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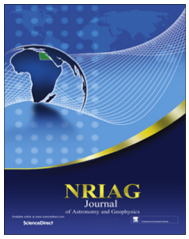

Earthquake ground motion simulation at Zoser pyramid using the stochastic method: A step toward the preservation of an ancient Egyptian heritage

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Abstract Strong ground shaking during earthquakes can greatly affect the ancient monuments and subsequently demolish the human heritage. On October 12th 1992, a moderate earthquake (Ms = 5.8) shocked the greater Cairo area causing widespread damages. Unfortunately, the focus of that earthquake is located about 14 km to the south of Zoser pyramid. After the earthquake, the Egyptian Supreme council of antiquities issued an alarm that Zoser pyramid is partially collapsed and international and national efforts are exerted to restore this important human heritage that was built about 4000 years ago. Engineering and geophysical work is thus needed for the restoration process. The definition of the strong motion parameters is one of the required studies since seismically active zone is recorded in its near vicinity. The present study adopted the stochastic method to determine the peak ground motion (acceleration, velocity and displacement) for the three largest earthquakes recorded in the Egypt's seismological history. These earthquakes are Shedwan earthquake with magnitude Ms = 6.9, Aqaba earthquake with magnitude Mw = 7.2 and Cairo (Dahshour earthquake) with magnitude Ms = 5.8. The former two major earthquakes took place few hundred kilometers away. It is logic to have the predominant effects from the epicentral location of the Cairo earthquake; however, the authors wanted to test also the long period effects of the large distance earthquakes expected from the other two earthquakes under consideration. In addition, the dynamic site response was studied using the Horizontal to vertical spectral ratio (HVSR) technique. HVSR can provide information about the fundamental frequency successfully; however, the ampli-

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fication estimation is not accepted. The result represented as either peak ground motion parameters or response spectra indicates that the effects from Cairo earthquake epicenter are the largest for all periods considered in the present study. The level of strong motion as indicated by peak ground acceleration reaches the value of 250 gals which is considerably high. At the end, it is worth to mention that the information resulted from the present work may be useful for the planned restoration decision of the Zoser pyramid site.

1. Introduction

Monumental sites are considered as a very important human heritage. In Egypt, valuable human heritages are widespread all over the Nile valley which extended back in history to thousands of years. Unfortunately, some of these monuments suffer from bad conditions under the effects of natural and manmade factors. The present area is near to relatively active earthquake area to the southwest of downtown Cairo. In that area, the most destructive event in recent history of Egypt took place in October 12th, 1992. The epicentral distance is only about 14 km. Damage report after that earthquake showed that Zoser pyramid was severely damaged, and few years later a restoration plan was inaugurated to save the pyramid from total collapse.

One of the most important decisions in carrying out proper design is to select a design earthquake that adequately represents the ground motion expected at a particular site and in particular the motion that would drive the structure to its critical response, resulting in highest damage potential. The quantification of such ground motion is not easy, it requires a good understanding of the ground parameters that characterize the severity and the damage potential of the earthquakes' ground motion and seismological, geological, and topographic factors that affect them. As a result, evaluation of the expected earthquake ground motion becomes a must for retrofitting against possible future large earthquake. Strong ground motion evaluation requires definition of both the most effecting earthquake source on the area and the dynamic site response that sometimes becomes more effective than the original ground motion.

This research is focusing on the application of stochastic method to simulate the ground motion time history during Cairo 1992 earthquake at Zoser pyramid. Accordingly, Simulation of the effective strong ground motion is conducted using the stochastic simulation method (e.g., Boore, 1983; Boore and Joyner, 1984; Boore and Atkinson, 1987; Boore et al., 1992; Atkinson and Boore, 1995; Roumelioti et al., 2000; Boore, 2003; Boore and Thompson, 2015), and the method is used due to its effective low computational efforts and short time consumption with reliable simulation results when applied to engineering applications. Determination of the site effect was used based on a previous work of the authors (Khalil and Abdel Hafiez, 2016), they determine response characterization of the site using HVSR technique (Nakamura, 1989), and the results of this work are so important in the future understanding of the area behavior during earthquakes taken into consideration the importance of this heritage area for national income.

2. Location and description of Zoser pyramid

Saqqara (Zoser) pyramid is located to the south of Cairo at a distance of about 20 km (Fig. 1). It is the first Egyptian step pyramid consisted of six Mastabas (of decreasing size) built atop one another in what were clearly revisions and developments of the original plan. The pyramid originally stood 62 m (203 ft) tall, with a base of 109 m × 125 m (358 ft × 410 ft) and was clad in polished white limestone (Fig. 2).

Despite the general belief that ancient Egyptians were skilled in selecting stable areas for their monuments, the present location is near moderately seismic active region. An active region that produced the October 12th, 1992 earthquake lies at about 14 km only. Earthquake monitor of the area shows that moderate earthquakes of magnitudes less than 5 are continuously recorded there. Considering that the area may be capable of producing earthquakes of magnitude like that of 1992 every 70 years, the pyramid may have witnessed 60 earthquakes of magnitudes around 6.0. If the proposition is true, the pyramid can be seen as a successful example of earthquake resistant structure. The damage encountered after the 1992 earthquakes might be a cumulative effect of the past earthquakes.

3. Seismicity and seismotectonics

The seismic activity in Egypt is concentrated in the northeastern part at gulfs of Aqaba and Suez, and most of the largest earthquakes were recorded there. In the gulf of Suez, the largest event took place near its entrance on 31st March 1969. The magnitude of such event was Ms = 6.9. It was the largest instrumental earthquake until 22nd November 1995, when an earthquake with magnitude Mw = 7.2 took place in the gulf of Aqaba. Numerous microearthquakes are recorded at both gulfs each year. In addition to these seismic sources, several other sources of low to moderate activities are observed. The border between the stable and unstable shelfs of Egypt exhibits earthquake activity of low to moderate sizes; geographically, this zone is known as Cairo-Suez district. East Beni Suef zone was discovered after the operation of the Egyptian National Seismological Network. This zone lies to the south of the Cairo Suez district zone.

In addition, other earthquake activities are observed at east Cairo, Abu Rawwash and Dahshour areas. Dahshour seismic zone constitutes the epicenter of the 12th October 1992 Cairo earthquake, and other seismic activity area produced earthquakes with magnitudes seldom reaching a magnitude of 5. However, due to their proximity from the dense population

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