Assessment of Tsunami Damage to Buildings in Resilient Byblos City and Uncertainty Considerations

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ABSTRACT: Byblos is a UNESCO World Heritage Site due to its resilience quality, as it is one of the oldest continuously inhabited cities in the world. It thrived for over 7000 years, mitigating shocks and stresses and still adapting and growing. Byblos is prone to seismic and tsunami risks. The latter can be generated by the Mount Lebanon Thrust fault about 18 km far in the Mediterranean Sea, facing the major Lebanese coastal cities. The 9 July 551 earthquake generated by this fault of 7.5 magnitude was followed by a tsunami which caused the coastal cities to lose their strategic, cultural, and commercial roles for centuries. This paper identifies the tsunami hazard and scenarios for Byblos, then studies and assesses the tsunami damage to Byblos buildings by means of likely tsunami scenarios. The article discusses the need to embed the uncertainties modeling in the hazard and damage analysis. Finally, results are presented, and recommendations are offered for future developments.

The city of Byblos lies on the Lebanese coasts only 40 km north of the capital Beirut. The area of Byblos is 5 km2 extending to the metropolitan of 17 km2, with a population of nearly 40,000. Byblos is 8000 years old, a UNESCO World Heritage Site, as one of the oldest continuously inhabited cities in the world. Thus, it was designated by the Rockefeller Foundation in 2014 among the 100 Resilient Cities. The city of Byblos outlived and flourished, facing 6,000 years of shocks and stresses, offering a rich resilience study. Nowadays, the city combines traditional heritage and modern sophistication (N. Makhoul et al., 2016).

Byblos chose for the 100 Resilient Cities Project in 2016. The pillars are: 1) a connected city, 2) a resource-efficient city, 3) a peaceful city, 4) a cultural city, and 5) a thriving city (Nisrine Makhoul et al., 2022). Those pillars mainly target daily stresses. However, among Byblos major threats is earthquakes and tsunami.

Lebanon is a seismic region, and enhancing its earthquake resilience is crucial. The country is known for its complex weaved fault system, the Lebanese Restraining Bend (LRB) (Walley, 1988). Among its major active faults, which generate earthquakes of magnitude larger than 7, Seghraya (SF), Yammouneh (YF), and the Mount

Lebanon Thrust (MLT), which is at sea, thus capable of generating tsunamis as well. The other relatively minor faults, Roum (RF) and Rachaya (RaF), can generate earthquakes of magnitude between 6 and 6.5. Lebanon seismicity is meticulously described in (Elnashai & El-Khoury, 2004) and (N. Makhoul et al., 2016).

Due to its history and diverse building typologies, the authors selected, in 2012, Byblos as a prototype for exploration. Numerous studies on Byblos earthquake loss estimations were accomplished ((N. Makhoul et al., 2016), (Nisrine Makhoul et al., 2020), (Nisrine Makhoul et al., 2022), (Nisrine Makhoul et al., 2018), (Nisrine Makhoul & Mikhael, 2016), (Nisrine Makhoul, 2018)). Afterward, a campaign for ambient noise measurement was achieved to study the dynamic characteristics Byblos building ((Nisrine Makhoul & Harb, 2017), (Nisrine Makhoul & Gueguen, 2022)), and the Fidar bridge was investigated ((Nisrine Makhoul, 2014), (Nisrine Makhoul, 2019), (Nisrine Makhoul, 2013), (Nisrine Makhoul & Gueguen, 2023)). Finally, geophysical experiments took place in the city to conduct seismic characterization of the Byblos site and assess site effects and microzonation (Abou-Jaoude et al., 2020).

In this article, we aim to present a preliminary study of the tsunami damage to Byblos buildings and discuss the necessity to include uncertainty considerations in tsunami models and platforms.

Section 1 presents the methodology for tsunami damage assessment. Section 2 the Byblos tsunami model and results. Section 3 discusses uncertainty considerations in tsunami models at the city level and future needs. Finally, Section 4 concludes.

