Pumped Storage Hydropower Projects in Active Seismic Zones along the Jordan Rift Valley, Israel

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1. Introduction

The Government of Israel through the Israel Electricity Authority (IEA) has decided to increase the quantity of instantaneous electrical power available on the grid by adding four Pumped Storage Plants (PSP) with a total capacity of 800MW to its existing generation capacity. Three of the four sites are located along the Jordan Rift Valley, which is part of the Great Rift Valley, a continuous approximately 6,000 km long trench that runs from Lebanon's Beqaa Valley to Mozambique in southeast Africa. Most documented earthquakes in Israel are located along the rift valley, especially within tectonically-active structures defined as pull-apart basins. These basins are located – from south to north – in the Gulf of Eilat, the Dead Sea, the Sea of Galilee and the Hula Valley. The PSP projects are comprised of upper and lower reservoirs, each with a capacity of 1.5 million cubic meters that are connected with turbines through tunnels and underground caverns. The lower reservoirs are located at the foothills close to a main fault. As a result, comprehensive seismic risk analyses are required at the design stage in order to evaluate earthquake ground motion and the risk of surface rupture if an earthquake occurs with a magnitude greater than 6.5. An investigation of the Manara site in northern Israel has also contributed new knowledge about complex geological conditions there during the Lower Cretaceous. Academic studies of rock cores suggest that this site was once located on the edge of two environmental zones in the primordial Tethys Sea (150 million years ago), at the border between the moderate continental slope and the deep sea. This border is characterized by a series of immense landslides of shallow marine sediments that interrupt the sequence of sedimentation in the deep sea. The geological and geotechnical investigation at the Manara site emphasized the importance of combining geological information in order to further the understanding of ancient environmental conditions, in order to perform geotechnical interpretation of the site on the basis of current conditions and in order to exercise judgment in determining seismic risk in engineering design.

2. Geological Background

Pumped storage plants need steep topography in order to optimize the production of electrical energy. Therefore, steep physiography is preferred for these sites and, in some cases, they will be located on the edge of active seismic zones. The Great Rift Valley is such a place, where the spreading process between the Arabian plate and the African plate has created the opening of the Red Sea and a series of inland depressions (Figure 1a). The earth’s crust is usually thinner in these areas, resulting in a high tendency toward volcanic activity and earthquakes. From the engineering point of view, the design of hydroelectrical projects that will cross active faults with structures that may be subjected to amplification of ground movement or, in the worst case, to surface rupture due to strong earthquake, is a serious challenge. The Dead Sea Rift, known also as the Jordan Rift Valley, runs along the eastern border of Israel from the Gulf of Eilat in the south to the Hula Valley in the north and further north toward Lebanon (Figure 1b). The documentation of earthquake activity presented in Figure 2 shows that the majority of earthquake epicentres are located along the Jordan Rift Valley. The historical record shows that earthquakes caused the destruction of the cities Beit Shean and Tiberias in 749 and Zefat in 1837. The last big earthquake had a magnitude of 6.2 documented in 1995 about 110 km south of the City of Eilat. This earthquake caused some minor damage to infrastructure and to 140 buildings. The fault geometry is not a characterized by a straight line; instead it has a complex geometry with areas of a “pull-apart basins” where the major fault is divided into secondary faults. Due to the relative horizontal displacement between the eastern and western sides, deep basins are created (Dead Sea, Sea of Galilee and Hula Valley). In these basins, soft sediments are deposited so that the soil profile within the basins and the soil profile along the foothills have different engineering characteristics. The geological map in Figure 5 shows that the upper reservoir and most of the underground structures of the Manara pumped storage facility are located in the Judea Group with ages ranging from the Lower to Upper Cretaceous (100-145 million year) while the lower reservoir is located in the relatively young sediments of the Hula Group with ages ranging from Pleistocene to Holocene (0-2.5 million years). The Judea Group, which is exposed along the Ramim Ridge, is comprised of interbedded layers of sandstone, marlstone and argillaceous limestone at the foothills and hard well-bedded limestone and dolomite at the top of the ridge. The soil profile at the Hula Valley is comprised of fat clay and layers of organic clay and peat. Signs of ancient landslides and deposition of talus deposits in the foothills has great importance in the risk analyses of earthquake-induced landslides, which will be further discussed below. Data from site investigations, especially from continuous cores taken from deep boreholes, has great importance for geological interpretation. A group of scientists from the Department of Marine Geosciences, Charney School of Marine Sciences (CSMS) at the University of Haifa and scientists from the Department of Geological and Environmental Sciences in Ben Gurion University of the Negev investigated the cores taken from Borehole MNUPH-1 using modern techniques and found that the paleogeographic location of the Manara site was on the border between the shallow and deep marine environments of the Tethys Sea (Figure 3). Academic research found that this paleogeographic zone created diverse sedimentation, which in some cases is the result of massive landslides so that a sequence of deep marine sediments may be interrupted by shallow marine sediments.

