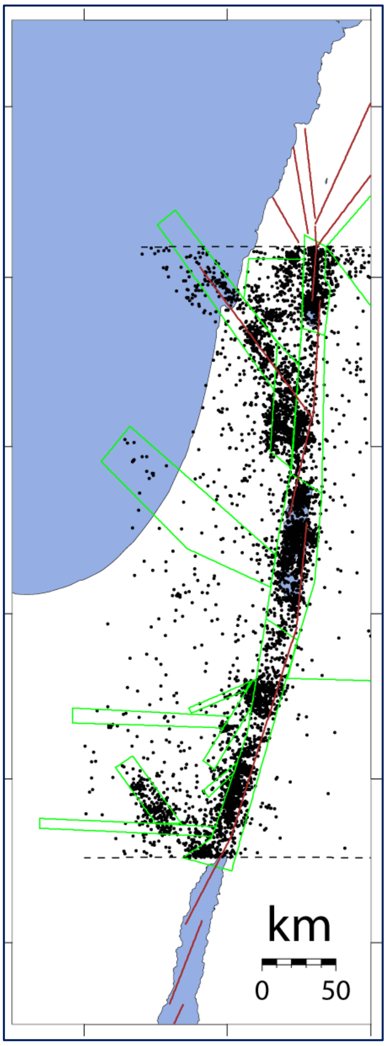
Ministry of National Infrastructures
Energy and Water Resources
Geological Survey of Israel

Sensitivity analysis of the regional Gutenberg-Richter parameters based on the revised catalog of historical earthquakes that caused damage in Israel

Tatiana Meirova, Amos Salamon, Motti Zohar



GSI/12/2017

Jerusalem, May 2017

Ministry of National Infrastructures
Energy and Water Resources
Geological Survey of Israel

Sensitivity analysis of the regional Gutenberg-Richter parameters based on the revised catalog of historical earthquakes that caused damage in Israel

Tatiana Meirova[1,3], Amos Salamon[1], Motti Zohar[1,2]

1. Geological Survey of Israel
2. Institute of Geographical Sciences, Department of Earth Sciences, the Freie University, Berlin, Germany
3. Tel Aviv University

GSI/12/2017 Jerusalem, May 2017

Table of Contents

List of Figures

List of Tables

Abstract

A dependable catalogue of historical earthquake with a unified magnitude scale is a critical component in any regional seismic hazard analysis. Unfortunately, the historical catalog of Israel that was used for the Israeli Building Code SI-413, is not supported by any explanation, set of criteria or reference list, and thus cannot be regarded reliable. Fortunately, the recent update of the historical catalog (Zohar et al., 2017) allowed us to evaluate its impact on the values of the ‘a-’ and ‘b-‘ Gutenberg-Richter hazard parameters.

Overall we were able to arrive at the following understandings: the examined ‘a-‘ and ‘b-‘ values of the updated historical catalogs are higher and closer to the values of the modern catalog than those resulted from the old historical catalog. In general, the rate of seismicity of the second Millennium AD seems stable and complete while the earlier period shows a decrease in these values, most probably due to incomplete documentation.

The updated historical catalog contains only general information about the origin of the historical earthquakes. In case there will be a change in the configuration of the seismogenic zones of the SI-413, there will be a need to better locate the origin of the historical events. We also found that the magnitude uncertainty of ± 0.5 unites in the revised historical catalog cannot significantly affect the estimates of the regional ‘a-’ and ‘b-’ values. The difference in the resulting ‘b-’ values is in the bounds of the standard error. With the increasing of the uncertainty to ±1 magnitude unit the effect on ‘a-‘ and ‘b-’ values increases and becomes significant. Thus, the greater the uncertainty of magnitudes is, the greater the bias in ‘a-’ and ‘b’-values estimation is.

Overall, the updated historical catalog performs more stable and complete than the old one. The epistemic uncertainty in the magnitude estimates should be handled with a logic tree of alternative ‘a-’ and ‘b-’ values.

1. Introduction

A reliable historical earthquake catalogue with dependable parameters and a unified magnitude is a highly critical component in any regional seismic hazard analysis. So far, the historical catalog in common use in Israel was that of the Seismological Division of the Geophysical Institute of Israel (GII) (Appendix 1A; L. Feldman, personal communication, 2010), and it was applied to model the regional Gutenberg-Richter (G-R) parameters of the seismogenic zones used for the Israeli Building Code SI-413. Unfortunately, there is no explanation, set of criteria or reference list that describe how this catalog was constructed. As far as we could understand, it was compiled from the lists of Turcotte and Arieh (1988) and Amiran and Arieh (1994). Nevertheless, extensive examination of the reliability of the historical catalogs of the Levantine region conducted in recent years (e.g. Karcz and Lom, 1987; Ambraseys, 2009; Guidoboni and Comastri, 2005; and others) showed considerable flaws and mistakes to the extent that questioned the reliability of these lists.

Recently, Zohar et al. (2016, 2017) reviewed the reports of historical earthquakes that affected Israel and compiled a revised catalogue that nowadays is considered the most up-to-date. Their catalogue includes the lists of reliable historical earthquakes that occurred and/or caused damage in the Israel, questionable earthquakes, and earthquakes that probably occurred elsewhere but were erroneously associated with damage in Israel.

Preliminary examination of the GII catalog in light of the updated catalogue revealed significant inconsistencies in the GII list. Wide variations exist in the content of the lists, the occurrence time, magnitude, epicenter, and number of events. Overall, large amount of the GII listed events were found questionable (Appendix 1B).

The differences in the historical catalogs, especially the number of events and the magnitude estimates, may have a substantial impact on the assessment of the regional seismic hazard. For example, a bias in the magnitudes may result in different ‘a-’ and ‘b’-values. It is thus important to re-examine the regional G-R parameters upon which the Israeli Building Code was based on according to the revised and updated catalog (Appendix 2, adopted from Zohar et al., 2016).

Here we investigate the potential impact of the updated historical catalog on the regional seismic hazard assessment and examine the importance and sensitivity of several main characteristics and parameters as describe below. We conclude what is the overall effect of the updated catalog on the hazard assessment and where the effort should put in order to improve the quality and reliability of the assessment.

2. Methodology

The first step was to compile the relevant updated list of historical events for use in our evaluation.

Next, in order to understand a sensitivity of regional G-R parameters to the revised historical catalog, we answered the following questions:

a. **Location of the events**: It is well known that there are large uncertainties in the location of the origin of the historical events. To what degree does it matter, if at all?
b. **The hazard parameters** ‘a-’ and ‘b-’ values: How do these values change with the updated list?
c. **Completeness of the list**: What is the threshold magnitude and time frame from which the updated list should be considered complete, if at all?
d. **Accuracy of magnitude determination**: What could be the impact of magnitude uncertainty on the hazard assessment in terms of ‘a-‘ and ‘b-’ values?
e. **Is the revised updated catalog any ‘better’ from the old one?**

We use the Weichert (1980) maximum likelihood method to solve for the Gutenberg-Richter ‘b’- value and the seismicity rate from a catalog whose completeness magnitude threshold changes with time. In the method the b-value is defined by the relation:

$$\frac{1}{\beta} = \bar{M} - M_0 - \frac{M exp(-\beta(M-M_0))}{1-exp(-\beta(M-M_0))} \qquad \text{where } \beta = b\ ln(10),$$

$\bar{M}$ is the average magnitude of the sample, M_0 is the minimal magnitude at which event observations are considered complete (Weichert, 1980). The standard error of the maximum-likelihood estimation of b is approximately b/√N, where N is a number of earthquakes with $M \geq M_0$.

3. The data used in the analysis

Our analysis is based on the updated historical catalog of the reliable moderate-to-large earthquakes that caused damage in Israel (Zohar et al., 2016; here in Appendix 2). Modern events, up to January 2016, were taken from the updated instrumental catalog of local and regional earthquakes, available from the Israel Seismic Network which is operated under the supervision of the Geophysical Institute of Israel (GII, 2016).

It is commonly suggested that ‘b’-values characterize regional tectonic regimes and in hazard studies it is required that the seismicity behaves in a time-independent mode (Giardini, 1999; Frankel, 1995). The time-independent part of seismicity has a Poissonian background distribution while the time dependent part is influenced by interaction between events and may not be representative of the regular behavior of a crustal volume. The $\chi 2$-test of magnitude distribution in instrumental catalog of regional earthquakes shows that the distribution is not exponential. It means that to avoid time-dependent data, the catalog has to be de-clustered. To resolve this problem we excluded from the processing the zones that seem to be influenced by clustered seismicity: Eilat and Aragonese. We also excluded from the analysis the historical and modern events that were originated from seismogenic zones that are not covered well enough by the Israeli Seismic Network (ISN) for that the record over there is most probably incomplete. In total, we removed from the processing the events from the Cyprus, Eastern Mediterranean Sea, Egypt, Suez, Arnona, Eilat, Aragonese and Yamouneh seismogenic zones (Shamir et al., 2001). In regard with the historical events, the southern zones were deserted during most of the history and thus allowed limited reporting only. For our purposes these zones are incomplete as well.

In parallel, we converted the duration magnitudes of the modern events to the moment magnitudes by the formula/relation: $M_w = 0.9\ M_d + 0.11$ (Hofstetter and Ataev, 2011). The magnitude of the historical events is far more complicated to homogenize for that they were determined in several methods by different researchers with little information.

Our ad-hoc list is thus consisted of the reliable historical earthquakes that caused damage in Israel (Table 1 and Figure 1, after Zohar et al., 2017) as well as the modern events that occurred with the area that is well covered by the ISN (Figure 2).

Table 1: The list of the reliable historical earthquakes most probably associated with the Dead Sea Transform (DST) that was used for analysis (modified from Zohar et al., 2017).

Date	**Average magnitude***
760-750 BCE	7.8-8.2
31	6.7
363	6.7
419	6.5
634	5.5
659	6.6
749	7.2
756	6
1033	6.6
1068	7.3
1068	6
1117	5.5
1202	7.3
1293	6.2
1458	6.5
1546	6.5
1643	5.5
1759	6.5
1817	5.5
1834	6.3

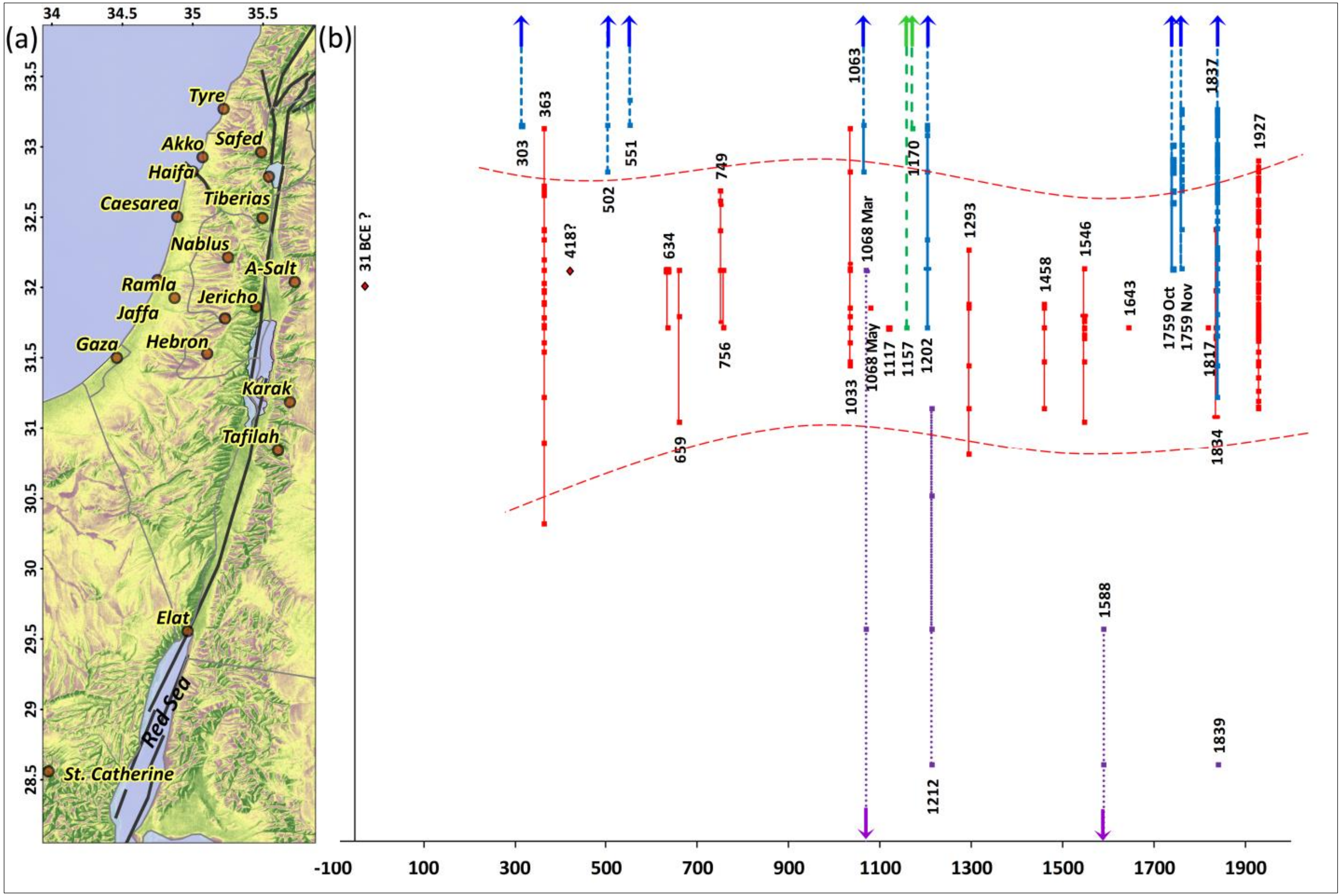


Figure 1: Time series of the distribution of damage from historical earthquake projected along N-S direction, in parallel with the DST (from Zohar et al., 2017). (a) Location map. The dashed black lines delimit the area used for our sensitivity analysis. (b) Time history of the spread of damage per each of the earthquakes, starting from the 31 BCE until to the 1927 events. The square dots denote the damaged localities and the vertical lines represent the total N-S extent of the damage caused by the noted earthquake.

