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RESEARCH ARTICLE

Looking into the quite unexpected and catastrophic Morocco Earthquake: time for resilience

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Abstract

There was a significant seismic event (MW 6.8) that occurred in Morocco during the evening of Friday, September 8, 2023. It resulted in the loss of numerous lives, injuries to a substantial number of individuals, and severe destruction to rural communities near the southern metropolis of Marrakesh. This earthquake is regarded as one of the most lethal in the nation's recent history. The earthquake was quite shallow at a depth of 19 km. According to Moroccan state television, the interior ministry reported that the number of fatalities has risen to 2,946, primarily concentrated in the hilly Al Haouz region. Additionally, there have been 5,674 reported cases of injuries. This concise work reports the seismicity as well as tectonic settings of the region. Apart from this, the attributes of damage are also briefly overviewed along with final comments on disaster resilience.

Keywords: Seismicity; damage; depth; fatalities; causative fault

1. Introduction

At approximately 11:11 p.m. on September 8, 2023, a seismic event of considerable size, measuring at least M_W 6.8 on the Richter scale, occurred in the rural vicinity adjacent to Marrakesh, resulting in significant and destructive consequences. The seismic event resulted in the complete destruction of residential structures in various communities situated in the High Atlas Mountains. Additionally, it caused severe damage to road infrastructure and induced significant vibrations in the historical edifices of Marrakesh, leading to the evacuation of local inhabitants who sought refuge in public spaces.

The construction of residences in the area frequently involved the utilization of delicate mud-brick structures that exhibited a deficiency in robust foundational support. Despite the efforts made by the authorities to enhance earthquake resilience, including the implementation of stricter construction rules, a significant number of Moroccan citizens continue to reside in vulnerable structures.

According to the United States Geological Survey, the tremors were perceptible in Spain and Portugal, spanning over 550 miles. Following the first seismic event, intermittent aftershocks have been observed in the vicinity, with a notable 4.9-magnitude tremor occurring approximately 20 minutes after the initial earthquake.

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The anticipated increase in the number of fatalities is attributed to the challenges faced by rescue crews, who have difficulties in accessing the various impacted regions due to the presence of rugged topography and obstructed roadways filled with debris. The catastrophic event under discussion is the most fatal seismic activity in Morocco since a 5.9-magnitude earthquake in 1960 caused extensive destruction to the coastal city of Agadir, located around 150 miles southwest of Marrakesh. This earlier earthquake resulted in a minimum death toll of 12,000 individuals and rendered others without shelter. [1-2]. Considering the significance, this short communication delves into the seismicity as well as tectonic settings of the region. Additionally, an attempt has been made to inspect the attributes of damage while advocating disaster resilience at the same time.

2. Seismicity of Morocco

Morocco is in a seismically active region known as the Mediterranean seismic belt, which extends from southern Europe to North Africa. This region is characterized by the interaction of the African and Eurasian tectonic plates, leading to frequent seismic activity. While Morocco is not as seismically active as some other countries in the Mediterranean region, it does experience earthquakes from time to time.

The most seismically active areas in Morocco are typically in the northern and western parts of the country, including the Rif Mountains and the Atlas Mountains. These areas are situated along major fault lines where tectonic forces are actively deforming the Earth's crust. Some notable earthquakes in Morocco's history include:

a. Agadir Earthquake (1960): This devastating earthquake had a magnitude of 5.7 and resulted in the near-total destruction of the city of Agadir, with significant loss of life.

b. Al Hoceima Earthquake (2004): This earthquake had a magnitude of 6.3 and struck near the town of Al Hoceima in northern Morocco. It caused significant damage and casualties.

c. Nador Earthquake (2016): This earthquake had a magnitude of 6.3 and occurred near the town of Nador in northeastern Morocco, close to the border with Algeria. It caused damage to buildings and infrastructure in the region.

Morocco has taken steps to improve its earthquake preparedness and building codes to mitigate the impact of future seismic events. The country is also part of regional and international efforts to monitor and respond to seismic activity in the Mediterranean region. It's important for residents and visitors in Morocco to be aware of the potential for earthquakes and to be prepared by following safety guidelines and building regulations designed to reduce the risk of earthquake-related damage and injuries [1-4].

