation equation (Eq. (2)), we suggest a new equation for the Dead Sca region:

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$$MMI = -0.64 + 1.7M - 0.00448d - 1.67\log(d) + C_4 \ln\left(\frac{Vs_{30}}{Vs_{refernce}}\right),$$
(5)

where $Vs_{referance}$ is the shear-wave velocity of the bedrock and C_{4} is an adjustable constant. Optimizing this constant to our data yields the final equation:

 $MMI = -0.64 + 1.7M - 0.00448d - 1.67\log(d) - 1.8\ln\left(\frac{Vs_{30}}{760}\right),\tag{6}$

We adopt here the value of V_A from Boore's equation (equation 2) as representing $Vs_{referrce}$. According to most national standards, including the one in Israel (SI #413), the reference bedrock shear wave velocity is set equal to 760 m/sec for all frequencies in the entire region. With these coefficients, 58% or 11 of 19 sites, were amplified or de-amplified as we expected. Based on the new attenuation equation (Eq. (6)) we reduced the site-effects (Figure 11) and compare the fitness of our attenuation curve with those of Avni (1999) and Hough & Avni (2011) (Figure 12). The new attenuation equation fits the data somewhat better for all four epicenters.

Boore et al.'s equation (Eq. (2)) is restricted for use only for earthquakes of magnitude 5.5-7.5 and epicentral distance up to 80 kilometers. After lithological corrections, sites located up to 70 kilometers from the epicenter are well predicted: the entire population of six anomalous sites shifted to the prediction boundary. On the other hand, sites located farther than 70 kilometers from the epicenter converge into the prediction boundary to a lesser extent (five sites of thirteen which are 38%) (Figure 11). This observation is consistent with Boore's restriction.

For the entire distance range (up to 250 km) the Vs₃₀ corrections leave 42% sites out of the prediction boundary (eight of nineteen sites). Seismic intensities in all these eight sites are underpredicted by the attenuation equation (Eq. (2)) (Figure 11).
 We expect that Vs₃₀ at these sites will be higher than 760 m/sec in order to obtain de-amplification. However, our results show the opposite effect – these eight sites are characterized by lower Vs₃₀ which drive amplification. This can be caused by the fact that measurements were taken over agricultural fields, of which the upper layers (the first few meters) are



characterized by low shear-wave velocity, decreasing the average Vs. Another reasonable explanation is that we did not succeed in extracting the average shear-wave velocity down to 30 meters and perhaps we missed some high velocity shear-wave layers at deeper layers. In such cases, we constrain the last layer to be thicker in order to estimate Vs₃₀ for all our surveys.

5 5 Conclusions

In this research, we investigated site amplification and de-amplification around Israel. According to previous studies (Aki, 1988; Boore, 2003; Borcherdt, 1994; Field and Jacob, 1995; Joyner and Boore, 1988) the local lithology can amplify or deamplify wave amplitude. The commonly used modern seismic method – MASW – allows the extraction of \sqrt{s} profiles at 20 <u>19</u> sites reportedly damaged by the 1927 <u>6.2</u>M_L<u>6.2</u> earthquake. We use these profiles to update the attenuation equation for the Dead Sea region by including the $\sqrt{s_{30}}$ term.

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According to this new equation, 11 sites, which constitute 58% of our measured samples, move into the 60% prediction boundary. This suggests that the prediction boundary actually encompasses over 80% of the macroseismic observations. This fit is better than any available attenuation equation for the Dead Sea region-(Figure 11). However, as we have used only 19 sites, we should consider further research and provide wider results. Although our final equation (Eq. (6)) shows

- 15 amplification and de-amplification depending on $Vs_{30\pm}$ it does not take into consideration any other factor such as building quality, foundation depth, topography, earthquake directivity, type of fault etc. Obviously, for better results we must use more methods and jointly invert some other seismic data such as: refraction (S and P waves), Horizontal to Vertical Spectral Ratio (HVSR), MASW of the transverse component of Love waves, MASW of the radial component of Rayleigh wave, Extended Spatial Auto-Correlation (ESAC), etc. Also, with these data in hand, a full inversion for the epicenter will be in
- 20 order.