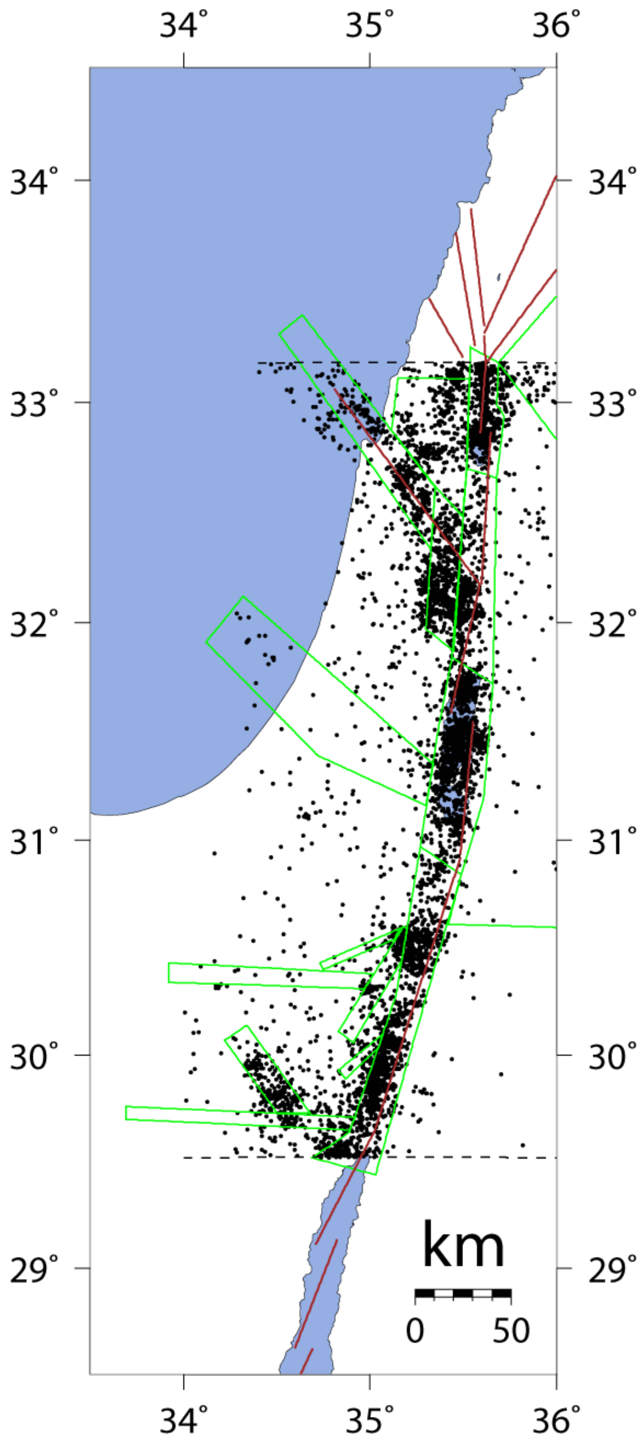


Figure 2: Map of the regional earthquakes selected from the GII instrumental catalog and used for our sensitivity analysis (see explanation in the text). Green lines indicate the seismogenic zones defined by Shamir (2001). Brown lines show the schematic pattern of the main faults of the DST. The dashed black lines delimit the area for the sensitivity analysis.

4. Sensitivity analysis

4.1 Location of the events

There are large uncertainties associated with the location of the origin of the historical events due to the lack of recorded data. Modern approaches draw isoseismals according to the felt and damage reports and infer the probable origin of the event. Advanced methods even try to calculate the magnitude, epicenter, depth and mechanism of the past events (e.g. Zohar and Marco, 2012, and references therein). Nonetheless, this has not yet been done in Israel. Paleoseismological data do allow the identification of surface rupture of past events but there still may be some dating uncertainties. For our purposes we need to know how far these limitations may influence the hazard assessment, if at all.

The model of seismicity defined by the Gutenberg–Richter relation is commonly accepted for Probabilistic Seismic Hazard Assessment (PSHA) in Israel. The current methodology of constructing the ground motion hazard maps of the SI-413 is based on delineating the seismogenic zones and evaluating the ‘a-’ and ‘b’- values of the past and modern seismicity within these zones. The past events contribute most of the strong activity and allow the construction of the high magnitude section of the G-R relationships.

The revised historical catalog determines the spatial distribution of the historical events in association with the geography of the DST, i.e. the Northern, Central and Southern regions (Zohar et al. 2016). The reason is that from geological, seismological and paleoseiamological perspectives, the DST was found to be the most suitable source of strong earthquakes. Such level of resolution is still relevant and good enough for our investigation. For a higher resolution, whether according to the present configuration of seismogenic zones or any other categorization in the future, there will be a need to locate more accurately the historical events.

4.2 The hazard parameters ‘a-’ and ‘b-’ values

In order to evaluate the impact of the differences between the historical catalog of the GII and the revised catalog of Zohar et al. (2016) on the regional ‘a-’ and ‘b–values’, we conducted sensitivity analysis in respect with different time windows. As was already mentioned before, we focused our examination on the central parts of Israel and neglected the remote areas that are away from the ISN (Figure 1, 2) and are not complete.

The level of the uncertainties in the G-R parameters is very sensitive to the completeness of the catalog. The completeness of the Israeli catalog for the time period of 1,900–2,000 was studied by Shapira and Hofstetter (2002), taking into account the local and regional seismicity at that time and the increasing number of seismic stations in Israel, Jordan and the neighboring countries. Through this period of time the detectability of seismic events has been improved and the completeness of the catalog is considered in the following time steps: $M_d \geq 5.0$ from 1900 to 1939, $M_d \geq 4.0$ from 1940 to 1962, $M_d \geq 3.0$ from 1963 to 1984, and $M_d \geq 2.0$ from 1983 to recent times. The detectability of earthquakes along the Israeli part of the Dead Sea Transform is rather uniform since 1985, due to the joint operation of the seismological networks of Israel and Jordan (Hofstetter et al, 2013).

Based on Shapira and Hofstetter (2002) and Hofstetter et al, (2013), we tested four models of completeness and time periods. Table 2 shows these models and the results obtained by these models. Figures 3 – 6 display the relative annual cumulative magnitude-frequency distributions of earthquakes. The top panel in each of the figures illustrates the model of completeness and the bottom panel shows the magnitude-frequency distributions of the events.

Table 2: Models of completeness threshold used for the estimation of the regional ‘a-’ and ‘b-’values on the base of the revised historical (Zohar et al., 2017) and updated instrumental (1900 – 2015) catalogs. Each element of the given models shows the time period and the associated magnitude above which it is considered complete. The bottom line shows the resulting ‘a-’ and ‘b-’ values.

Model A		**Model B**		**Model C**		**Model D**	
Period	Mw	Period	Mw	Period	Mw	Period	Mw
1700-1899	6	1200-1899	6	1000-1899	6	300-1899	6
1900-1939	5	1900-1939	5	1900-1939	5	1900-1939	5
1940-1962	4	1940-1962	4	1940-1962	4	1940-1962	4
1963-1985	3	1963-1985	3	1963-1985	3	1963-1985	3
1985-2015	2	1985-2015	2	1985-2015	2	1985-2015	2
a=3.5; b= 0.9		a=3.5; b = 0.9		a=3.5; b = 0.9		a=3.6; b = 0.83	

Overall, the estimated ‘a-’ and ‘b-’ values that were calculated according to the revised historical and updated instrumental GII catalogs, in all of the four models, are higher (b=0.83 – 0.9) than those obtained by processing the old historical and instrumental GII catalogs (b= 0.78 – 0.8, see Appendix 3).

Model A (Table 2) is considered to be complete with the magnitude threshold level of M_w = 6.0 after 1,700 AD since the ‘a-’ and ‘b-’ –values look similar to those of modern times. Zohar et al. (2016) suggest that starting from the 18th century and onwards there is a significant improve of documentation of felt earthquakes due to the sharp development of the public media (see Appendix A). For the time period of 1700-2015 the defined seismicity model predicts 3.2 events with $M_w \geq 6$ while the examined catalog includes 3 as such events.

The ‘a-’ and ‘b-’ –values obtained for Models A, B, and C are the same. It means that the seismicity rate stays stable for the time period since 1000 AD. Model B predicts 6.7 events with $M_w \geq 6$ while the catalog includes 7 as such events. Model C predicts about 13.1 $M_w \geq 6$ events for the time period of 1000 – 2015 AD while the historical record consists of 10 events only. It indicates that the examined catalog for this time period might be incomplete, or that this period was less active than the others.

Model D supports the ‘b-’ value of 0.83, lower than that of the A, B and C models. For the previous 1715 years that spanned the time window of 300 – 2015 AD, it predicts 33.5 events with $M_w \geq 6$ while the catalog includes only 15 events for the same analyzed period.

Overall, the calculations above propose a constant seismicity rate (‘a-‘ and ‘b-‘ values) for the 1000 – 2015 AD time period (see Table 2) while the earlier period appears to be less stable. However, this difference is still within the range of standard deviation estimated (SD) for the ‘b-’ value determined for the models A, B and C. The SD ranges between 0.2 – 0.4 ($SD=b/\sqrt{N}$, where N is a number of earthquakes with magnitude greater than the threshold magnitude at which event observations are considered complete) for the four models and thus the decrease in seismicity rate is not significant. Further discussion and supportive evidence on this topic appear in section 4.3.