3. Tectonic settings of Morocco and mediterranean region in large

Morocco's tectonic setting is complex and is primarily influenced by the convergence of several major tectonic plates. The country is situated at the junction of the African Plate, Eurasian Plate, and the smaller Alboran Plate. This complex plate boundary interaction results in various geological features and seismic activity in the region. Here are the key tectonic elements in Morocco:

African Plate: The majority of Morocco lies on the African Plate, which is a large tectonic plate that includes the African continent. The African Plate is moving northward and is converging with the Eurasian Plate.

Eurasian Plate: The northern part of Morocco, including the Rif Mountains and the northern coast, is in contact with the Eurasian Plate. The convergence of the African and Eurasian Plates is responsible for the formation of the Atlas Mountains.

Alboran Plate: The Alboran Plate is a smaller tectonic plate located in the western Mediterranean Sea. It is subducting beneath the African Plate in the Alboran Sea, which is located to the north of Morocco and southern Spain. This subduction process is related to the seismic activity in the region.

Atlas Mountains: The Atlas Mountains, which run through Morocco, are the result of the convergence and collision of the African and Eurasian Plates. This tectonic interaction has led to the uplift of these mountains.

Rif Mountains: The Rif Mountains in northern Morocco is also formed due to the convergence of the African and Eurasian Plates. They are part of the larger Alpine Mountain range system.

Rift Valleys: In addition to mountain building, the tectonic forces in Morocco have created rift valleys. The most notable is the Middle Atlas Rift in central Morocco, which is associated with extensional tectonics.

Seismic Activity: The interaction of these plates and the complex tectonic boundaries in Morocco make the region seismically active. Earthquakes are relatively common, particularly in the northern and western parts of the country.

Overall, Morocco's tectonic setting is a dynamic one, with ongoing geological processes shaping the landscape and leading to seismic events. The Atlas Mountains, which dominate the country's interior, are a testament to the tectonic forces that have been at work in the region for millions of years. The seismic activity in the Mediterranean region can be attributed to the ongoing northward convergence of the African plate relative to the Eurasian plate along a complex plate boundary. This convergence is estimated to occur at a rate of 4-10 mm per year. The process of convergence commenced some 50 million years ago and was linked to the gradual closure of the Tethys Sea. The Mediterranean Sea can be regarded as the contemporary remains of the Tethys Sea. The Mediterranean region exhibits the most pronounced levels of seismic activity in specific areas, namely the Hellenic subduction zone located in southern Greece, the North Anatolian Fault Zone situated in western Turkey, and the Calabrian subduction zone found in southern Italy. The Hellenic subduction zone exhibits notable levels of convergence, with a local high rate of 35mm per year. This convergence is linked to the occurrence of back-arc spreading in the regions of Greece and western Turkey, which are situated above the subducting Mediterranean oceanic crust. The presence of crustal normal faulting in this area can be attributed to extensional tectonic processes that are linked to back-arc spreading. The Marmara Sea regiois situated as a transitional area between the extensional regime located to the west and the strike-slip regime associated with the North Anatolian Fault Zone situated to the east. The North Anatolian Fault plays a significant role in facilitating the right-lateral horizontal movement (23-24 mm/yr) between the Anatolian micro-plate and Eurasian plate. This movement is primarily driven by the westward push exerted on the Anatolian micro-plate, which aims to facilitate the closure of the Mediterranean basin. The closure of the Mediterranean basin is a consequence of the collision between the African and Arabian plates, particularly in the southeastern region of Turkey. The process of subduction, whereby the Mediterranean Sea floor is forced beneath the Tyrrhenian Sea, occurs at the Calabrian subduction zone and gives rise to a notable region of seismic activity in the vicinity of Sicily and southern Italy. Active volcanoes can be found in the Cyclades of the Aegean Sea and in southern Italy, specifically above moderate depth earthquakes.

