Earthquake Risk and Slope Stability in Jerusalem

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ABSTRACT / Jerusalem is located 25 km from the active Dead Sea fault, which is a part of the Dead Sea Rift System Despite its proximity to the fault, the city has escaped past seismic events relatively undamaged. In contrast to the rest of the city, the Mount of Olives did suffer damage as a result of landslides, as evidenced by a large landslide scarp found in the western slope The unstable slopes in Jerusalem are located on soft Senonian chalk. In the past, these areas were left undeveloped and as a result, damage from earthquakes was relatively slight However, during the past 15 years, with the expansion of Jerusalem, construction has been taking place on unstable slopes as well This could result in heavy damage during future earthquakes A map showing the areas of highest risk is presented. It is recommended that the unstable slopes be reserved as green areas

Introduction

Jerusalem is located 25 km from the seismically active area of the Dead Sea (Fig. 1) (Arieh 1967; Ben-Menachem and Aboodi 1981). The highest magnitude recorded for a particular event in the Jordan Rift Valley was 6.25 during the 1927 earthquake (Vered and Striem 1977). The epicenter of this event was located about 30 km northeast of Jerusalem. It is assumed that stronger earthquakes have occurred in the past, but there is not sufficient information to determine their magnitudes. Vered and Striem (1977) suggest a slightly higher magnitude for the earthquake of 1837, but Wachs and Levitte (1981) question their conclusion. According to Shalem (1949), one of the strongest earthquakes in the area was that described in the Bible as the Uzziah event, which probably happened between 790 and 745 B.C.

Vered (1978) calculates "the probable maximum magnitude" associated with the Jordan Rift as M(L) = 7.5–8. Based on this calculation and on the fact that Jerusalem is only 25 km from the Jordan Rift Valley, earthquakes should be considered a serious hazard to the city. According to Shapira (1981), there is a 1% probability of exceeding a ground acceleration of 0.1 g in Jerusalem. Therefore, seismic risk evaluation is crucial for this area.

Stratigraphy

The rocks exposed in the Jerusalem area are mainly of Cenomanian, Turonian, and Senonian age. The center of the city (including the Old City) is built on Turonian limestones and dolomites. To the west, Cenomanian dolomites and limestones are exposed, while to the east Senonian chalks are found (Arkin 1976). Quarternary alluvium is found in the lower areas, where it is a few meters thick.

The Cenomanian age is represented by the Kefar Shaul and Weradim formations. The lower part of the Kefar Shaul formation is composed of chalk and the upper part of limestone, and the Weradim formation consists mainly of dolomites with some limestones. The Turonian age is represented by the Bina limestone. The Senonian Menuha formation is composed of soft chalk, overlain by the upper Mishash formation which is composed of chalk and chert. The Menuha formation consists of two members (Israeli 1977): the lower, Ka'akule, which is a hard chalk, and the upper, softer Menuha chalk, of which most of the formation is composed.

Past Events

It could be expected that Jerusalem would suffer heavy damage during an earthquake, due to its proximity to the seismically active area of the Dead Sea. However, Shalem (1949) points out that, although Jerusalem is often mentioned in connection with earthquakes, the resulting damage reported has always been slight. In 1837 and 1927, when the Galilee villages and the town of Nablus suffered heavy damage, only minor damage occurred in Jerusalem.

The epicenter of the 1927 earthquake occurred 25 km north of the Dead Sea, and 30 km from Jerusalem (Arieh 1967), whereas the Galilee region is located 125 km from the Dead Sea. This indicates that the heavy damage in the Galilee, as compared to the minor damage in Jerusalem, was not the result of distance from the epicenter. Wachs and Levitte (1978) contend that the damage in the Galilee during the 1837 and 1927 earthquakes was due to landslides and to the fact that buildings were built on thick, unconsolidated material. They point out that villages located on solid limestone and dolomite were not damaged.

On the basis of these observations, it is suggested that damage from earthquakes has been slight in Jerusalem because the city is built on solid foundation material. Because the Uzziah event resulted in heavy damage to the city, it should be studied in greater detail.

Shalem (1949) notes that the Mount of Olives suffered more damage than the rest of Jerusalem during the Uzziah event and was also affected more severely on other occasions. This

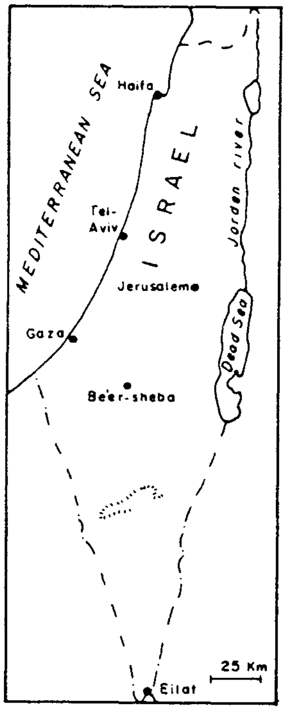

Figure 1. Location map.

situation, resembling that found in the Galilee (Wachs and Levitte 1982), indicates that poor rock foundation is responsible for the heavier damage to the Mount of Olives.