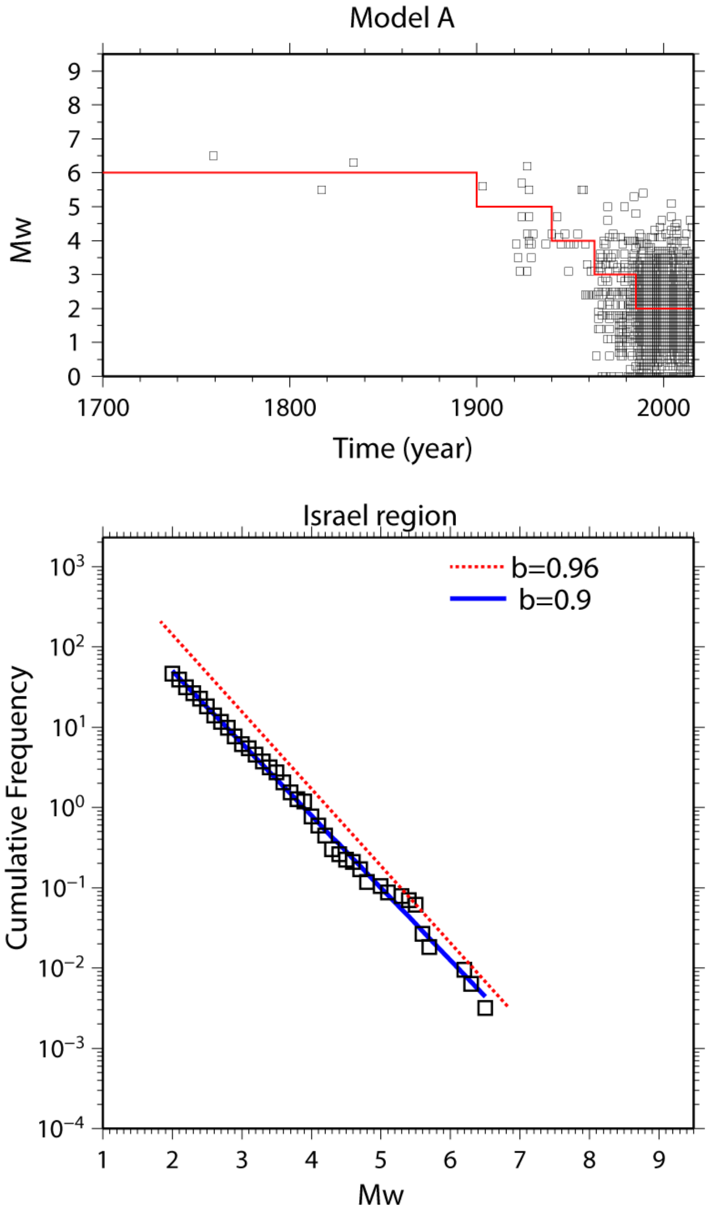


Figure 3: Top panel: Model A of completeness used in the calculations of the regional ‘a-’ and ‘b-’ values (Table 2)

Lower panel: Gutenberg – Richter relationship for Model A. Open squares show the observed seismicity. The Blue solid line delineates the ‘b-’ value according to the seismicity of this model. For comparison, the red dotted line demonstrates the cumulative frequency with b=0.96 that is currently in use by the Israeli Building Code without the reference to the actual regional ‘a-’ value.

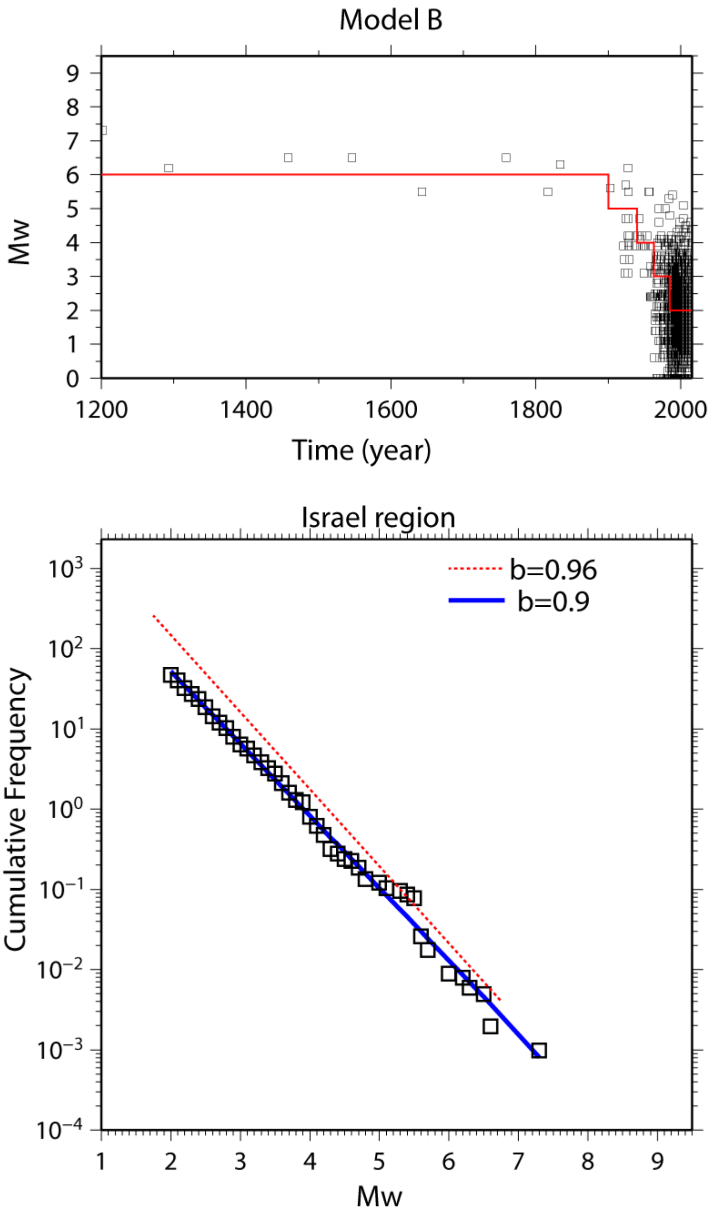


Figure 4: Top panel: Model B of completeness used in the calculations of the regional 'a-' and 'b-' values (Table 2)

Lower panel: Gutenberg – Richter relationship for Model B. Open squares show the observed seismicity. The Blue solid line delineates the 'b-' value and indicates the modeled seismicity line. For comparison, the red dotted line demonstrates the cumulative frequency with b=0.96 that is currently used by the Israel Building Code without the reference to the actual regional 'a-' value.

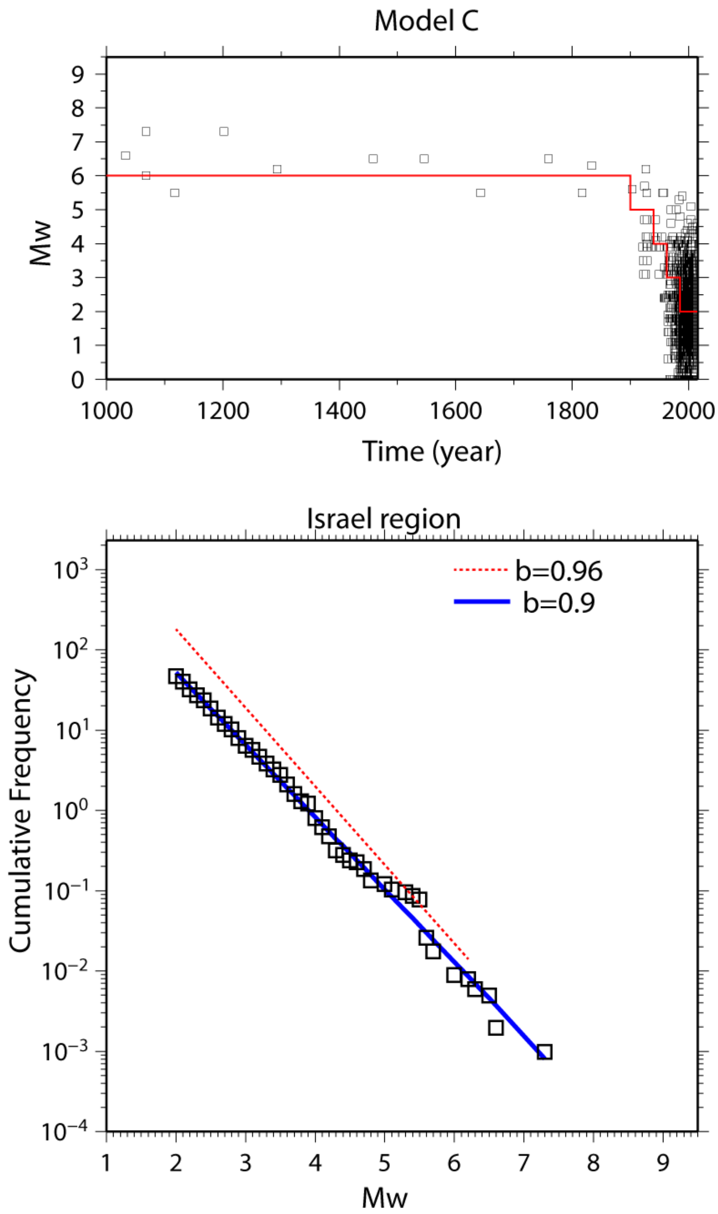


Figure 5: Top panel: Model C of completeness used in the calculations of the regional ‘a-’ and ‘b-’ values (Table 2)

Lower panel: Gutenberg – Richter relationship for Model C. Open squares show the observed seismicity. The Blue solid line delineates the ‘b-’ value and indicates the modeled seismicity line. For comparison, the red dotted line demonstrates the cumulative frequency with b=0.96 that is currently used in the Israel Building Code without the reference to the actual regional ‘a-’ value.

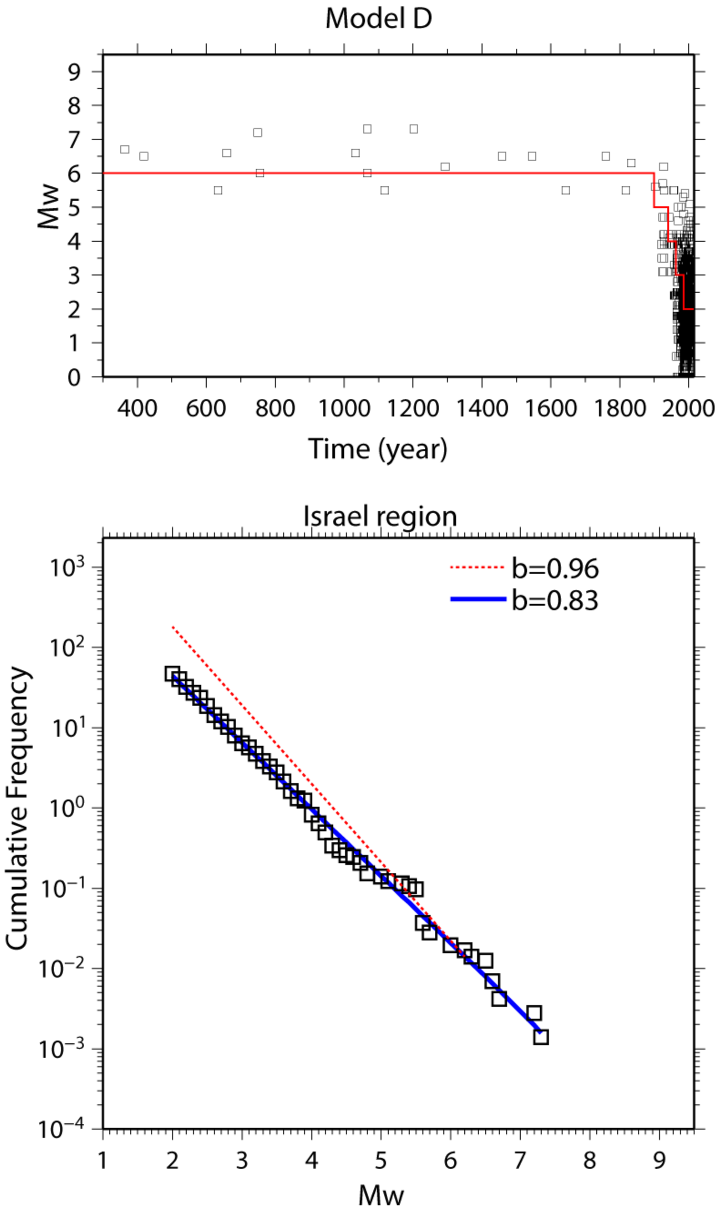


Figure 6: Top panel: Model D of completeness used in the calculations of the regional 'a-' and 'b-' –values (Table 2)

Lower panel: Gutenberg – Richter relationship for Model D. Open squares show the observed seismicity. The blue solid line delineates the b-value and indicates the modeled seismicity line. For reference, the red dotted line demonstrates a cumulative frequency with b=0.96 that is currently in use by the Israeli Building Code without the reference to the actual regional 'a-' value.

4.3 Completeness of the historical list

The completeness of a given catalog is crucial for estimating the reliable seismicity rates and, consequently, for its use in seismic hazard assessment. The completeness of historical catalogs is rather complicated and needs the use of statistical techniques. Nevertheless, the statistical methods may fail to estimate the threshold of completeness because of the sparse occurrence of strong events. In such cases, there is a need to rely on the reliability of the historical chronicles with no hint as to the completeness of the list. Hence, the estimation of the completeness of historical datasets is largely a matter of expert judgment with respect to the nature of historical sources.