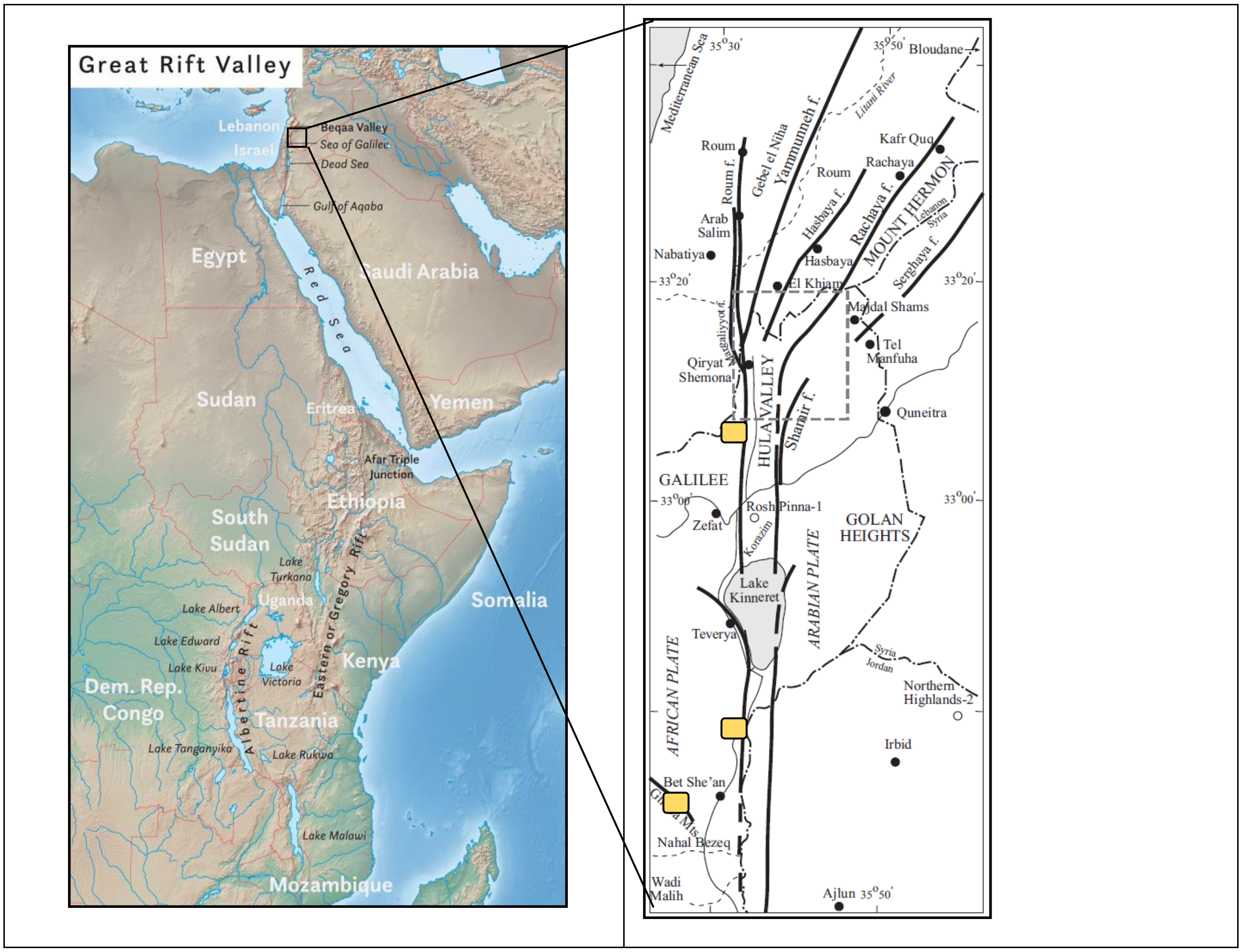

Figure 1: a) The Great Rift Valley from the Beqaa Valley in Lebanon to Lake Malawi in Mozambique; b) the northern section of the Jordan Rift Valley and locations of three pumped storage projects in Israel