1. METHODOLOGY

The tsunami damage assessment method comprises four main modules: 1) the tsunami hazard presented in the form of scenario herein the wave height; 2) the inventory which contains the topologies and characteristics of the elements at risk; 3) the vulnerability were fragility functions are utilized for typologies of the elements at risk and 4) the tsunami damage estimations obtained by simulating various hazard scenarios which incorporates the preceding modules. Those modules are presented in Table 1.

In this paper, the tsunami building damage in Byblos is modeled using the INCORE platform (INCORE, 2020).

It links the cause and effects of catastrophic events using consequence-based risk management (CRM). It helps, thus, suggesting several mitigation alternatives and permits the decision-makers to advance risk reduction strategies and recovery plans.

Table 1: Main modules of the tsunami damage estimation methodology

Main Modules	Methods and content
Tsunami hazards	Tsunami hazard scenarios, herein in terms of wave height
Inventory	Inventory/typology for the building attributes, occupant, and monetary
Vulnerability	Fragility curve dataset
	Fragility mapping dataset
	Match fragilities to different inventory types based on attributes
Damage estimations	Running several scenarios based on the steps above successively

2. BYBLOS TSUNAMI MODEL AND RESULTS

For the Byblos case study, the following steps methods were done to assess the preliminary tsunami damage:

2.1.1. Tsunami hazards

Several studies exist on tsunamis in the Eastern Mediterranean sea ((Meral Ozel et al., 2011), (Yolsal et al., 2007) and (Hamouda, 2010)). However, few detailed the Levantine Segment.

(Meral Ozel et al., 2011)) studied the Tsunami hazard in the Eastern Mediterranean, its connected seas, and its influence.

(Yolsal et al., 2007) investigated potential tsunami source regions and tsunami-prone mechanisms in the Eastern Mediterranean. They considered the three possible tsunami source areas: 1) between Rhodes and SW of Turkey, 2) the Crete earthquake, 3) the Paphos earthquake of M= 7.5, and the tsunami of 11 May 1222.

(Meral Ozel et al., 2011) explored the effects of tsunami scenarios along the Egypt Mediterranean coast. For the Levantine Segment scenario, the Egyptian coast's wave height varied between 0.4 to 1.4. Thus, the wave height of the Lebanese coast must have been higher. Moreover, for this scenario of A.D. 551 earthquake of a moment magnitude, Mw of 7.5 (Elias et al., 2007), they considered that it was generated by Beirut thrust scenarios where only a small part of the fault stretched into the sea. This was common knowledge until, lately, the Mont Lebanon Trust fault was discovered at sea by SHALIMAR (Briais et al., 2004). Due to her greater length along Lebanon, it might have generated higher waves.

(Davies et al., 2018), developed based on earthquake sources, a global probabilistic tsunami hazard assessment, where the tsunami wave heights in Lebanon can reach 10 meters. This article considers two scenarios: 2.5m and 5m heights. Figure 1 shows the Byblos Tsunami hazard scenario for a 2.5 m wave height.

2.1.2. Inventory

The inventory for Byblos data was gathered through a field mission, and each building was surveyed to gather its typology, number of stories, occupancy, etc.

2.1.3. Vulnerability

The fragility functions offered by (Suppasri et al., 2013) were used, and the structure types for Byblos buildings were mapped to the fragilities. Figure 2 shows Byblos buildings' typologies.

2.1.4. Damage estimations

The damage analysis was executed for the two chosen scenarios of wave heights of 2.5m and 5m.