To analyze the completeness of the revised historical catalog we used the most simple and robust method that is based on the plots of cumulative frequency of earthquakes with time. This method can be used for both stationary (Poisson process) and nonstationary (not Poisson process) seismicity. In this method the completeness is defined by the point in which the frequency–magnitude curve starts to deviate from a linear trend. Visual inspection of the plots of the cumulative frequency versus magnitude (Figures 3-6) indicates that the compiled instrumental and updated historical catalogs gives robust results for magnitudes up to M_w=5 and confirms a suggestion that the instrumental catalogue is probably complete after 1985 for M_w=2. Determining the completeness of magnitudes above M_w=5 requires additional analysis.

In addition we applied another simple statistical analysis and computed the annual earthquake rate for sub-catalogues with sliding time periods that cover the full time span of the GII as well as the revised catalog (Zohar et al, 2016). Figure 7 demonstrates the fluctuations of the resulted earthquake rates of the two catalogs. It appears that in recent times the two graphs (earthquake rate) are relatively stable. As the examined time-segment is extended into the past, the average rate drops, indicating that there might be earthquakes that are missing from the list, i.e. the list is incomplete. The breakpoint of the curves reflect the transition from the incomplete period to the stable one. Based on this figure it is reasonable to assume that the GII catalog is complete for the time period of 1200 – 1900 AD while the updated historical catalog is complete for ~1000 - 1900 AD. That is, the rate of seismic activity for this time period is approximately stable. Until ~1000 AD, the average rate is influenced by short-term fluctuations, most probably due to the incompleteness of the catalog. Indeed, Zohar et al. (2016) note that there are "holes" in the historical catalog, most probably due to the missing of some $M_w \leq 6$ events.

4.4 Accuracy of magnitude determination

The type of magnitude scale is a fundamental source parameter in earthquake catalogs. Physical models of seismicity are relying on the size distribution of the listed earthquakes as well as on the values of the parameters of the distribution. Thus it is important to homogenize in advance the magnitudes of a given catalog according to a specific scale. The use of instrumental catalogues does not allow inferring the G-R parameters for a time span longer than a century which is too short of a window in terms of seismic cycles. It is thus of great importance to extend the scope of modern seismicity and use historical catalogues. Yet the magnitude determination of historical events is associated with large uncertainties, including the type of scale to assign (e.g. M_L, M_w, etc.).

The magnitude uncertainty was analyzed by Tinti and Mulargia (1985). They pointed out that observational errors might not cause any bias in the estimation of the ‘b-’ value of the frequency-magnitude law but an ‘a-’ -value can be overestimated because of magnitude errors. An error with a standard deviation of 0.7, for example, which may apply to some historical earthquakes (Kagan et al. 2006), may easily cause an overestimation of the seismicity rate by a factor more than 3!

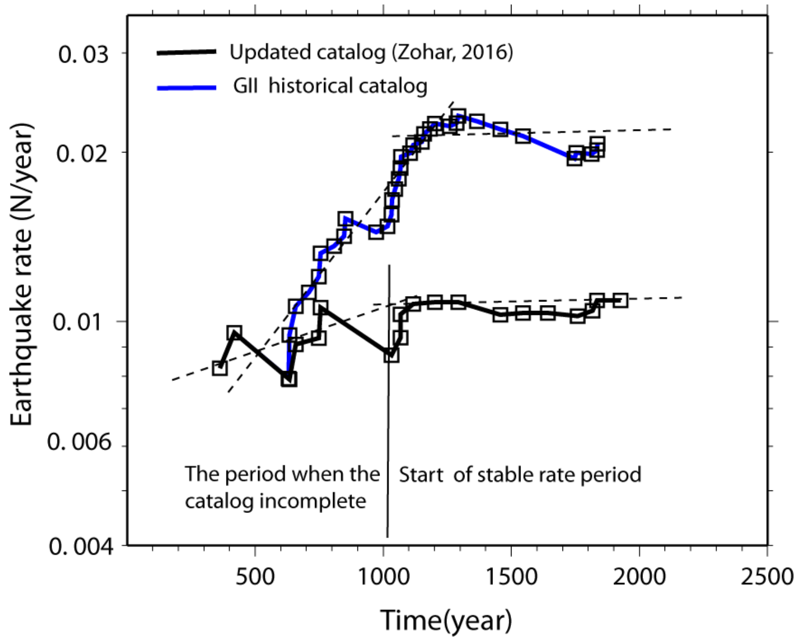


Figure 7: The earthquake rate fluctuations of the GII and the revised historical catalog of Zohar et al. (2016), in blue and black lines, respectively. The solid lines show the fluctuations of the seismicity rate, and the segments of the dashed lines indicate the average rate of earthquake activity.

For that reasons it is important to examine the possible impact of magnitude uncertainty in historical catalog on the ‘a-‘ and ‘b-' estimates. We conducted this test on the second Millennium time frame of the historical catalog with the same magnitude completeness threshold as a function of time which we have already found complete in the previous section. In the following tests we first increased and decreased artificially by 0.5 units the magnitude values that were determined by Zohar et al. (2016) catalog, and then repeated the test with ±1 unit of magnitude. The results of the first test are presented in Table 3 and Figures 8 and 9, and the results of the second test in Table 4.

Table 3: Models of completeness used for the analysis of the uncertainties associated with magnitude determination of ±0.5 units. The bottom line shows the resulting ‘a-’ and ‘b-’ values

Model C1 Magnitudes are increased by 0.5 unit		**Model C2** Original magnitudes		**Model C3** Magnitudes are decreased by 0.5 unit	
Period	Mw	Period	Mw	Period	Mw
1985-2015	2	1985-2015	2	1985-2015	2
1963-1985	3	1963-1985	3	1963-1985	3
1940-1962	4	1940-1962	4	1940-1962	4
1900-1939	5	1900-1939	5	1900-1939	5
1000-1899	6	1000-1899	6	1000-1899	6
a=3.3; b = 0.83		a=3.5; b = 0.9		a=3.6; b = 0.92	

The results of the first test show that the model of the ‘increased’ magnitudes (C1, Figure 8) shows lower ‘a-’ and ‘b-’ values in relation with the model of the ‘original’ magnitudes (C2, Figure 5). In turn, the Model of 'decreased' magnitudes (C3, Figure 9) shows higher 'a-' and 'b-' values. It thus appears that magnitude uncertainties within the range of ±0.5 unit, increases the uncertainty of the b-value estimates. Nonetheless, the differences in the resulting 'b-' values seem to be bound by the standard error which is 0.1.

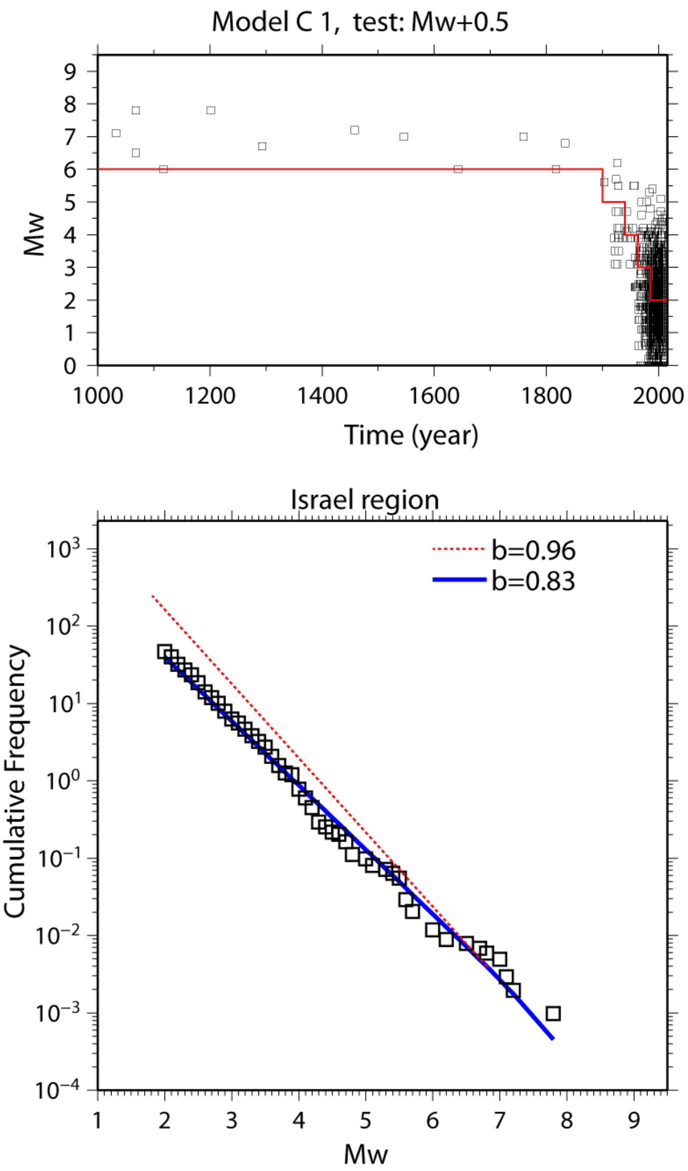


Figure 8: Top panel: Model C1 of completeness (Table 3, magnitudes of historical events are increased by 0.5 units).

Lower panel: Gutenberg – Richter relationship for Model C1. Open squares show the observed seismicity. The blue solid line delineates the b-value and indicates the modeled seismicity line. For reference, the red dotted line demonstrates a cumulative frequency with b=0.96 that is currently used in the Israel Building Code, without a reference to the actual regional a-value.

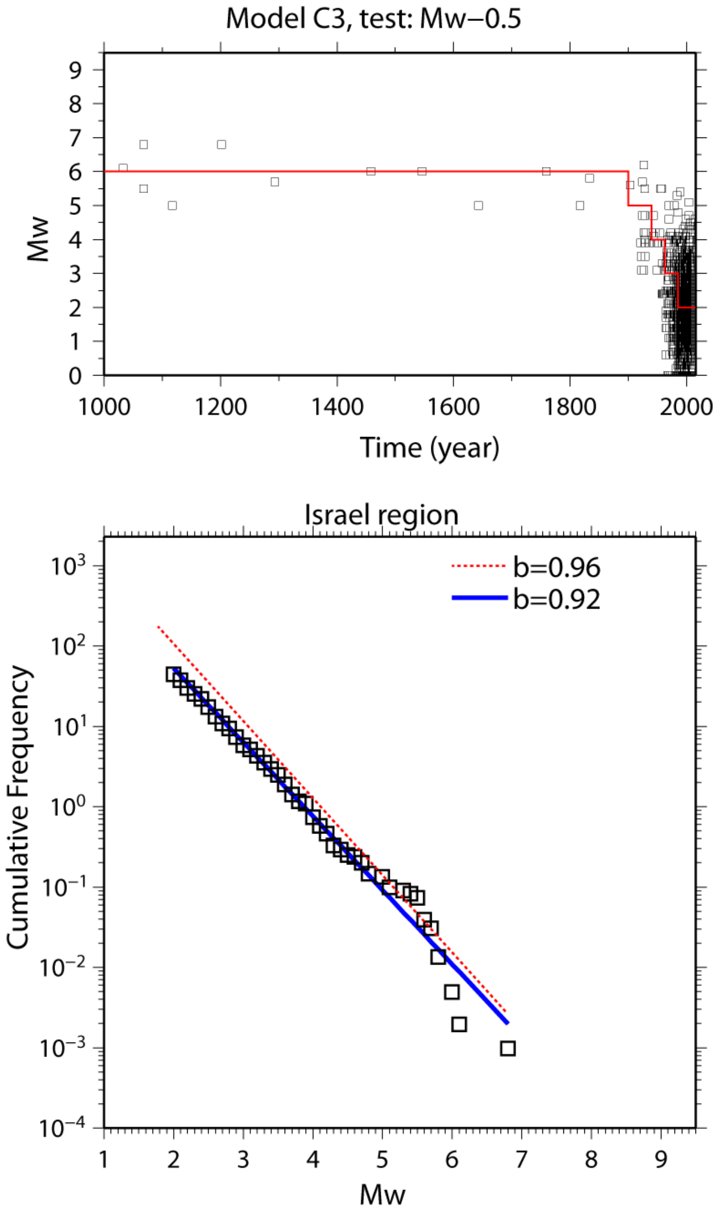


Figure 9: Top panel: Model C3 of completeness (Table 3)

Lower panel: Gutenberg – Richter relationship for Model C3 with the magnitudes decreased purposely by 0.5 units. Open squares show the observed seismicity. The blue solid line delineates the b-value and indicates the modeled seismicity line. The red dotted line models the seismicity for reference value of b=0.96 that is currently used in Israel Building Code, without a reference to the actual regional a-value

In the second test we increased and decreased artificially the magnitude values that were determined by Zohar et al. (2016) by ±1.0 unit, using the same models of completeness and magnitude thresholds as in the previous test (Table 3). The results of this test are presented in the last row of Table 4 and they demonstrate the significant effect on the 'b-' value, mainly in Model C1, in which the 'b-value' drops sharply to 0.71. The bias of 'b-' value estimate is significant and is on the limits of the 'b-value' standard error.