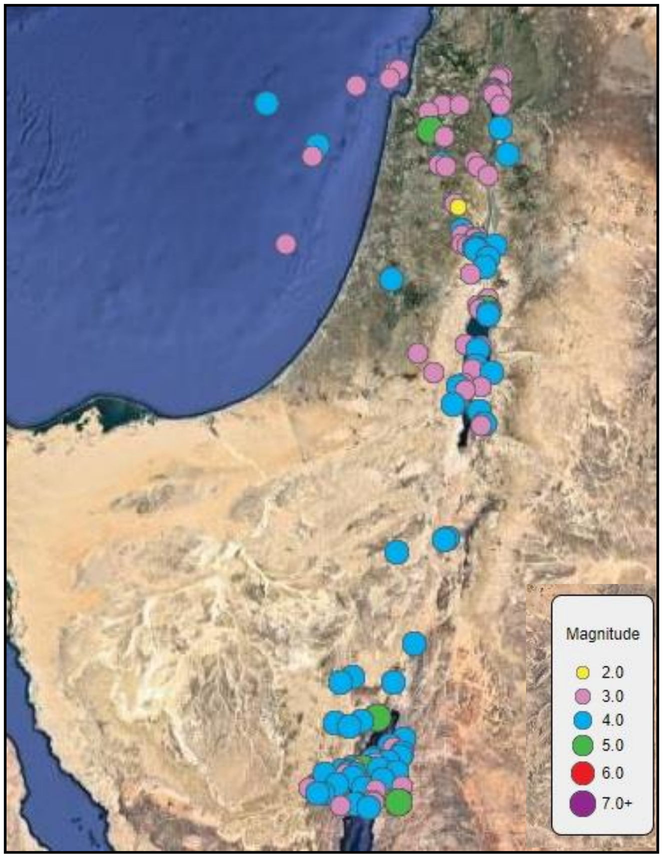

Figure 2: Recorded seismic events with magnitudes greater than 3 along the Jordan Rift Valley

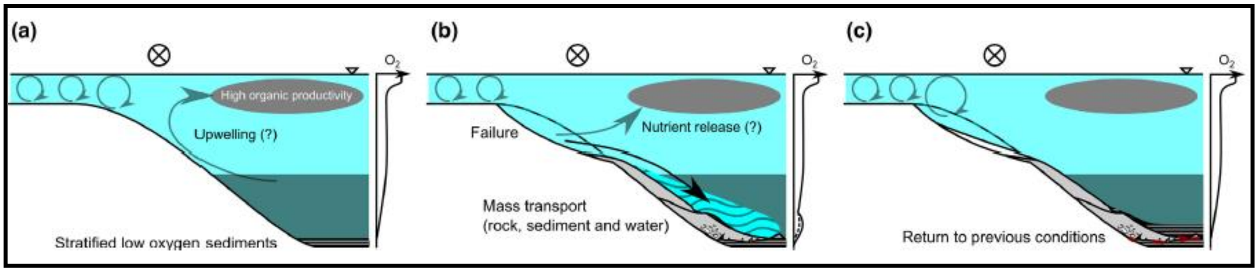

Figure 3**:** Simplified geological model of the marine environment of Ramim Ridge in the Lower Cretaceous based on petrographic analysis of MNUPH-1 cores: a) shallow and deep sea environments; b) mass transport due to landslides create a heterogenic mixture of sediments at the bottom; c) return to previous conditions

3 Description of the three Gilboa, Kokhav Hayarden and Manara projects

There are three pumped storage projects currently in design and construction in Israel. The 300MW Gilboa PSP will start operations in 2019, the 344MW Kokhav Hayarden PSP is under construction and is planned to start operating in 2021; the 156MW Manara PSP is in the detailed design stage and is planned to start operating in 2023. The three projects, all located along the northern section of the Jordan Rift Valley (Figure 1b), are designed in sensitive seismic zones but with differing geological and rock conditions. The Gilboa site is located in Eocene marine sediments comprised mostly of limestone, chalk and marl; the Kokhav Hayarden site is located in a sequence of basaltic rocks from the Miocene to young lacustrine sediments from the Pleistocene; and the Manara site is located in an ancient sequence of sandstone and marlstone from the Lower Cretaceous to a sequence of limestone from the Cenomanian. All three projects include upper and lower reservoirs, a vertical shaft, high-pressure (HP) and low pressure (LP) tunnels with an underground power facility between the HP and LP tunnels. In all three projects, the low pressure tunnel is designed to cross a potentially active fault. The left horizontal slip movement along the Jordan Rift Valley (sinistral fault) is illustrated in Figure 4. The basaltic outcrops of the Golan Heights (east side of the rift) have relatively northern displacements as compared to the outcrops of the Lower Galilee (west side of the rift). The total relative horizontal displacement along the Jordan Rift Valley is estimated at 105 km.