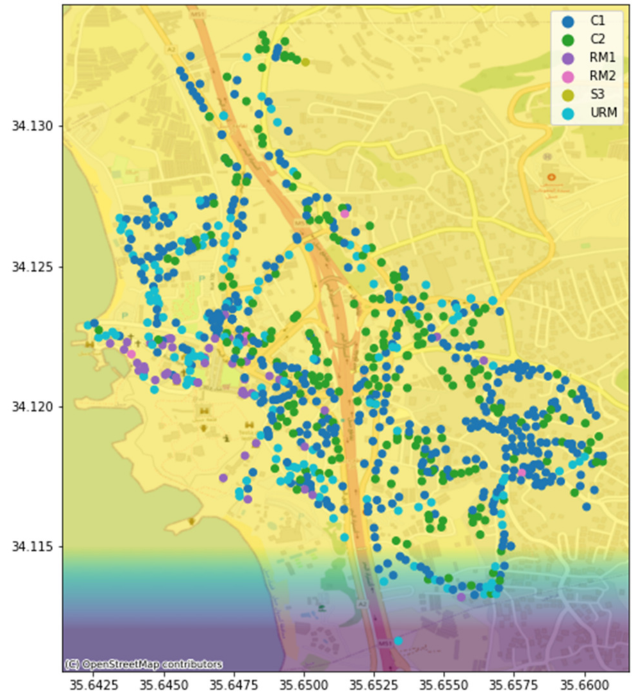

Figure 1: The Byblos Tsunami hazard scenario for 2.5 m wave height.

Figures 3 and 4 show the building damage for scenario 2.5 m and 5m wave height, respectively. The yellow color indicates the highest damage probability, and the blue is the lowest building damage probability.

Figure 5 and 6 shows the buildings’ complete damage distribution for the 2.5 m and 5 m wave height scenario, respectively. For the 2.5 m wave height scenario, around 220 buildings have 0.13% damage probability, 420 buildings have 0.2% damage probability, and 150 buildings have 0.48% damage probability. For the 2.5 m wave height scenario, around 220 buildings have 0.42% damage probability, 420 buildings have 0.5% damage probability, and 150 buildings have 0.88% damage probability.