Table 4: Models of completeness used for the analysis of the uncertainties associated with magnitude determination of ±1.0 units. The bottom line shows the resulting 'a-' and 'b-' values.

Model C1 Magnitudes are increased by 1 unit		**Model C2** Original magnitudes		**Model C3** Magnitudes are decreased by 1 unit	
Period	Mw	Period	Mw	Period	Mw
1985-2015	2	1985-2015	2	1985-2015	2
1963-1985	3	1963-1985	3	1963-1985	3
1940-1962	4	1940-1962	4	1940-1962	4
1900-1939	5	1900-1939	5	1900-1939	5
1000-1899	6	1000-1899	6	1000-1899	6
a=2.7; b = 0.71		a=3.5; b = 0.9		a=3.7; b = 0.94	

Overall, it appears that the calculation of 'a-' and 'b-' values is adversely affected by magnitude error, especially when the errors vary systematically with the magnitude. The greater the magnitude uncertainty, the larger it affects the 'a-' and 'b-' values. The uncertainty in magnitude determination within the range of ±0.5 magnitude unit appears to be already insignificant for G-R parameters evaluation. With the increasing of the uncertainty to ±1 unit, the bias of 'a-' and 'b-' estimates becomes significant.

4.5 Is the revised catalog any 'better' than the old one?

From seismological perspective it is not trivial to distinguish which one of a given set of catalogs is 'better' than the others. It is necessary to assume beforehand that in general the seismicity of a given region follows some empirical lows such as stable 'a-' and 'b-' values along time. Nevertheless, nature does not necessarily need to obey strictly these empirical laws (Wesnousky et al., 1983), which makes this task even more difficult.

Assuming that a good catalog does show stable 'a-' and 'b-' values along time, we demonstrated (sections 4.2 and 4.3 above) that the revised historical catalog is more consistent and complete than the old one at least for the time period of ~1000 - 1900 AD. Of course, if 'a-' and 'b-' values change with time and space, then there is no way to favor a given catalog other than regarding the reliability of its content.

In terms of reliability it is easier to show which catalog is better, simply because one can check whether each of the listed events can be detected backwards to its original contemporaneous account. Unfortunately, the GII historical catalog seems not to withstand this criterion (Appendix 2).

5. Discussion and Conclusions

Following our investigation about the potential influence of the historical catalog on the seismic hazard assessment in Israel, we were able to arrive at the following understandings:

Comparison between the historical catalog of the GII and the updated list of historical events (Zohar et al., 2016) shows significant discrepancies in the occurrence time, magnitude, epicenter, and number of events (Appendix 1B). Unfortunately, the GII catalog is not supported by any explanation or a reference list and thus we could not check the reasons for these discrepancies.

The examined b-values of the new historical (Zohar et al, 2016) and updated instrumental earthquake (1900-2015) catalogs were found to be higher and closer to the modern catalog than those resulted from the old historical and updated instrumental earthquake catalogs (Appendix 3). The calculations indicate that no significant changes in the b-values of the revised historical catalog were observed for the time periods of 1000 – 1200, 1200 – 1700 and 1700 – 1900, while the time period of 300 AD to 1000 AD shows decrease in the b-value.

Due to the insufficient amount of information relating to earthquakes in Israel before 1900, the completeness of the historical catalog is hard to establish. Our analysis indicates, with some degree of uncertainty in magnitude determination, that the updated historical catalog (Zohar et al., 2016) is most likely complete for the time period of ~1000 - 1900 AD. The rate of seismic activity for this time period seems stable (Figure 7).

The updated catalog contains only general information about the origin of the historical earthquakes. In case there is a change in the configuration of the seismogenic zones there will be a need to better locate the origin of the historical events.

We found that magnitude uncertainty of ± 0.5 unites in the revised historical catalog (Zohar et al, 2016) cannot affect significantly the estimates of the regional 'a-' and 'b-' values. The difference in the resulting 'b-' values is within the bounds of standard error. With the increasing of the uncertainty to ±1 magnitude unit, the effect on 'a-' and 'b-' estimates increases and becomes significant. This epistemic uncertainty in the magnitude estimates should be handled with a logic tree of alternative 'a-' and 'b-' values.

6. Acknowledgments

We thank Dr. Gony Yagoda-Biran for initiating the project and leading its first phase.

7. References

Ambraseys, N. N. (2009). Earthquakes in the Mediterranean and Middle East. A Multidisciplinary Study of Seismicity up to 1900 (1 ed., pp. 947 .(New York: Cambridge University Press.

Amiran, D., H., K and Arieh, E. and Turcotte, T., (1994). Earthquakes in Israel and adjacent areas: Macroseismic observations since B.C.E..

Frankel, A. (1995). Mapping seismic hazard in the central and eastern United States, Seism. Res. Lett. 66, no. 4, 8–21.

Giardini, D., G. Grunthal, K. Shedlock, and P. Zhang (1999). Global Seismic Hazard Map (GSHAP). International Decade on Natural Disaster Reduction, United Nations, http://seismo.ethz.ch/GSHAP/.

GII (2016). Catalog of regional and local earthquakes. http://seis.gii.co.il/heb/earthquake/searchEQS.php. Last accessed January 2017.

Guidoboni, E., & Comastri, A. (2005). Catalogue of Earthquakes and Tsunamis in the Mediterranean Area from the 11th to the 15th Century. Bologna: INGV-SGA

Hofstetter, R. and Ataev G., (2011). Re-examination of correlation coefficients of earthquake source parameter. *GII report 556/638/11*.

Hofstetter, A., Dorbath, C., Dorbath, L., (2013). Instrumental data on the seismic activity along the Dead Sea Transform. In: Dead Sea Transform Fault System: Reviews. (Z. Garfunkel, Z. Ben-Avraham, E. Kagan, eds.), Springer-Verlag, ISBN 978-94-017-8871-7

Kagan, Y., Y., (1991). Seismic moment distribution, *Geophys. J. Int*., 106, 123-134.

Kagan, Y., Y., (1994). Seismic moment-frequency relation for shallow earthquakes: regional comparison, *J. Geophys. Res*. 02, 2835-2852.

Karcz, I., & Lom ,P. (1987). Bibliographic reliability of catalogues of historic earthquakes in and around Israel: methodology and background (pp. 89). Jerusalem: Geological Survey of Israel.

Rhoades, D. A. (1996). Estimation of the Gutenberg-Richter relation allowing for individual earthquake magnitude uncertainties. *Tectonophysics 258*, 71–83.

Shamir, G., Bartov, Y., Sneh, A., Fleisher, L ., Arad, V. and Rosensaft, M., (2001). Preliminary seismic zonation in Israel, GSI Report No. GSI/12/2001.

Shapira, A. and Hofstetter, A., (2002). Seismicity parameters of seismogenic zones. http://www.seis.mni.gov.il/heb/Teken/seismicity-rprt.htm

SI (Standards Institute) 413 (1995). Design provisions for earthquake resistance of structures, Amendment No. 3, 2009; Amendment 5, 2013. *The Standards Institution of Israel.*

Tinti, S. and F. Mulargia (1985). Effects of magnitude uncertainties on estimating the parameters in the gutenberg-richter frequency-magnitude law. *Bull. Seis. Soc. Am. 75*, 1681–1697.

Turcotte T, Arieh, E. (1988). Catalog of earthquakes in and around Israel. Israel Electric Corporation, Haifa.

Weichert, D. H. (1980). Estimation of the earthquake recurrence parameters for unequal observation periods for different magnitudes. *Bull. Seis. Soc. Am. 70*, 1337–1346.

Wesnousky S., Scholz, C., Shimasaki K. and Matsuda T. (1983). Earthquake frequency distribution and the mechanics of faulting. *J. Geophys. Res*, 88, 9331-9340.

Zohar, M. and Marco, S. (2012) Re-estimating the epicenter of the 1927 Jericho earthquake using spatial distribution of intensity data. Journal of Applied Geophysics, 82, 19-29. doi: 10.1016/j.jappgeo.2012.03.004

Zohar, M., Salamon, A. and Rubin, R., (2016). Reappraised list of historical earthquakes that affected Israel and its close surroundings. *J Seismol*, DOI 10.1007/s10950-016-9575-7.

Zohar, M., Salamon**, A.** and Rubin, R., (2017). Earthquake damage history in Israel and its close surrounding - evaluation of spatial and temporal patterns. *Tectonophysics*, 696-697, 1-13. http://dx.doi.org/10.1016/j.tecto.2016.12.015.

Appendix 1A

List of historical earthquakes currently in use by the Seismological Division of the Geophysical Institute of Israel (GII). The list was sent to us by Mrs. L. Feldman on 4/10/2010. There were no explanation and references available to support this list.

* PTH: location, magnitude and intensity normally relate to the observation point not to the focal point.

	Year	Day	Month	O.T.	Ml	Ms	Lat(N)	Lon(E)	Intensity	Region	Code	Code	Code
BC	2100	0	0		7		31.50	35.05					BEM
BC	1250	0	0		6.5		32.00	35.50					BEM
BC	854	0	0		6.6		32.70	35.40		Sea of Galilee			BEM
BC	759	10	11		7.3		33.00	35.50	11		BM		BEM
BC	525	0	0		7.5		32.50	35.00	11				BEM
BC	222	0	0		7.2		36.50	28.20					BEM
BC	92	2	28		7.1		34.00	32.00			AMR		
BC	64	0	0		7.7		36.20	36.10					BEM
BC	31	9	2		7		32.10	35.50	Io=9	Jordan Valley			
BC	26	0	0		7.3		34.70	32.20	10.5				BEM
BC	15	0	0		6.8		34.70	32.20	9				BEM
***	***	***	***	***	***	***	***	***	***	***	***	***	***
	19	0	0		6.8		34.00	34.00	9	O.C.Sidon			
	33	0	0		7	7.4	32.00	35.50	9		ABK	ABK	BEM
	48	0	0		6		30.00	35.10	8	Arava			
	76	0	0		7		35.00	34.00	10				BEM
	115	0	0		7		34.00	34.00	9	Syr C			
	128	0	0		6		34.00	36.00	8	Beka'a			
	306	0	0		7		34.00	34.00	9	O C Sur			
	342	0	0		6.9		34.70	32.20	10				BEM
	348	0	0		7	7.4	34.00	35.50	10		ABK	BEM	BEM
	363	5	19		6.5		31.10	35.50	9	E of Lisan			
	419	0	0		6.2		33.00	35.60	9	near Safed			
	447	12	8		7.6		40.30	29.30		NW Turkey	AMR	BEM	
	500	0	0		7.3		36.20	36.10	11				BEM
	502	8	19		7		33.30	34.50	10	O C Syria			
	528	11	29		7.1		36.20	36.10	10.5				BEM
	551	7	9		7		34.00	34.50	10	O C Beirut			
	565	0	0		6.7		34.00	36.00					BEM
	588	10	31		6.4		36.20	36.20					BEM
	631	0	0		5.5		32.50	35.50	7	D S Fault			
	634	0	0		6.6	6.85	32.00	35.50	9		ABK	HAS	BEM
	658	6	0		6		32.50	35.50	8	nr B-Shan			
	710	0	0		5.5		32.20	35.50	8	Jor Val			
	713	3	20		6.8		36.50	36.20	9		PTH*		
	749	1	18		7		32.20	35.50	9	Jor Val			
	756	3	8		6		32.00	35.50	8	D S fault			
	765	5	3		5.5		34.00	36.00	8	Beka'a			