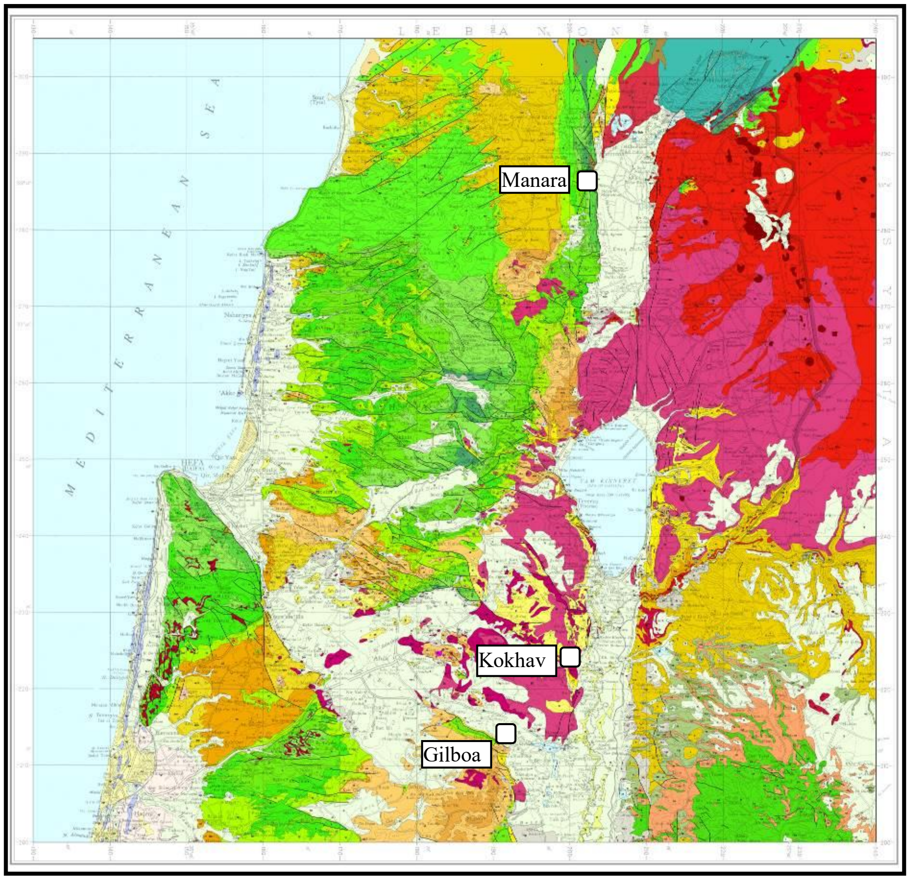

Figure 4: The three pumped storage site marked on a geological map (Israel Northern Sheet, GII, 1998)

4 Preliminary Evaluation of Seismic Hazards

Israeli regulations and design guidelines reference five seismic hazards: surface rupture, amplification of ground motion, slope stability, liquefaction and tsunami. A preliminary seismic hazard survey must be part of the design documents of any master plan of a city, power plant or other strategic infrastructure. This preliminary seismic hazard survey includes all available data from maps and other investigations that have been performed in adjacent areas and should indicate major risks. Further investigations should be part of the advanced and detailed stages of design, where the end goal is to produce baseline parameters for design, including peak ground accelerations for each soil type, to locate traces of active or potentially active faults and to suggest means to mitigate the risk in order to create a safer and optimized design. The following paragraphs describe preliminary evaluation and design considerations related to slope stability, surface rupture and peak ground acceleration at the Manara site.

4.1 Slope stability

One of main concerns of the project is siting of the power plant. The alternative of siting the power plant in the open on the foothills was considered at the feasibility stage. However, after partial analysis of slope stability along the Ramim Ridge indicated a potential of earthquake-induced rockfall and landslide and with signs of ancient landslide scars in the geological map (Figure 5), it was decided that it would be best to site the structure underground instead of in the open. This decision was reinforced later by the conclusions of academic research on the MNUPH-1 cores, which showed that this area was subjected to ancient landslides and deposition of turbidites that interrupted the sequence of deep sea sediments.

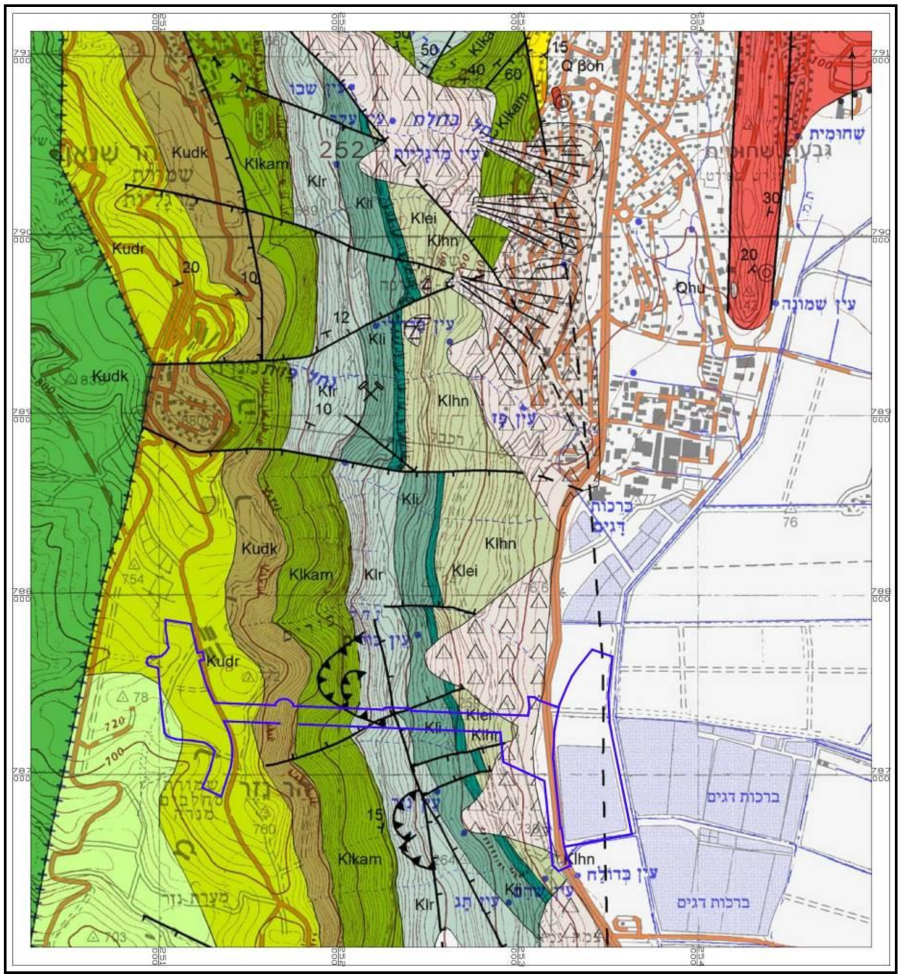

Figure 5: Geological Map showing the Ramim Ridge and the site identified for Manara project. (Origin: Metula sheet 1:50,000 GSI, Israel)