The Mediterranean region possesses an extensive written record spanning many centuries that documents seismic activity prior to the advent of modern instrumentation, specifically before the 20th century. Throughout history, seismic events have resulted in extensive destruction in several regions, including central and southern Greece, Cyprus, Sicily, Crete, the Nile Delta, Northern Libya, the Atlas Mountains of North Africa, and the Iberian Peninsula. The seismic events that occurred in 1903 and 1926, known as the Kythera and Rhodes earthquakes respectively, hold the distinction of being the most significant Mediterranean earthquakes ever recorded using instrumental methods. These seismic events are closely linked to the tectonic processes associated with subduction zones. From 1939 to 1999, a sequence of highly destructive strike-slip earthquakes with a magnitude of M7+ occurred in a westward manner along the North Anatolian Fault Zone. This seismic activity commenced with the 1939 Erzincan earthquake, which had a magnitude of M7.8, and took place at the eastern extremity of the North Anatolian Fault system. The seismic event that occurred in 1999, known as the Izmit earthquake with a magnitude of 7.6, impacted the westernmost section of the fault line. That earthquake had a devastating impact on an urban region in Turkey that was characterized by high population density and extensive industrialization, resulting in a tragic loss of over 17,000 lives. Despite the relatively low seismicity rates observed around the northern frontier of the African continent, there have been documented instances of significant and devastating earthquakes occurring from Morocco in the western Mediterranean to the Dead Sea in the eastern Mediterranean. The El Asnam earthquake of 1980, with a magnitude of 7.3, stands out as one of the most significant and devastating seismic events to occur in Africa during the 20th century.

Significant and destructive tsunamis have been observed to occur because of large-scale seismic events in the Mediterranean region. The Lisbon earthquake of November 1, 1755, is one of the notable seismic events in the region. Its magnitude, as determined by non-instrumental data, is estimated to be approximately 8.0. The occurrence of the 1755 Lisbon earthquake is believed to have taken place either within or near the Azores-Gibraltar transform fault. This fault delineates the boundary separating the African and Eurasian tectonic plates, situated off the western coast of Morocco and Portugal. The seismic event is noteworthy due to its significant loss of life, estimated at around 60,000 individuals, as well as its production of a tsunami that affected the Portuguese coastline, leading to the submergence of coastal communities and the city of Lisbon. In 1693, a seismic event with an estimated magnitude of 8.0 occurred near Sicily, resulting in the generation of a substantial tsunami wave. This powerful wave inflicted significant damage upon multiple towns situated along the eastern coast of Sicily, leading to their destruction. The M7.2 earthquake that occurred on December 28, 1908, in Messina is often regarded as the most fatal European earthquake on record. The convergence of intense ground shaking and a localized tsunami resulted in an approximate range of 60,000 to 120,000 fatalities.

4. The recent earthquake

The earthquake that took place on September 8, 2023, near Oukaïmedene, Morocco, with a magnitude of 6.8, was the result of oblique-reverse faulting at a shallow depth within the Moroccan High Atlas Mountain range **Figure.1.** This location is approximately 75 km southwest of Marrakech. The focal mechanism solutions suggest that the event was caused by the rupture of either a steeply dipping oblique-reverse fault oriented towards the northwest, or a shallow dipping oblique-reverse fault oriented towards the east. The High Atlas Mountains are characterized by a diverse array of mapped strike-slip and thrust faults, exhibiting predominant trends in the east-west and northeast-southwest directions. The seismic event took place within the Africa Plate, situated approximately 550 km to the south of the plate boundary between the Africa and Eurasia plates. The African plate exhibits a relative west-southwestward movement of roughly 3.6 mm/year with respect to the Eurasia plate at the epicenter of this seismic event.

Although earthquakes of this magnitude are sometimes represented as spots on maps, it is more accurate to characterize them as displacement occurring along a broader fault zone. Typically, reverse faulting events, such as the Morocco earthquake that occurred on September 8, 2023, have dimensions of approximately 30 km in length and 20 km in width. Earthquakes of this magnitude within the vicinity are infrequent yet within the realm of predictability. Since the year 1900, a total of nine earthquakes with a magnitude of 5 or greater have occurred within a 500-kilometer radius of the event under consideration. However, none of these earthquakes have exceeded a magnitude of 6. Most of these occurrences have taken place in the eastern region subsequent to the seismic event that transpired on September 8, 2023.