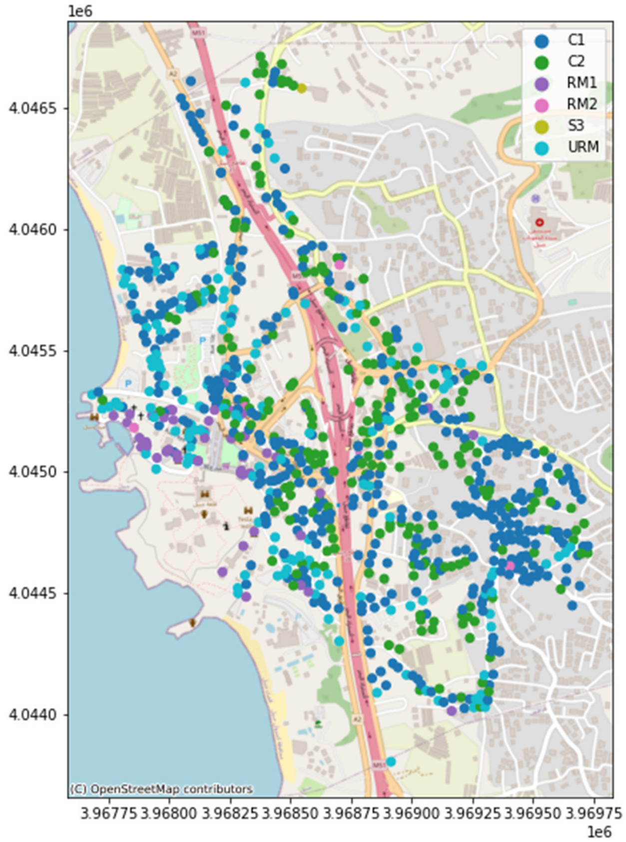

Figure 2: The typologies of Byblos buildings

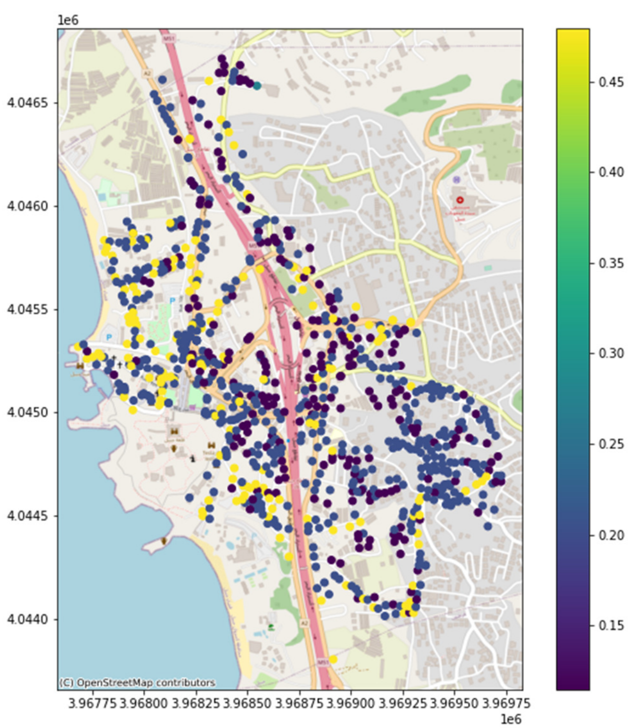

Figure 3: The building damage for the 2.5 m wave height scenario.

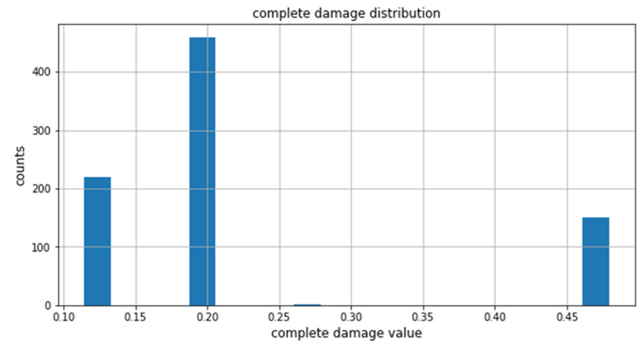

Figure 4: The buildings' complete damage distribution for the 2.5 m wave height scenario.

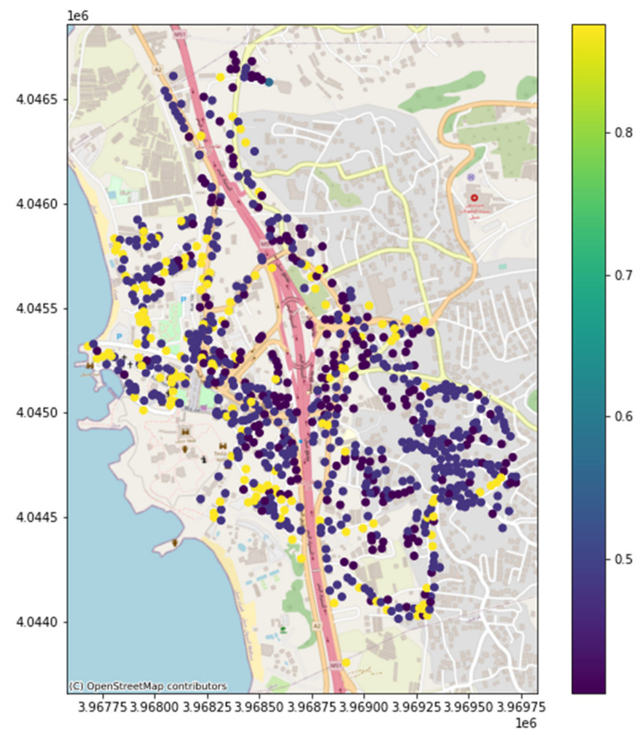

Figure 5: The building damage for the 5 m wave height scenario.