4.2 Surface rupture

Evaluation of the extent of displacement caused by surface rupture along an active fault is one of the challenging aspects of seismic risk analysis. The common approach is to evaluate the dimensions or the area of the active segment that would be affected by an earthquake and, by applying empirical relationships between magnitude and length of rupture, suggest a value for maximum and average expected displacement (Wells and Coppersmith 1994). The evaluation of magnitude is based on a statistical approach whereby a range of displacement values is calculated for each magnitude. The final decision on the baseline parameter should be based on engineering judgment and the fact that no surface rupture occurs in most earthquake events. Therefore, a balance must be struck between the worst case scenario of a large displacement that cannot be handled by engineering solutions and an intermediate situation where expansion joints are designed in sensitive sections that can mitigate the risk or a decision is taken to design a very stiff structure at the point where the pipe crosses the fault line in order to reduce the damage to the pipe and allow its quick repair in case of shear displacement. Historical evidence from the archaeological site at Tel Ateret located 15 km south of the Manara site at the eastern border of the Jordan Rift shows a measured displacement range of 0.5m to 1.6m which is related to single earthquake event with magnitude of 7.5-7.8 (Ellenblum et al, 2015).

4.3 Peak Ground Acceleration (PGA)

Seismic design of structures, according to Israeli standard SI 413, requires consideration of an earthquake event with a 10% probability of exceedance over a 50-year period (i.e. a return period of 475 years). Site specific analysis is then carried out according to American standards such as ASCE-7-05, which states that if site specific analysis is required, the analysis shall be based on a probabilistic approach, using a probabilistic maximum considered earthquake (MCE) with a 2% probability of exceedance over a 50-year period (i.e. a return period of 2,475 years). It became clear that different PGA values are required for the upper reservoir, which is located on rock outcrops, and the lower reservoir, which is characterized by stiff and soft clayey soil profiles.

5. Seismic site response analyses

5.1 General considerations

One of the challenging issues in the design of a hydroelectric project that is located in a sensitive seismic area is to be able to define baseline parameters that will support the design of safe structures. It is clear to geotechnical engineers and geologists that there is a residual risk in any project located at a seismic site, but design approaches for analyzing risk and methods for improving site conditions are available that reduce this risk to an acceptable minimum according to regulations and codes.

Israeli standard SI 413, EN 1998 (Euro code 8), ASCE 7-10 and USBR-Chapter 13 are the relevant codes for the design of structures and dams. The instructions and analyses in these codes were employed as part of the design approach used at the Manara site and the other two sites. However, it should be emphasized that lack of seismic data from recorded earthquake events or lack of information of the geological model of the site can lead to misinterpretation of the baseline parameters and this must be considered when evaluating the overall risk of every project. Reliable parameters are always a result of comprehensive site investigations including boreholes, geophysical methods, long term measurements of groundwater level and in-situ tests. Other methods of investigations in boreholes like BHTV (image oriented photographing), lugeon tests (Packer tests) and hydro-jacking tests were performed during the site investigation in Manara site.

Seismic site response analyses have been carried out for the upper and lower reservoir areas of the planned Manara PSP. In view of site geology, liquefaction was not an issue at the site. However, induced landslides along the slope of Ramim Ridge were part of the risk analysis and the final consideration for the location of the power plant was influenced by the geological findings of ancient landslides along the slope as presented in Figure 5 and as was analyzed in the academic research of the rock cores (M. Bialik and N. Waldman, 2018). Site response has been studied in the upper reservoir area for two earthquake probability conditions – 10% exceedance in 50 years and 2% exceedance in 50 years, the latter corresponding to the maximum considered earthquake (MCE). The analyses were performed according to an updated version of Israeli standard, SI 413. Response spectra corresponding to 5% structural damping have been developed for these conditions (Figure 9). Since site conditions at the lower reservoir vary from east to west, two different soil profiles were considered – a stiffer profile in the west and a softer profile in the east.

5.2 Site investigations at the Manara site

Prior to the seismic site response analysis, a geotechnical site investigation was carried out by performing drilling and geophysical investigations. The core drilling included deep boreholes up to depth of 765 m (MNHPS-1) and 360 m (MNUPH-1). The rock cores from MNUPH-1 were later used for academic research by the Department of Marine Geosciences of the Charney School of Marine Sciences (CSMS), University of Haifa, Israel. The research showed new evidence of oceanographic reconstructions of the northern Arabian platform during the early Cretaceous. The findings of this research strengthen the engineering evaluation of landslide risk.