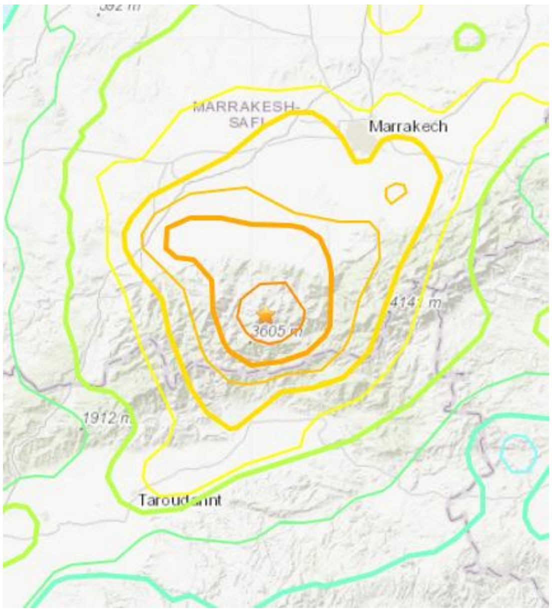

Figure 1. The Morocoo Event as shown by the star symbol [courtesy USGS]

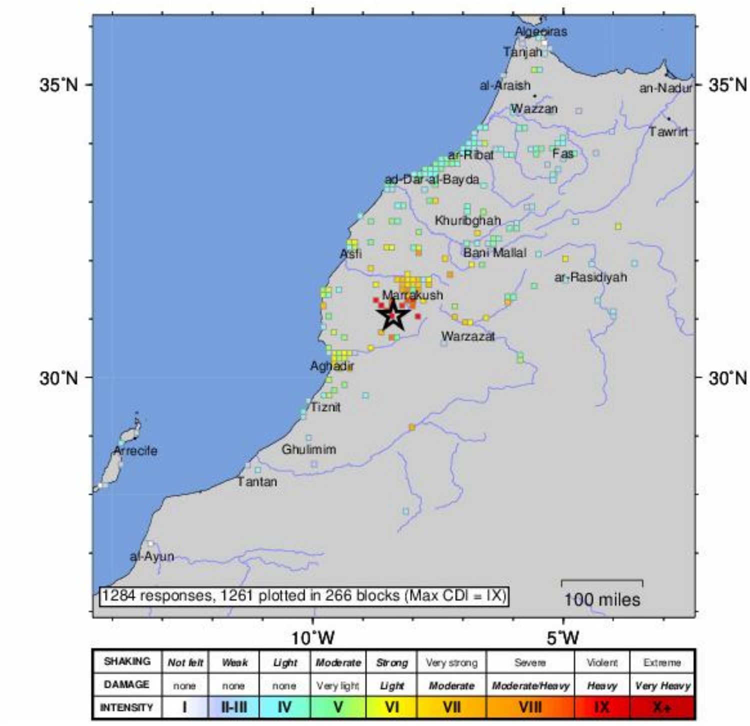

Figure 2. The Intensity map related to the Morocco Event [courtesy USGS].

5. Damage attributes

The seismic activity in Northern Africa might be described as modest. Tremors are a geological phenomenon that can be attributed to the persistent convergence of the African and Eurasian tectonic plates. The collision accounts for the seismic activity observed in the region spanning from Turkey to Gibraltar. The geological impact of the collision has resulted in the upward displacement of rock, hence giving rise to the formation of the Atlas Mountains in the vicinity of the seismic event that occurred on Friday. The incident in question is characterized by its intricate nature and antiquity. The specific cause of this earthquake has yet to be determined. The epicenter of the earthquake was in proximity to a fault that was accountable for a seismic event in Agadir in 1960, thus indicating its likely involvement in the current occurrence.

Due to the region's moderate level of seismic activity, occurrences of significantly large earthquakes are infrequent, transpiring at intervals spanning many centuries. The available seismological records are insufficient to determine the maximum magnitude of earthquakes in this region. Evaluating the maximum magnitude is a significant challenge, particularly in locations characterized by moderate seismic activity, due to the limited duration of our observations.