	796	4	7		7.1		34.20	24.80					BEM
	808	0	0		5.5		32.20	35.50	7	Jor Val			
	835	0	0		0		36.50	36.20	9		PTH*		
	845	0	0		0		33.30	36.20	9		PTH*		
	847	11	25		6.2	6.25	33.00	36.00	9		ABK	ABK	BEM
	853	0	0		5.5		33.00	35.60	8	Rachaya f			
	854	0	0		0		32.50	35.30	11		PTH*		
	857	0	0		0		30.00	31.20	7		PTH*		
	859	4	8		8		36.20	36.10					BEM
	885	11	0		0		30.00	31.20	10		PTH*		
	950	7	26		0		30.00	31.20	9		PTH*		
	956	1	1		0		36.10	29.60	8		PTH*		
	956	0	0		0		30.00	31.20	6		PTH*		
	972	0	0		6.3	6.5	31.00	35.50	9		ABK	ABK	ETA
	974	0	0		0		33.20	36.20	9		PTH*		
	991	4	5		6 +		34.00	36.00	9	Beka'a			
	1016	0	0		5.5		32.20	35.50	8	Jor Val			
	1032	3	6		6.8		34.80	35.10		Leb Syr off coast	AMR		
	1033	12	10		6.5		32.20	35.50	9	J V&O C S			
	1034	1	4		6.5	6.7	32.00	35.50	10.5		ABK	PTH*	BEM
	1042	8	21		7.2		34.30	38.10					BEM
	1047	0	0		6.3	6.5	31.00	35.50	9		ABK	PTH*	ETA
	1060	0	0		6		32.20	35.50	8	Jor Val			
	1063	7	0		0		36.50	36.20	No Data		PTH*		
	1068	3	18		6.5		30.00	35.00	9	Arava			
	1070	2	25		5.5		30.00	35.00		Arava ?	AMR	BEM	
	1091	9	17		0		36.50	36.15	9		PTH*		
	1094	6	0		0		33.30	36.20	6		PTH*		
	1105	12	24		5.5		32.20	35.50	7	Jor Val			
	1114	8	10		7		36.50	36.00					
	1115	12	25		7.5		37.00	38.00					BEM
	1117	6	26		5.5		32.20	35.50	8	Jor Val			
	1139	10	0		0		33.30	36.20	8		PTH*		
	1139	10	12		7.4		36.10	37.10	10.5				BEM
	1151	9	28		6.2	6.5	32.60	36.70	9		BEM	BEM	BEM
	1152	2	3		5.2	4.75	33.50	36.00	6		ABK	PTH*	ETA
	1157	8	15		7.3	7.8	35.10	36.30	10.5		AMB	BEM	BEM
	1160	0	0		6.1	6.1	32.00	35.50	8		ABK	HAS	BEM
	1170	6	29		7.4	7.6	34.60	36.20	10.5		ABK	BEM	ETA
	1182	0	0		6.7	7	32.60	36.70	9.5		BEM	BEM	BEM
	1201	6	2		7.3	7.8	34.00	36.12	11		ABK	BEM	BEM
	1202	5	20		7.3		33.10	35.60	10	Jordan Gorge			
	1212	5	2		6		27.70	34.00	9	N Red S/S?			
	1222	5	0		6.7		34.50	33.00	9				BEM
	1260	3	0		6.1	6.5	32.50	35.50	-		ABK	-	BEM
	1261	0	0		6.9	7.3	34.00	35.50	-		ABK	-	BEM
	1284	0	0		6.85	7	33.50	36.00	10		ABK	PTH*	ETA
	1287	3	11		6.3	6.5	35.09	36.44	9		PTH*	PTH*	ETA
	1287	4	2		6.3	6.5	33.00	35.50	8.5		ABK	PTH*	ETA

	1293	1	11		5.8		31.70	35.50	8	Dead Sea			
	1303	8	8		7.6		36.30	27.30					BEM
	1312	5	1		6.5		27.70	34.00	9	N Red S/S?			
	1322	0	0		5.5	5.3	33.50	36.00	7		ABK	PTH*	ETA
	1339	0	0		6	6	34.50	36.00	8.5		ABK	ABK	ETA
	1366	10	0		5.5		33.00	35.60	7	Rachaya f			
	1374	0	0		5.5-				7	D S f/Beka			
	1399	9	19		4.75	4.2	33.50	36.00	5		ABK	PTH*	ETA
	1407	4	29		7		35.70	36.30			BEM		AMB
	1408	12	30		7.3		36.50	36.20	10.5				BEM
	1457				7.6		39.90	40.40			AMR	BM	
	1458	11	8		6		31.70	35.50	8	Dead Sea			
	1459	0	0		5.9				8	Dead Sea	ASH		
	1481	3	18		7.7		39.90	40.40	7		BEM		
	1491	4	25		6.8		35.20	33.20	9.5				BEM
	1541	0	0		5.3				7	D S f			
	1546	1	14		6.8		32.20	35.50	9	J V			
	1588	1	14		6		27.70	34.00	9	N Red S/S?			
	1605	1	8		5.5-				8	Sinai?			
	1608	12	14		5.5-				8	Sinai?			
	1656	2	0		7		34.90	36.20					BEM
	1735	12	0		6.5		35.00	34.00	9		BEM		
	1746	7	5		5.2	4.75	33.00	36.00	6		ABK	ABK	ETA
	1753	12	16		6	5.9	33.00	36.00	8		ABK	ABK	ETA
	1759	10	30		6		33.50	35.80	9	Jordan Gorge			
	1759	11	25		7		33.80	35.90	10	Yammoune f			
	1796	4	26		6.6		35.70	36.00					AMB
	1802	0	0		6.2	6.3	34.00	36.00	9		ABK	ABK	BEM
	1814	0	0		5.5-		32.80	35.80	8	E of S Gal			
	1822	8	13		7.2		36.70	36.90					BEM
	1834	5	23		5.5		31.10	35.60	8	E of Lisan			
	1837	1	1		6.5		33.20	35.60	9	Roum f.			
	1846	3	28		7.6		36.00	25.00		Crete			
	1859	10	24		5					Dead Sea f			
	1863	4	22	20:33	7.5		36.50	28.00		Rhodos			
	1870	6	24		7				10 O	C N Eg/Nil			
	1872	4	3	07:45	7.2		36.40	36.50	9.5		BEM		AMB
	1873	2	14		6					O C Tyre			
	1874	3	3		5.0-				7	D S f			
	1879	12	31		5.0-				7	D S f			
	1896	5	2		5.2	5.3	34.00	36.00	7		ABK	BEM	ETA
	1896	6	29		6.8		34.20	33.00	9.5				BEM

Appendix 1B

Preliminary evaluation of the reliability of the list of historical earthquakes of the Seismological Division of the Geophysical Institute of Israel (Appendix 1A). The evaluation considered the majority of the events and focused only on whether these events occurred or not. Other parameters were not examined. Suggestion of alternative dates appears in brackets alongside the original dating.

Date	Reliability
2100 B.C.	Doubtful
1250 B.C.	Doubtful
854 B.C.	Doubtful
759 B.C. (760-750)	Reliable
525 B.C.	Doubtful
222 B.C.	Doubtful
31 early spring B.C.	Reliable
26 B.C. (c. 20)	Reliable
15 B.C. (15-17)	Reliable
19	Doubtful
33	Doubtful
48 (41-54)	Reliable
76	Reliable
115 12 13 night	Reliable
128 (127-130)	Reliable
306	Doubtful
342 (341)	Reliable
348/9	Reliable
363 05 18-19 (night)	Reliable
419 (418)	Reliable
447	Doubtful
500	Doubtful
502 08 22 night	Reliable
528 11 29	Reliable
551 07 09	Reliable
565	Doubtful
587/588	Reliable
631	Doubtful
634 09	Reliable
658 (659-660)	Reliable
710	Doubtful
713 02 28 / 03 10	Reliable
749 01 18	Reliable
756 03 08	Reliable
765 05 03	Doubtful
796 04 07	Reliable
808	Doubtful
835	Doubtful
845	Doubtful
847 11 24	Doubtful
853	Doubtful
854	Doubtful
857	Doubtful
859 04 08	Doubtful
885 11	Doubtful
950 07 26	Doubtful
956 01 01	Doubtful
956	Doubtful
972	Doubtful
974	Doubtful
991 04 05 night	Reliable
1016	Doubtful
1032 03 06	Doubtful
1033 12 05 (1034 01 04?) before sunset	Reliable
1034 01 04	Doubtful
1042 08 21	Doubtful
1047	Doubtful
1060	Doubtful
1063 07 30 – 08 27	Reliable
1068 05 29	Reliable
1070 02 25	Doubtful
1091 09 17	Reliable
1094 06	Reliable
1105 12 24	Reliable
1114 08 10	Reliable
1115 11 29	Doubtful
1117 06 26	Reliable
1139 10 (Jun 21)	Reliable
1139 10 12	Not Checked
1151 09 28	Reliable
1152 02 03	Reliable
1157 08 15	Reliable
1160	Doubtful
1170 06 29 (0345 UT)	Reliable
1182	Not Checked
1201	Doubtful
1202 05 20 (0240 UT)	Reliable
1212 05 01	Reliable
1222 05 11 (06:15 UT)	Reliable
1260 03 (1259 03)	Reliable
1261	Doubtful
1284 10 13	Reliable
1287 03 11	Reliable
1287 04 02	Not Checked
1293 01 11 – 02 08	Reliable
1303 08 08 (03:30 UT)	Reliable
1312 05 01	Doubtful
1322	Doubtful
1339	Reliable
1366 10	Doubtful
1374	Not Checked
1399 09 19	Reliable
1407 04 29	Reliable
1408 12 29	Reliable
1457	Reliable
1458 11 08/16	Reliable
1459	Doubtful
1481 10 03 (Mar 18)	Reliable
1491 04 25	Doubtful
1541	Doubtful
1546 01 14 (Afternoon)	Reliable
1588 01 04 (13:00)	Reliable
1605 01 08	Doubtful
1608 12 14	Not Checked
1656 02	Doubtful
1735 12	Doubtful
1746 07 05	Not Checked
1753 12 16	Reliable
1759 10 30 (03:45 UT)	Reliable
1759 11 25 (19:23 UT)	Reliable
1796 04 26 (09:05)	Reliable
1802	Doubtful
1814	Reliable
1822 08 13 (20:40)	Reliable
1834 5 26 (04:00)	Reliable
1837 01 01 (14:34)	Reliable
1846 03 28	Reliable
1859 10 24	Reliable
1863 04 22	Reliable
1870 06 24 (17:00 UT)	Reliable
1872 04 03 (07:40)	Reliable
1873 02 14	Reliable
1874 03 03	Reliable
1879 12 31	Reliable
1896 05 02	Doubtful
1896 06 29	Reliable

Statistics:

	# of events	% of Total
Reliable Earthquakes:	70	55.5
Doubtful Earthquakes:	50	39.7
Not Checked:	6	4.8
Total	**126**	**100**

In parallel, we found several events that were not included in the GII list. This is a just partial list and we present it in order to show another aspect of the problematics of the GII list.

Date	Reliability
760-750 B.C.	Reliable
199 – 198 B.C.	Reliable
148 02 21 or 130 B.C.	Reliable
69 – 65 B.C.	Reliable
17 B.C.	Reliable
37 03 23 morning	Reliable
127-130	Reliable
303/4	Reliable
502 08 22 night	Reliable
526 05 20/29 mid-day	Reliable
c. 570	Reliable
601-602	Reliable
659/660	Reliable
746 01 18 morning	Reliable
1002 11 10 – 1003 10 29	Reliable
1068 03 18 (08 30)	Reliable
1138 10 11	Reliable
1138-9	Reliable
c. 1150	Reliable
1156 09	Reliable
1156 10	Reliable
1156 12 09	Reliable
1157 04 02	Reliable
1157 07 05	Reliable
1157 08 12	Reliable
1163 08	Reliable
1170 06 29 (0345 UT)	Reliable
1287 02 ? – 03 22	Reliable
1344	Reliable
1404 02 20	Reliable
1408 12 29	Reliable
1626	Reliable
1705	Reliable
1738 09 25	Reliable

Appendix 2

List of reliable historical events that occurred between c.760 BCE and 1927 CE and damaged at least one locality in Israel and its close surroundings. The list is adopted from Zohar et al. (2016).