Figure 6: The MNUPH-1 borehole site on the mountainside above the lower reservoir.

Geophysical investigations (Geophysical Institute of Israel, 2009) included a 2505 m long reflection line GP-5091 that extends from the foothills close to the location of the lower reservoir upward to the location of the intake of the HP shaft. The results of interpretation of the reflection line are presented in Figure 7. These show the En-Te’o fault, and 3 inferred lines related to the Qiryat Shmone fault zone, which is defined as the western border of the Jordan Rift Valley. The structure of the 3 lines may be related to the typical flower structure of a strike slip fault. A series of shorter refraction lines were performed in order to measure the seismic velocity profile (Figure 8). The lines present a soft soil profile along the east side (8b), a stiff soil profile along the west side (8c) and the differences between the west and east side, which may be related to one of the branches of an active fault line. This heterogeneous soil profile requires the application of different geotechnical considerations in the design of the embankments, in particular due to different rates of consolidation and shear resistance.

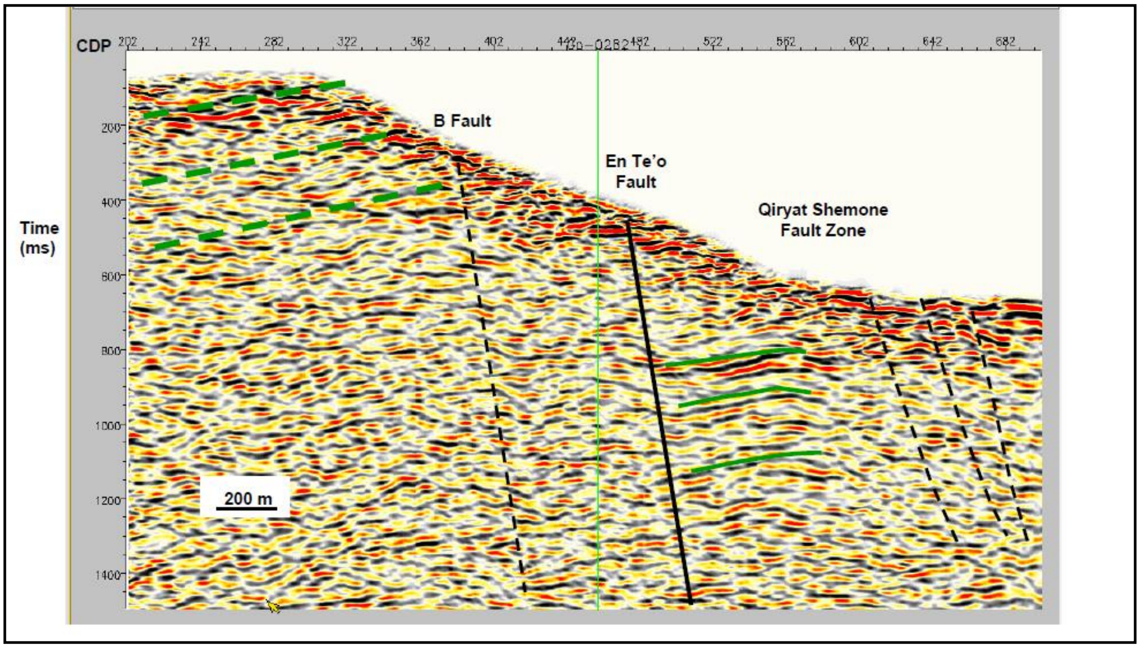

Figure 7: Interpretation of line GP-5091 (time migrated stack). Vertical black lines mark the main faults (dashed where assumed), green markers are Cretaceous and Jurassic sedimentary layers.