The Mount of Olives consists of chalk of the Senonian Menuha formation, whereas the area to the west of it (the Old City of Jerusalem and its surroundings) is composed of limestone and dolomite of the Turonian Bina formation (Arkin 1976). In contrast to the soft chalks of the Menuha formation just above, the rocks of the Turonian Bina formation are hard. According to Shalem, the "splitting" of the Mount of Olives, as described in the book of Zachariah (Zachariah 14), was one of the unusual events to take place during the Uzziah earthquake. In addition to the splitting, the Bible describes the formation of a large valley in one place and the filling in of an existing valley nearby. Also mentioned is the appearance of new springs, as a result of the earthquake and the splitting of the mountain. This description suggests that a landslide caused the damage to the Mount of Olives, and may explain why the rest of the city was not damaged.

Willis (1928) writes that the Mount of Olives "assumes the character of a fault in its northern extension." He continues to say that the Augusta Victoria Hospital, the hospice of the Order of St. John, is standing "almost over the Mount of Olives fault." Referring to the 1927 earthquake, he suggests that the greater damage suffered on the Mount of Olives was due to this

Figure 2. The old landslide in the Mount of Olives. The area clear of trees above the Gesthemane church is the slide unit. Immediately above it, partly hidden behind the trees, is the main scarp (*large arrow*). Younger, smaller scarps can be seen in the left portion of the main slide unit (*small arrow*).

structural feature. However, he adds that "no fracture is visible in the surface" where the axial fault is supposed to be. In a footnote describing the 1927 event, Willis mentions the "exaggerated reports of great fissures in the ground near Jerusalem." He continues to note that considering "the nearly precipitous walls" of the Kedron canyon, it is not surprising that during the earthquake fissures should appear with dust rising from them. In this footnote, Willis' own description of the 1927 earthquake suggests that the greater damage occurring on the Mount of Olives was caused not by an active fault existing there (an idea unsupported by geological evidence) but by slope collapse.

Both field study and the study of air photographs reveal the existence of a large, old landslide on the northwestern slope of the mountain, although there is no indication of its age. It is possible that the geological event described in Zachariah corresponds to this landslide. However, this matter requires further study.

The Mechanism of Sliding on the Mount of Olives

Figures 2 and 3 show the scarp of the landslide, and the slide unit. The scarp is 10 m high and the slide unit has the typically hummocky surface. In some places, new, younger scarps have formed on the slide unit. These scarps and tilted trees indicate that the colluvial material on the surface is unstable.

Israeli (1977) published a detailed geotechnical map of Jerusalem in which the Ka'akule and the Menuha chalk (the two subdivisions of the Menuha formation) are indicated. Field study and aerial photographs reveal that the landslide involves

Figure 3. Detail of Figure 2, showing the main scarp and the slide unit. The small trees on the slide unit are young olive trees 2–3 m high. The light spot on the main scarp is a recent small scarp. The hummocky surface and the younger scarps (*arrow*) of the colluvial material on the surface of the slide unit are best seen in the center of the photograph, where the large trees are growing.

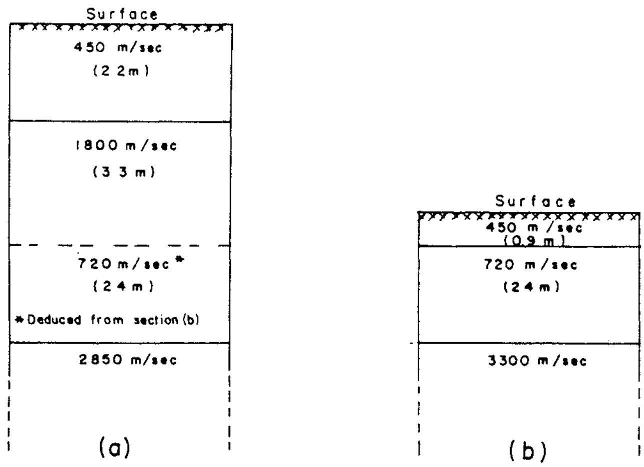

Figure 4. Seismic velocities and thickness of layers in the slide unit of the Mount of Olives landslide.

only the Menuha chalks, with the rupture surface just above the Ka'akule.

In order to obtain more information on the qualities of the rock involved, and particularly of the layer in which the rupture occurs, two seismic refraction traverses were done. The geophysical study was carried out using the Bison Geo Pro 8012 seismograph, equipped with 12 channels and signal enhancement capability. The source of energy was a 5-kg hammer.

The first traverse was made on the top of the slide unit next to the main scarp (Fig. 4A); the second traverse was made along the lower part of the slide unit, just above the Ka'akule (Fig. 4B). The velocities of the different layers are shown in Figure 4.