An additional complexity arises from the characteristics of the plate boundary. There exists a network of faults in a somewhat broader region in northern Africa. Rather than being confined to a specific geographical location characterized by a heightened likelihood of seismic activity, a vast expanse has a comparatively lower nevertheless noteworthy susceptibility to earthquakes.

The seismic event exhibited significant intensity due to the substantial accumulation of energy between fault lines located along the southern boundary of the High Atlas range **Figure.2**.

As we know, it is not earthquakes themselves that cause fatalities, but rather the collapse of infrastructure. The impact of this event was profound due to the lack of preparedness among individuals. Morocco is unfortunately deficient in terms of earthquake prevention measures and early warning systems. If communities are not well prepared, even earthquakes of moderate magnitude might result in fatalities.

Prior to the seismic event that occurred on 8 September, there existed a basis for asserting the potential occurrence of significant seismic activity in Morocco. In a study conducted in 2007, which documented a total of 1,739 significant earthquakes in the country between the years 1045 and 2005 [1]. These earthquakes were classified as major, with a magnitude greater than 3, and excluded aftershocks from the analysis. The study mostly relied on historical descriptions as a source of information. Most structures in the impacted region were constructed using masonry and aggregate materials, which are susceptible to collapse. Implementing measures to reinforce structures with stronger materials such reinforced concrete could potentially be beneficial. However, it is important to consider the practicality of such measures in a given area, which is characterized by significant levels of poverty.

The architectural design of buildings in Morocco frequently prioritizes the management of temperature extremes, which provide a constant threat. In contrast, considerations for seismic resistance have received less attention, partly due to their infrequency. Nevertheless, in certain geographical areas, conventional construction materials like masonry or adobe have been effectively modified to exhibit earthquake-resistant properties [1-4].

6. Disaster resilience and prevention: way forward

Disaster resilience and prevention are critical aspects of mitigating the impact of earthquakes like the recent one in Morocco. The following points can be taken into consideration.

1. **Early Warning Systems**: Establishing robust early warning systems is crucial in earthquake-prone regions like Morocco. These systems can provide advance notice, allowing people to take necessary precautions and evacuate if necessary.
2. **Building Standards**: Ensuring that buildings and infrastructure are constructed to withstand seismic activity is paramount. Adhering to earthquake-resistant construction codes can significantly reduce casualties and damage during an earthquake.
3. **Education and Awareness**: Public education campaigns can help raise awareness about earthquake preparedness and response strategies. The population should know what to do during an earthquake, including how to "Drop, Cover, and Hold On" and how to evacuate safely if required.
4. **Community Resilience**: Building resilient communities involves fostering self-sufficiency and cooperation among residents. Communities, that are well-prepared, can support each other during disasters are more likely to recover quickly.
5. **Infrastructure Resilience**: Critical infrastructure such as hospitals, emergency services, and utilities should be designed with redundancy and disaster resilience in mind. This ensures that essential services can continue to function during and after an earthquake.
6. **Government Preparedness**: Governments play a crucial role in disaster prevention and response. They should invest in disaster management agencies, allocate resources for preparedness, and develop comprehensive disaster management plans.
7. **International Cooperation**: Earthquakes often transcend national boundaries. As such, international cooperation is essential for sharing knowledge, resources, and expertise. Morocco can collaborate with neighboring countries and international organizations to enhance earthquake preparedness.

In conclusion, disaster resilience and prevention are integral components of minimizing the impact of earthquakes in Morocco and around the world. Through a combination of early warning systems, building standards, public education, community resilience, infrastructure planning, government preparedness, and international cooperation, Morocco can better prepare itself to withstand and recover from seismic events—thereby reducing the loss of life and property damage. A crucial aspect in enhancing the earthquake resilience of structures involves engaging in dialogue with local communities. The reason is they possess a comprehensive understanding of architectural principles and are knowledgeable about the most suitable designs that cater to their specific requirements. It is imperative to include earthquake resilience as an integral component of sustainable development. Considering the decade deadliest earthquake Türkiye and this recent earthquake of Morocco, it is high time to look at early preparedness and stringent measures to incorporate seismic resilience in existing as well as upcoming buildings [5].

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Conflict of Interest

The author declares no conflict of interest.

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