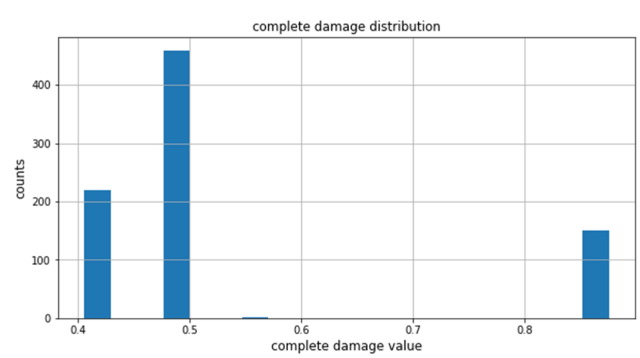

Figure 6: The buildings' complete damage distribution for the 5 m wave height scenario.

3. UNCERTAINTY CONSIDERATIONS IN TSUNAMI MODELS AT CITY LEVEL

This article offers a preliminary study of Byblos tsunami building damage. However, a more detailed analysis needs to be done considering the momentum flux, wave height, and inundation depth. Then a study of earthquake and tsunami combined damage can be done. Moreover, uncertainty considerations need to be accounted for in the model.

Tsunami loss assessment analysis has attracted attention lately, and a significant amount of studies have dealt recently with uncertainties related to tsunami hazards.

(F. Løvholt et al., 2019) discussed global trends in understanding and advancing tsunami science, especially hazard, and risk. They noted that probabilistic tsunami hazard analysis (PTHA) methods have surfaced since 2004, such as (Burbidge et al., 2008) and (Horspool et al., 2014).

Most of the studies on tsunami uncertainties were related to tsunami hazards such as ((Guillas et al., 2018), (Davies et al., 2018), (Gibbons et al., 2020), (Giles et al., 2021), (Basili et al., 2021), (Basili et al., 2021), (Selva et al., 2016), (Melgar et al., 2019), (Zengaffinen - Morris et al., 2022), (Sarri et al., 2012), (Molinari et al., 2016), (Goda et al., 2020), (Behrens & Dias, 2015), (Annaka et al., 2007), (Parsons & Geist, 2008), (Power et al., 2013), (Mueller et al., 2021) (Fukutani et al., 2015), (Ohno et al., 2022)), and (Zhang et al., 2020). Some used the Bayesian method for probabilistic tsunami hazard assessment (Grezio et al., 2010).

Human immediate tsunami response capability was discussed by (Post et al., 2009). Probabilistic early warning tsunami forecasting was debated by (Selva et al., 2021), and urgent tsunami computing was offered by (Lovholt et al., 2019). Tsunami evacuation approaches were proposed by (Muhammad et al., 2021), and landslide tsunami and hazard considering uncertainties were investigated by (Finn Løvholt et al., 2020).

Fragilities functions were also offered, such as in (FEMA, 2020) and (Suppasri et al., 2013). And a complete modeling for tsunami risk mapping and damage analysis with consideration of uncertainties is offered by (Yamazaki et al., 2011).

Some interesting platforms for tsunami modeling and resilience considerations exist, such as Hazus, Ergo, and INCORE (Nisrine Makhoul & Argyroudis, 2019). However, until now, no unique platform is available to consider tsunami modeling with considerations for uncertainties in all its parts (i.e., tsunami hazards, inventory, vulnerability, damage estimations) as well as losses and community resilience and metrics. More effort, work, and considerations are recommended for involving further probabilistic modeling and uncertainties considerations in such promising platforms.

4. CONCLUSIONS

This article presents a preliminary study of the tsunami damage to Byblos buildings and discusses the necessity to include uncertainty considerations in tsunami models and platforms. This study showed that most Byblos buildings would suffer complete damage with different probabilities for 2.5 m and 5 m wave height scenarios. Finally, the article identified a significant amount of research work considering uncertainties in the tsunami hazard; however, lesser in the damage modeling. Thus, more effort is needed to include more probabilistic and uncertainties considerations in tsunami models and platforms.

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