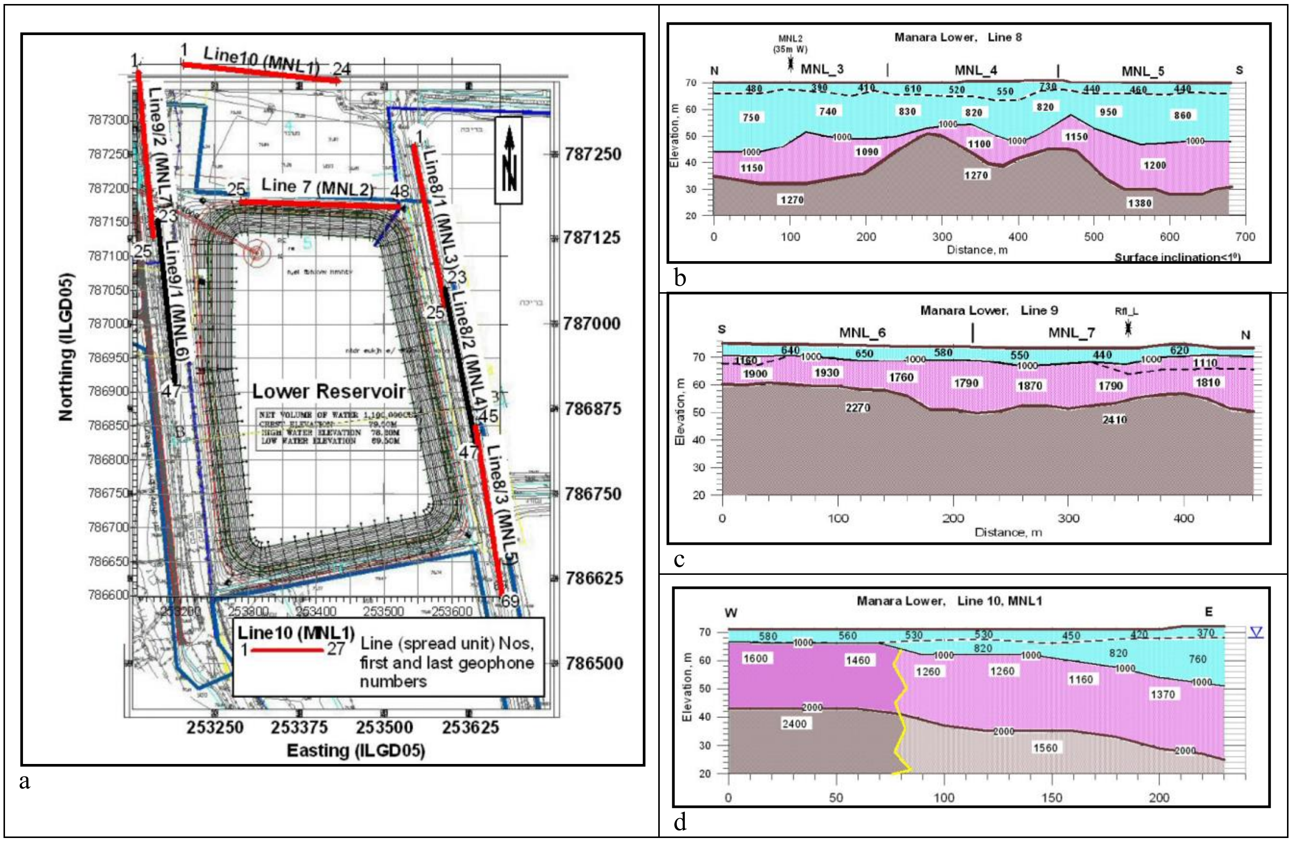

Figure 8: Geophysical refraction lines in the lower reservoir: a) general location map; b) eastern line no. 8 represents the soft soil profile c) western line no. 9 represents the stiff soil profile d) perpendicular line no. 10 represents differences in the soil profile between the west and east sides and a line that may be related to an inferred fault line.

5.3 The seismic analysis approach

The following description of the seismic analysis approach is a summary of the detailed site response report prepared by Geotech (S. Freedman and M. Talesnick, 2010). According to the seismic hazard maps developed by GII, peak ground accelerations at rock (PGA) corresponding to each of the above earthquakes at approximately central coordinates for the top and bottom reservoir areas are given in Table 1.

Table 1: PGA values considered in these analyses

Probability of exceedance in 50 years	10%	2%
Upper reservoir	0.2513g	0.3869g
Lower reservoir	0.2694g	0.4157g

Based on the above information, the following analysis procedure has been followed for each site (upper and lower areas) and for each PGA (Table 1) in accordance with Chapter 21 of the ASCE-7-05 standard (Site specific ground motion procedures for seismic design). The analysis procedure included the following steps:

(a) Five horizontal ground motion acceleration time histories, recorded on rock, have been selected from past events that had magnitudes, focal depths and fault distances consistent with the MCE. Internet data banks (e.g. Cosmos) were used to select time histories recorded on rock of magnitudes above 6.0, with focal depths (D) less than 20 km, recorded at distances (X) of between 0 – 35 km from the activating fault.

(b) Each selected acceleration time history has been scaled so that its maximum value is consistent with the calculated PGA and its response spectrum is approximately at the level of the SI 413 design rock response spectrum over the period range of significance to structural response.

(c) Response spectrum scaling of the rock records was performed using the RspMatch approach (Abrahamson, 1992; Hancock et al., 2006).

(d) On the basis of the available geotechnical and geophysical data presented in Section 5.2, a site profile model was developed that represents the soil layers and their non-linear shear-stress-strain relations. The non-linear relations express the change in Vs, or shear modulus, G, and the damping ratio, ζ, of the soil as a function of shear strain. Non-linear stress-strain relations that have been developed for seismic analysis and published in the literature were adopted; for clays, Vusetic and Dobry (1991) relationships for rock relations presented by EPRI (1993) were used.

(e) Each modified rock acceleration history was then used as input at the profile base (defined in Section 5.2) and a seismic site response analysis was performed, taking account of the low strain-shear wave velocities and non-linear stress-strain behaviour of the soil layers.

The results of the analysis for the lower reservoir for a 10% probability are presented in Figure 9 and suggest two different design spectra – one for the stiff profile based on the code spectra and the second for the soft profile is a modified spectrum with higher specific accelerations within a period of 0.2-0.39 sec.