The layer with a velocity of 450 m/sec is the topsoil, in this case the colluvium. The layer with a velocity of 1,800 m/sec (Fig. 4A) is the soft Menuha chalk. The higher velocities (2,850 and 3,300 m/secs) are of the harder chalk, the Ka'akule. The layer with the lower velocity (720 m/sec) above the "Ka'akule" (Fig. 4B) is of very low strength and elasticity (as estimated from the low velocity) and has characteristics resembling uncompacted soil. In the first traverse, this layer was not recognized because its velocity is lower than that of the layer above. It is believed that the surface of rupture forms in the layer of lower velocity, i.e., 720 m/sec. Using laboratory tests, Israeli (1977) found a marly chalk with very high plasticity and characteristics similar to clay in the Menuha chalk (upper member). He notes that this chalk, which is four times weaker when wet, should be treated as soil for engineering purposes. It is believed that this is the layer with the velocity of 720 m/sec described above.

As mentioned previously, landslides in the Senonian formations in the Galilee are known to have been triggered by earthquakes (Wachs and Levitte 1981). There, the surface of rupture occurs within the Kabri Marl, which is a few meters thick and has a low velocity (675 m/sec) and which is found immediately above the top of the Ka'akule member (Wachs and Levitte 1981). The situation at the Mount of Olives is similar, as indicated by the seismic velocities of the rocks. The Menuha chalk at the Mount of Olives has the same velocity as the Senonian chalk in the Galilee (1,800 m/sec). The low-velocity layer found between the Menuha chalk and the Ka'akule on the Mount of Olives has a velocity similar to that of Kabri Marl of the Galilee, and is believed to be its equivalent.

Based on the above, it is concluded that the mechanism of landslides on the Mount of Olives is similar to that of the Galilee, as described by Wachs and Levitte (1981). The landslide on the Mount of Olives is of the slump type and could well have been triggered by a seismic event.

Seismic Risk due to Landslides in Jerusalem

When the earthquakes of 1837 and 1927 occurred, Jerusalem was a small town with very few buildings located on the unstable slopes of Senonian chalk. It is conceivable that at the time people were aware of the danger in building on unstable slopes. However, in the past 15 years, as Jerusalem has grown in population and area, new neighborhoods have been built on rock formations that previously had been undeveloped. Some of these neighborhoods were constructed on unstable slopes.

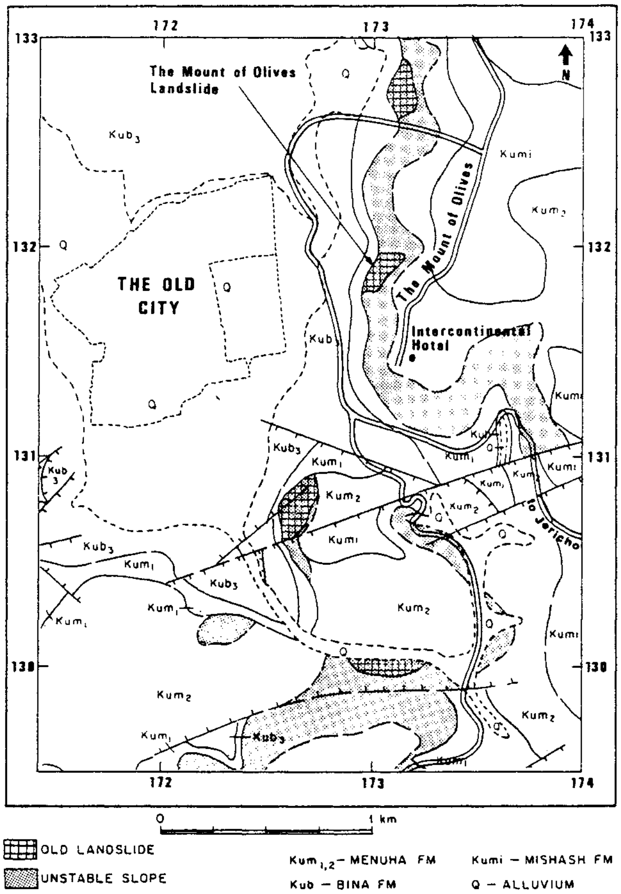

Figure 5. Slope stability map of the eastern part of Jerusalem.

Shortly after construction was completed, cracks appeared in the roads and in some of the buildings.

In order to avoid further construction on unstable slopes where the seismic risk is highest, a slope-stability map has been drawn up (Fig. 5), based on Israeli's (1977) geological map of Jerusalem. The unstable areas that were recognized from aerial photographs are marked. These areas are of the highest seismic risk and are located on slopes that are steeper than 15 degrees, just above the Ka'akule. It was found that as a result of old landslides, the Ka'akule was covered in places, indicating that the discontinuity of the Ka'akule in Israeli's map is not a facies change. The map also points out some of the more prominent old landslides in the area.

Recommendations

Steep chalk slopes are converted by landsliding into slump benches covered by thick colluvium. These are ideal horticultural sites and in the past many of the old landslides were planted with olive trees. We assume that these areas were recognized as unsuitable for housing because of the continuous downslope movement of the colluvial material. These sites should be zoned as green areas, and no buildings or roads should be constructed on them.

Leaving these sites undeveloped is an economical and logical means of preserving the quality of the environment. Green areas, which are often located on expensive property, would hence be situated on land that is, in any case, unsuitable for development, thus reducing expenses.

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