Date – time of occurrence in year and whenever possible - also the month, day and hour; Reported damaged localities – localities reported to have been damaged within the research area (Fig. 1) that we consider of moderate (M_R) or higher degree of reliability (Table 2). Asterisk denotes events that caused damage also beyond our area of interest; Estimated magnitude in previous studies – list of studies and the magnitudes they estimated for that event. Abbreviations: AMARB – Ellenblum et al. (1998); AMBR - Ambraseys and Barazangi (1989); AMJA - Ambraseys and Jackson (1998); AM3 - Ambraseys (1997); AMME - Ambraseys and Melville (1988); AUS - Austin et al. (2000); AVN - Avni (1999); AVN2 - Avni et al. (2002); BEG - Begin (2005); BM - Ben-Menahem (1991); BM2 - Ben-Menahem et al. (1976); BM3 - Ben-Menahem and Aboodi (1981); BM4 - Ben-Menahem (1981); BM5 - Ben-Menahem (1979); DAR - Darawcheh et al. (2000); GC - Guidoboni and Comastri (2005); GOM - Gomez et al. (2003); HOAV - Hough and Avni (2010); KA2 - Karcz (2004); MAR - Marco et al. (2003); MIG - Migowski et al. (2004); NEM - Nemer and Meghraoui (2006); TUAR - Turcotte and Arieh (1988); WECO - Wells and Coppersmith (1994); ZIL - Zilberman et al. (2005); Avg. mag. – the average value of the estimated magnitudes (see Zohar et al., 2016); Size deg. – In terms Table 3suggested by Ambraseys and Jackson (1998). See explanation in Table 3; N-S extent (km) – the distance between the northernmost and southernmost damaged localities, in km; and Casu. – estimated scope of casualties according to the historical reports: '-' – no casualties or not mentioned or not known, F - Few (10 or less), M - Many (more than 10).

Date	*Reported damaged localities*	*Estimated magnitude in previous studies*	*Avg. mag.*	*Size Deg.*	*Extent of damage (N-S, in km)*	*Casu.*
c.760-750 BCE	Jerusalem (?), Judea (?)	7.8-8.2 (AUS); 8.2 (BM5); 7.3 (BM)	-	-	-	-
31 early spring BCE	Judea	6-6.5 (KA2); 6.7 (MIG); 6.7 (BM); 7 (BM5); 7 (TUAR)	6.7	Str	?	M
303 Apr 2*	Tyre	7.1 (BM); 7.1 (MIG after BM)	7.1	Maj	153	M
363 May 18-19 (night)	Antipatris, Caesarea, Gophna, Hada (Unknown location), Areopolis, Ashdod, Zippori, A-Salt, Haifa, Jaffa, Banyas, Tiberias, Bet-Govrin, Petra, Sebastia, Samaria, Zoar, Bet-She'an, Jerusalem, Nicopolis [Israel], Ashqelon, Lod	6.7 (BM); 6.4 (BM5); 7 (TUAR); 6.7 (MIG after BM)	6.7	Str	453	M
418	Palestine	6.2 (TUAR); 6.9 (MIG)	6.5	Str	?	-
502 Aug 22 night*	Acre (Akko), Tyre	7 (TUAR); 7 (MIG after BM); 7 (BM)	7.0	Maj	113	-
551 Jul 9*	Sarafand [Lebanon], Tyre	7.8 (TUAR); Ms 7.2 (DAR); 7.5 (MIG); 7.5 (BM)	7.5	Maj	284	M
634 Sep	Jerusalem, Palestine	5.5 (Light damage, personal judgment, Zohar et al., 2016)	5.5	Mod	47	-
659 Jun 7	Jericho, St. John, Palestine	6.6 and 6.6 (BM; BM5)	6.6	Str	154	M
749/Early 750	Jordan River, Palestine, Tabor Mt., Tiberias, Bet-She'an, Khirbet al Karak	M> 7 (MAR); 7-7.5 (MIG); 7.3 (BM); 7.3,	7.2	Maj	160	M

Date	*Reported damaged localities*	*Estimated magnitude in previous studies*	*Avg. mag.*	*Size Deg.*	*Extent of damage (N-S, in km)*	*Casu.*
		7.3 (BM5, BM3); less than 7 (KA2, BEG)				
756 Mar 9	Jerusalem, Palestine	6 (Moderate damage, personal judgment, Zohar et al., 2016)	6.0	Str	70	-
1033 Dec 05 (night)	Jericho, Ramla, Banyas [Israel], Ashqelon, Jerusalem, Akko, Gaza, Nablus, Hebron, el-Badan	7.1 (MIG); 6.7 (BM); 6.7 (BM5); Me = 6 (GC)	6.6	Str	190	M
1063 Aug*	Acre (Akko), Tyre	6.5-7 (MIG); Me = 5.6 (GC)	6.1	Str	357	F
1068 Mar 18*	Palestine, Elat	6.9 (MIG); 6.6 - 7 (ZIL); 7.0 ≤ MS ≤ 7.8 (AMJA); 7 (BM); Me = 8.1 (GC)	7.3	Maj	780	M
1068 May 29	Ramla	Me =6 (GC)	6.0	Str	?	M
1117 Jun 26	Jerusalem	5.5 (Light damage, personal judgment, Zohar et al., 2016)	5.5	Mod	?	-
1157 Aug 12 (night)*	Jerusalem	7-7.5 (MIG); M > 7 (AMBR); 7.3 (BM)	7.2	Maj	515	M
1170 Jun 29 (0345)*	Banyas [Israel]	7 (MIG); M > 7 (AMBR); 6.6 (HOAV); 7.9 (TUAR); 7.0 ≤ MS ≥ 7.8 (AMJA); 7.5 (BM); Me = 7.7 (GC)	7.3	Maj	497	M
1202 May 20 (0240)	Akko, Samaria, Tebnine, Vadum-Jakub, Banyas [Israel], Hunin Castle, Nablus, Tyre, Jerusalem	7.5 (MIG); 7.5 (AMME); 7.6 (HOAV); 6.8 (BM); 6.8 (BM4); M > 7 (EMARB); 7.0 ≤ MS ≥ 7.8 (AMJA); Me=7.6 (GC)	7.3	Maj	380	M
1212 May 01	Karak, Elat, St. Catherine, el-Shaubak	6.7 (MIG); Me=5.8 (GC)	6.2	Str	330	F
1293 Jan 11–Feb 08	Lod, Ramla, Gaza, Qaqun, Tafilah, Karak	6.6 (MIG); Me = 5.8 (GC)	6.2	Str	185	-
1458 Nov 16	Ramla, Lod, Hebron, Jerusalem, Karak	6.5 (MIG); Me = 5.6 (GC)	6.1	Str	70	M
1546 Jan 14 (Afternoon)	Hebron, Maa'yan Elisha, Jericho, St. John, Bethany, Jerusalem, Jordan River, Nablus, Beit-Jala, Bet-Lehem, Batir	M ~ 6 (KA2); 7 (TUAR); 6.1 (MIG); 7 (BM,BM5, BM3);	6.5	Str	140	M
1588 Jan 04 (13:00)*	Elat, St. Catherine	6.7 (MIG)	6.7	Str	600	-
1643 Mar 23	Jerusalem	5.5 (Light damage, personal judgment, Zohar et al., 2016)	5.5	Mod	?	-
1759 Oct 30 (03:45)*	Akko, Quneitra, Benot-Ya'aqov Bridge, Sasa, Nazareth, Safed, Tiberias, Nablus	Ms ~ 6.6 (AMBR); 6.5 (BM)	6.5	Str	350	M
1759 Nov 25 (19:23)*	Hula, Deir Hanna, Safed, Nabatiya, Nablus, Sassa, Mt.Hermon, Akko, Beit-Jann, Hasbaya, Deir Hanna, Quneitra, Caesarea, Marjuyun, Tiberias, Haifa, el-Rama	7.4 (MIG); MS ~ 7.4 (AMBR, 1989); Ms = 7.4 (AMJA; WECO); 7 ≤ M ≤ 7.2 (GOM); 7.4 (BM)	7.3	Maj	580	M
1817 Mar	Jerusalem	5.5 (Light damage, personal judgment, Zohar et al., 2016)	5.5	Mod	25	-
1834 May 26 (13:00)	Dead Sea Southwest, Caesarea, Jerusalem, Jaffa, Umm al-Rassas, Deir Mar-Saba, Bet-Lehem, Medaba	6.4 (MIG); 6.3 (BM)	6.3	Str	170	-
1837 Jan 01 (16:35)*	Nabatiya, Qana, el-Fara, el-Salha, Jish, Marun Al-Ras, Bint-Jbeil, Malkiyya, Qadas, Ya'tar, Tebnine, Hunin Castle, Banyas [Israel], Metulla, Zeqqieh, Deir Mimas, el-Khiam, el-Tahta, Deir Mar-Elias, Qaddita, Jibshit, Gaza, Arraba, Attil, Qaqun, Tubas, Ajloon, Nablus, Zeita, Harithiya, Jerusalem, Kefar Bir'im, Sea of Galilee,	7.4 (MIG); M > 7 (AM3); MS = 7.4 (WECO); Ms 7.1 (NEM after AM3); 6.7 (BM)	7.1	Maj	635	M

Date	Reported damaged localities	Estimated magnitude in previous studies	Avg. mag.	Size Deg.	Extent of damage (N-S, in km)	Casu.
	Hasbaya, Kafr Aqab, Jeresh., Areopolis, Hula, Tarshiha, Dallata, Jaffa, Mrar, Ein-Zeitun, Tyre, Atlit, Meron, Eilabun, Akko, Migdal, Irbid, Reina, Safed, Tiberias, Hadatha, Haifa, Zemah, Kafr Kanna, Kafr Sabt, Lubiya, Nazareth					
1839	St. Catherine	5.5 (Light damage, personal judgment, Zohar et al., 2016)	5.5	Mod	25	-
1927 Jul 11 (15:04)	Salfit, Soreq River, Nabi-Musa, Abadia, Ajloon, Gaza, Atara,, Meslovia, Lod, Ein-el-Kelt, Ein-Dok, Azraa', Deir, Mar-Saba, Merhavya, Massada, Mrar, Maa'yan Elisha, Moza, Medaba, Migdal, Karak, Kafaringi, En-Harod, Ramat Yishai, Migdal Yava, Qiryat Anavim, Tel Aviv, Nablus, Shunam, Refidie, Ramat, Rachel, Dara'a, Ramla, Shiloach Village, Rehovot, Amman, Reina, Ramallah, En-Karem, Qalqilya, Kabab, Zora, Safed, Zemah, Petah Tiqwa, Eqron, Afula, Akko, Ein-Fara', Ein Qinya, Ein-Musa, Rosh Ha-ha'Ayin, Be'er-Sheva, Jiftlik, Gimzoo, Gedera, Batir, Beit-Sorik, Bet-She'an, Beit-Liqya, Bet-Lehem, Bet-haKerem, Beit-Jimal, Bet-Govrin, Toov, Mt., Bira, Jisr Magmi, a-Ram, Irbid, A-Salt, el-Hama, Abu-Tlul, Nazareth, Jaffa, Yarmouk Fall, Jordan River, Abu-Dis, Abu-Ghosh, Beit-Jala, Zarka Ma'in, Jericho, Holly Mt., Armon Ha-Naziv, Jerusalem, Yalo, Tulkarm, Tiberias, Tabgha, Jaljulya, Hebron, Jenin, Zikhron Yaa'qov, Zarka, Wadi al-Shueib, Mt.Scopus, Olives, Mt., Deir A-Shech, Daharia, Benot-Ya'akov Bridge, Allenby Bridge, Gesher, Jeresh, Michmash village, Haifa	6.25 (AVN; AVN2); 6.2 (BM2); 6.3 (MIG) = 6.25	6.25	Str	220	M

Appendix 3

Gutenberg – Richter relationships for the DST region based on the old historical (GII, Appendix 1) and the new instrumental (1900-2015) catalogs.