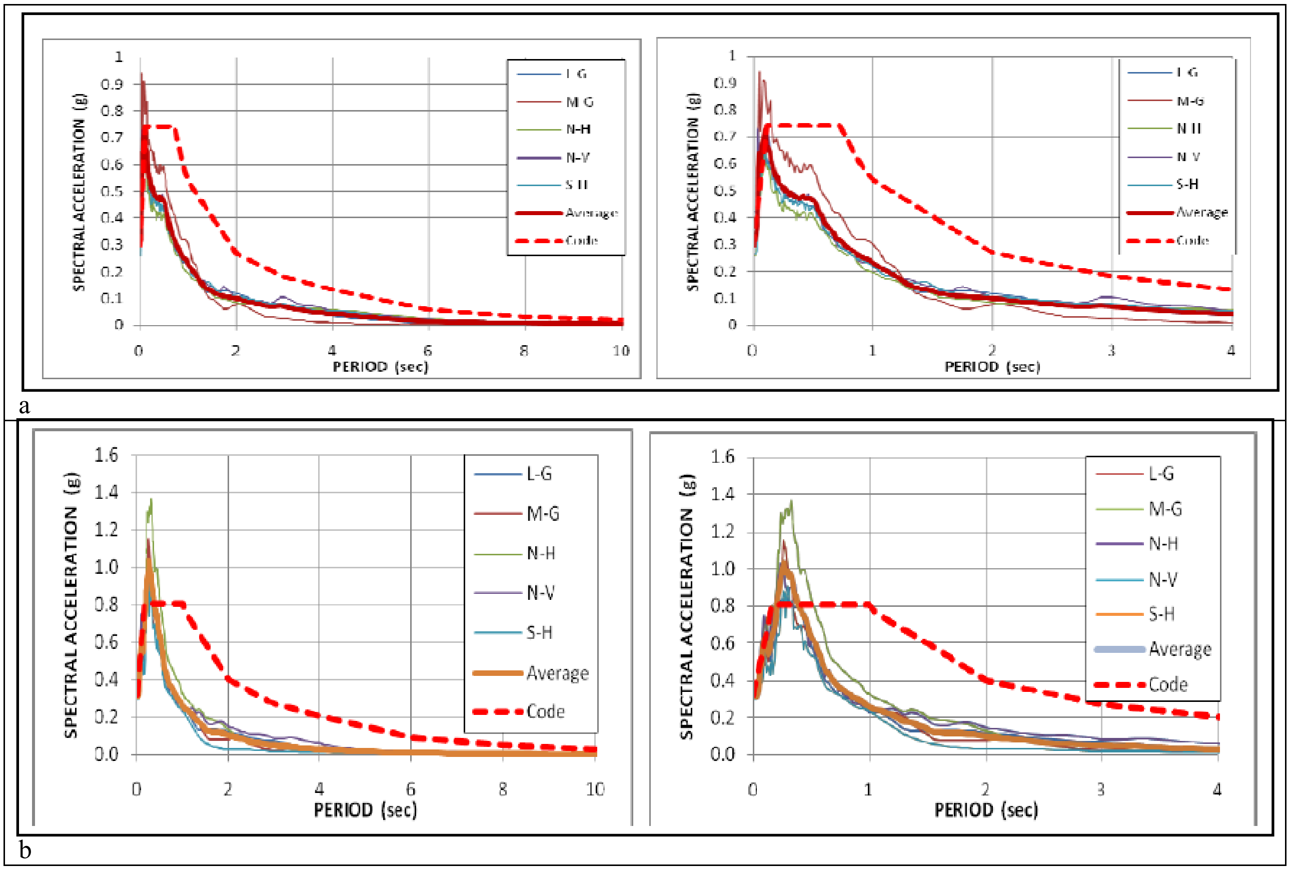

Figure 9: Surface response spectra for a 10% exceedance probability earthquake – lower area: a) stiff profile and b) soft profile (Origin: Geotech report)

6 Conclusions

Seismic analyses require a deep understanding of the geology and current structure of the rock and soil units, as well as the ancient environment and the processes of sedimentation that created the geological formations. The academic study of borehole MNUPH-1 cores at the Manara site supports a better understanding of the relations among the geological formations, made possible due to the long time that has passed between the preliminary geotechnical investigation held in 2009 and the detailed design performed in 2019. Historical evidence of ancient surface rupture can be a factor in preliminary evaluation but requires further analysis combining a deterministic approach (DSHA) and a probabilistic approach (PHSA) in order to obtain reasonable values that can be used as baseline parameters for design and in order to avoid costly and over-conservative design. The design spectra in the codes that are related to rock outcroppings should be checked and a modified design spectrum is required in order to adapt the design to different soil profiles with different ground motion characteristics. If possible, verification of the design baseline parameters should then be performed during the construction works in a defined schedule that will allow design modifications without causing construction delays. Geological documentation and supervision during the construction stage are therefore essential in order to avoid misinterpretation of site conditions and in order to mark a “red flag” in the case where the geological findings have ramifications for stability and on soil behaviour that differ from those considered in the design.

7 References

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