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Despite the scarcity of data, this is the first time that an integration of historical data with <u>shear-wave velocity profile modern</u> seismic-measurements improves the attenuation relation. In order to better estimate the peak ground acceleration or the seismic intensities that will caused by future earthquakes, attenuation relations are necessary for areas characterized by high <u>seismicity</u>. worldwide, <u>especially in areas characterized by high seismicity</u>. Some of the regions of low to moderate seismicity have rich <u>sources of historical earthquake</u> data. The integration of historical data with <u>shear-wave velocity</u> <u>profilesmodern</u> measurements will lead to a better understanding of future earthquakes.

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Figure 1: Schematic view of site amplification due to reverberations. Seismogram at the surface shows amplification in comparison to the seismogram located over the bedrock. See new fig



-Main faults • Optional epicenters

Figure 2: A) Middle East area. B) Optional epicenters for the 1927 earthquake event with all sites that were investigated placed over the DTM map made by John K. Hall. C) Location of the optional epicenters. See new figure



Figure 3: Wreckage of the Winter Palace Hotel, Jericho, after the 1927 earthquake. American Colony (Jerusalem). Photo Dept., photographer.



Figure 4: Isoseismal map. The epicentral locations in red and black circles. Red and <u>yellow-green</u> dots are suspect amplified or deamplified sites (respectively). Blue dots are sites which have MSK values expected from the attenuation equation (with 60% prediction boundary).



Figure 5: M<u>Multichannel Analysis of Surface Waves (MASW) technique: A. Acquisition – Using a sledgehammer as an artificial source and a linear array of geophones that receives all wavelets. B. Signal process – A fundamental mode and first higher mode over the dispersion image. C. Inversion – Final V_s profile which best fits the dispersion curve, altichannel Analysis of Surface Waves (MASW) technique: A. Acquisition – Using a sledgehammer as an artificial source and a linear array of geophones that receives all wavelets. B. Signal process – A fundamental mode and first higher mode over the dispersion image. C. Inversion – Final V_s profile which fits the best to the dispersion curve.</u>



Figure 6: Data processing (example from Binyamina): A – Seven dispersion curves of each offset. B – The smoothest and clearest dispersion image (Offset -10), C – Best dispersion curve and a suitable theoretical one. D – Shear-wave velocity model and Vs_{30} value. See new figure



Figure 7: Avni's seismic intensity (MMI) estimates of all 133 sites. Distance is corrected according to Zohar & Marco epicenter. Red and yellow dots suspected amplified or de-amplified sites (respectively). Sites with pin are sites where we measured the Vs profile. Blue dots are sites which have MSK values expected from the attenuation equation (with 60% prediction boundary). See new figure



Acquisition parameters

Number of geophones	24
Geophone spacing	2-3 meters
Array length	46-69 meters
Sampling rate	8 kHz
Record length	0.5-2 second
Receivers	4.5 Hz vertical
Source	5 kg hammer

Table 1: Acquisition parameters.

ID	Site	Vs ₃₀ [m/sec]	Mean Vs ₃₀ [m/sec]	
1	Acre	240	240	
2	Ashkelon	490	490	
3	Be'er Sheva	360	360	
4	Beit Hakerem	1450	1450	
5	Beit Alfa	230	230	
6	Binyamina	300	300	
7	Givatayim	410	410	
8	Herzliya	320	320	
9	Jasar-Majami	260	260	
10	Lod 1	320	340+20	
11	Lod 2	360	540±20	
12	Motza 1	1030	940+90	
13	Motza 2	850	J+0±J0	
14	Mt. Scopus	580	580	
15	Nahalal	380	380	
16	Nahariya	830	830	
17	Peqi'in	1330	1330	
18	Ramleh 1	320	350±30	
19	Ramleh 2	380		
20	Tzemach 1	220	245+25	
21	Tzemach 2	270	243123	
22	Tzora	310	310	
23	Yavneh 1	540	450±90	
24	Yavneh 2	360		





Figure 8: Comparison between our Vs30 results and those calculated from GII's reports. See new figure





Figure 10: Vs_{30} as a function of a number of layers.







Figure 12: <u>See new figure</u>R² comparison of all epicentral locations and attenuation equations.