Table App 3.1:

Models of completeness threshold for b-value estimation for the whole DST

Model A		Model B		Model I	
Period	Mw	Period	Mw	Period	Mw
1700-1899	6	1200-1899	6		
1900-1939	5	1900-1939	5	1900-1939	5
1940-1962	4	1940-1962	4	1940-1962	4
1963-1985	3	1963-1985	3	1963-1985	3
1985-2015	2	1985-2015	2	1985-2015	2
b = 0.80 a= 3.31		b = 0.78 a=3.36		b = 0.93 a=3.88	

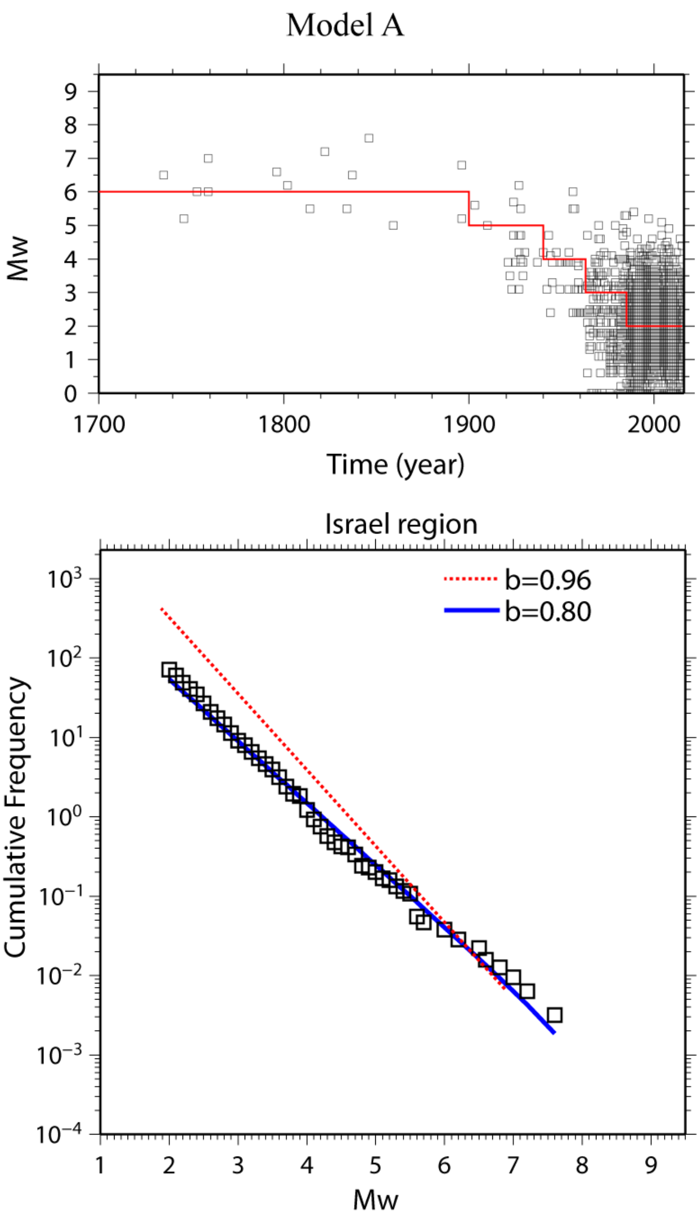


Figure App 3.1

Top panel: model of completeness used in the calculations of the seismic parameters for the Dead Sea Transform (model A).

Lower panel: Gutenberg – Richter relation for the Dead Sea Transform according to model A. Open squares show the observed seismicity and the blue solid line with the slope equal to the b-value indicates the modeled seismicity line. The red dotted line models the seismicity for a reference value of b=0.96 that is used in Israel Building Code 413, without a reference to the actual a-value.

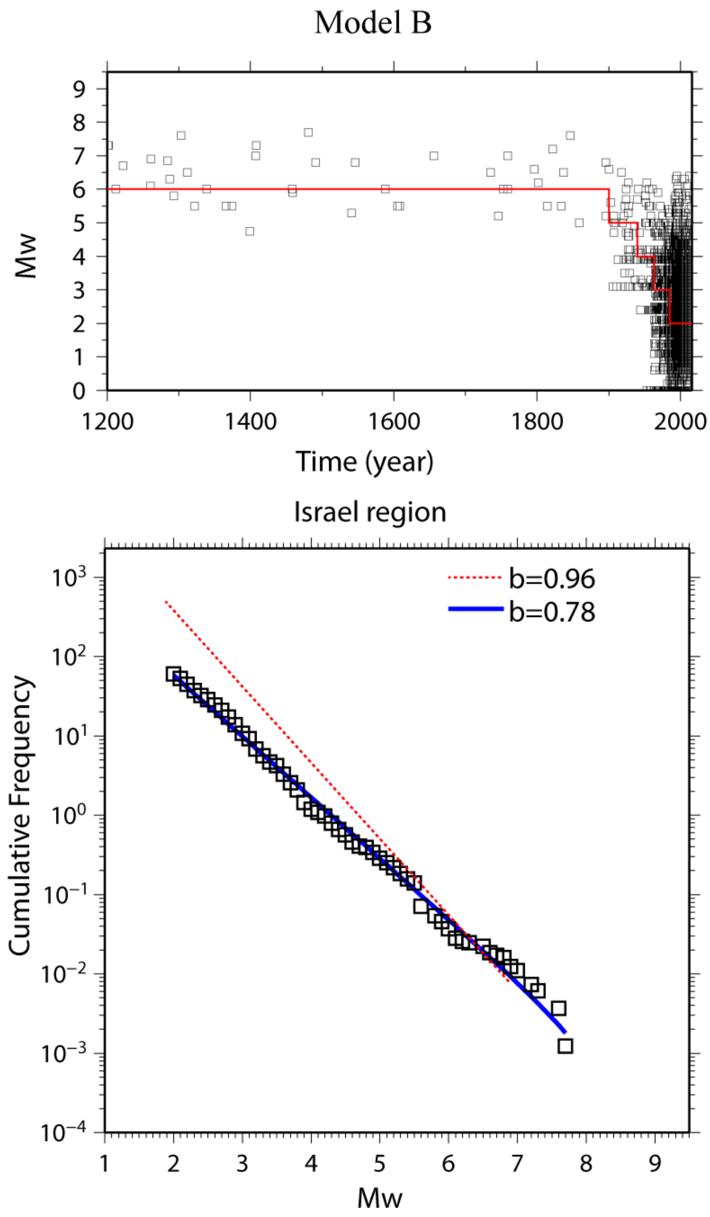
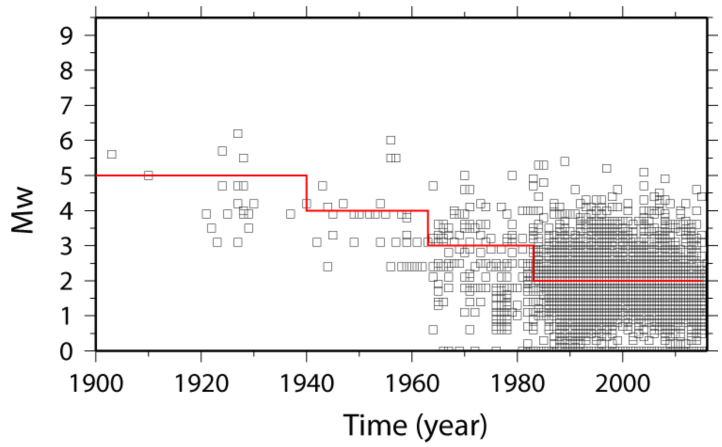


Figure App 3.2

Top panel: model of completeness used in the calculations of the seismic parameters for the Dead Sea Transform (model B).

Lower panel: Gutenberg – Richter relation for Israel region for model B. The open squares show the observed seismicity and the blue solid line with the slope equal to the b-value indicates the modeled seismicity line. The red dotted line models the seismicity for reference value of b=0.96 that is used in Israeli Building Code 413, without a reference to the actual a-value.

Model I



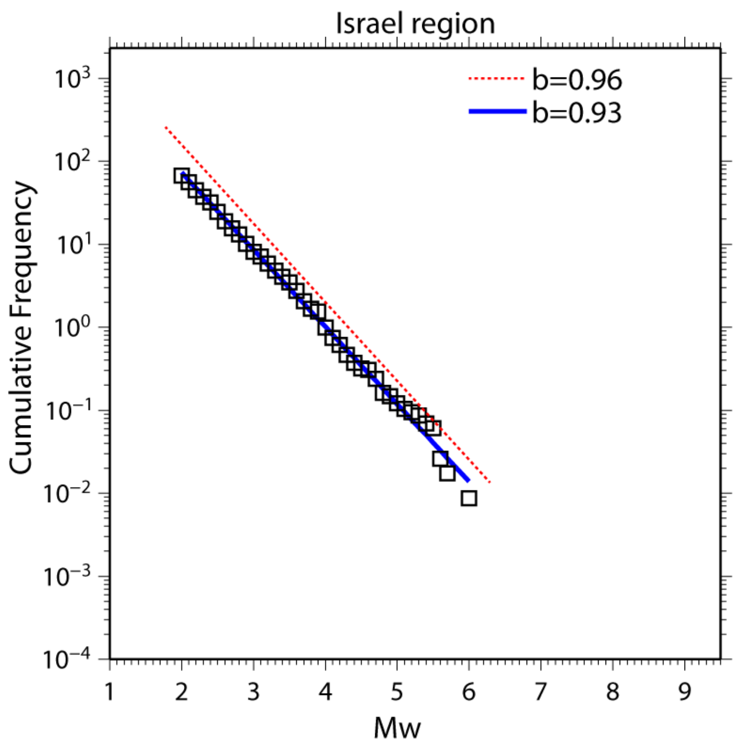


Figure App 3.3

Top panel: model of completeness used for the calculations of the seismic parameters of the Dead Sea Transform (model I).

Lower panel: Gutenberg – Richter relation for Israel region for model I. The open squares show the observed seismicity and the blue solid line with the slope equal to the b-value indicates the modeled seismicity line. The red dotted line models the seismicity for a reference value of b=0.96 that is used in Israeli Building Code 413, without a reference to the actual a-value.

תקציר

קטלוג רעידות אדמה היסטוריות אמין המבוסס על סולם מגניטודה אחיד הינו מרכיב הכרחי בהערכת סיכוני רעידות אדמה. הקטלוג ההיסטורי עליו מבוסס תקן הבניה הישראלי ת״י 413, אינו נתמך בדברי הסבר, חסר הפניה למקורות היסטוריים וללא קריטריונים של מיון וסיווג אמינות המידע, ועל כן אינו קביל. כעת, עדכון הקטלוג ההיסטורי שנעשה לאחרונה על ידי Zohar et al. (2016, 2017), מאפשר להעריך לראשונה את השפעתו על ערכי גוטנברג-ריכטר (ערכי 'a' ו- 'b') החיוניים בהערכה של הסיכון הסיסמי.

בחינה של ערכי גוטנברג-ריכטר על בסיס הקטלוג ההיסטורי המעודכן מעלה שהם גבוהים וקרובים יותר לערכי הקטלוג המודרני מאשר הערכים שמתקבלים מניתוח הקטלוג ההיסטורי הישן. ככלל, קצב הפעילות הסיסמית באלף השני לספה״נ נראה יציב ושלם יותר מאשר באלף הראשון, ככל הנראה כתוצאה מתיעוד חסר של האירועים ההיסטוריים.

המידע עליו מתבסס הקטלוג ההיסטורי המעודכן אינו מאפשר לקבוע את המיקום והמגניטודה של המקורות הסיסמיים בפרוט מספק. במידה ויידרש לארגן מחדש את מפת המקורות הסיסמוגנים עליה מתבסס התקן הישראלי, יידרש לשפר את הערכת המיקום של הרעידות ההיסטוריות ביתר פרוט לידוע כעת. עוד נמצא שאי וודאות בהערכת המגניטודה של הרעידות ההיסטוריות במידה של ±0.5 יחידות מגניטודה אינה משפיעה באופן מהותי על ערכי הסיכון הסיסמי ערכי 'a' ו- 'b'. אולם במידה ואי הוודאות הינה בסדר גודל של ± 1 יחידה, ההשפעה על ערכי הסיכון הסיסמי נעשית משמעותית.

ככלל, הקטלוג ההיסטורי המעודכן מציג קצב פעילות סיסמית יציב ושלם יותר לאורך הזמן מאשר הקטלוג הישן, בפרט באלף השנים האחרונות. יחד עם זאת, אי הוודאות המובנית במידע עליו מתבסס הקטלוג ההיסטורי מחייבת בחינה של הסיכון הסיסמי בשיטת העץ הלוגי תוך התייחסות לכל הטווח האפשרי של ערכי הסיכון ערכי 'a' ו- 'b'.

משרד התשתיות הלאומיות
האנרגיה והמים
המכון הגיאולוגי

בחינת רגישות הפרמטרים הסיסמיים של גוטנברג-ריכטר (ערכי 'a' ו- 'b') על בסיס הקטלוג המעודכן של רעידות אדמה היסטוריות שגרמו נזק בישראל

טטיאנה מאירוב[1,3], עמוס סלמון[1], מוטי זוהר[1,2]

1. המכון הגיאולוגי, ישראל
2. המחלקה לגיאוגרפיה, מדעי כדור הארץ, אוניברסיטת פריי, ברלין, גרמניה
3. אוניברסיטת תל-אביב

דוח מס' GSI/12/2017 מאי 2017