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Original Research Articles

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Original Research Article

Emerging trends in sustainable design: Integrating museums for a resilient future

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ABSTRACT: The paper unfolds the intricate tapestry of sustainable design, weaving in the pivotal role of renewable energy systems and astutely tying it to the eco-conscious blueprint of modern museums. The introduction sheds light on the potent impact of sustainable design in mitigating environmental hurdles and fostering a greener, more sustainable future, with a nuanced nod towards sustainability in museum management and design. Motivated by an aspiration to traverse diverse viewpoints and methodologies in sustainable design, the research stretches across numerous sectors—encompassing construction, architecture, engineering, manufacturing, software development, and notably, museum design—intending to carve out energy-sparing and ecologically mindful solutions. This paper underscores the imperative of astute design practices that optimize structures, such as museums, to maximize the utilization of renewable energy resources like solar arrays, wind turbines, and geothermal systems. It advocates for a burgeoning need to escalate the horizon of sustainable design beyond singular buildings, intertwining standalone energy systems at multiple tiers—from community power grids to expansive urban networks—ensuring a streamlined energy distribution and curbing waste. Wading through the literature review, an exploration of varied sustainable design strategies unfolds, encompassing facets like supply chain management, product safety, architectural design, manufacturing, food packaging, transportation, and pedagogy, with a specific lens on embedding sustainability in museum infrastructure and operations. The culmination of the paper discerns ten cardinal trends in sustainable design, spanning from the integration of renewable energy systems to the infusion of sustainable education and positive psychological interventions in educational institutions, thereby spotlighting the metamorphosing terrain of sustainable design across an array of disciplines.

KEYWORDS: sustainable design; renewable energy systems; smart design; energy efficiency; museum sustainability; environmental mindfulness

1. Introduction

In recent years, there has been a growing consensus on the importance of sustainability in various sectors, including the museum field. As global environmental and socio-cultural challenges intensify, museums, traditionally seen as repositories of culture and heritage, are now being re-envisioned as platforms for sustainability and change. The connection between museums and sustainability is not merely about making institutions environmentally friendly or energy-efficient but encompasses a broader perspective on how these institutions interact with and contribute to society.

Several researchers have ventured into this domain, each shedding light on different facets of the museum-sustainability nexus. Kristinsdóttir[1] probes into the realm of sustainable museum education, underscoring the necessity of supportive frameworks and the empowerment of educators, thereby confronting the prevalent challenges and uncertainties in this realm. Pop and Borza[2] elaborate on the intricacies of how a sustainable museum can induce sustainable regional development. Their subsequent research[3] dives deeper, seeking to understand the myriad factors that influence museum sustainability and proposing a model for gauging sustainability levels across museums.

Furthermore, King and Lord[4] provide a holistic overview of museum planning, underscoring the significance of sustainable spaces, facilities, and operations. Besterman[5] introduces a thought-provoking discourse on cultural equity in sustainable museums, advocating for Western museums to recognize and rectify their cultural footprints. Kampasakali et al.[6] further the narrative by investigating sustainable conservation practices, focusing on contemporary art and design object maintenance.

Merriman's[7] stance delves into the harmonization of social and economic sustainability in museums, while Brown et al.[8] share insights on community-oriented sustainable museums. Alcaraz et al.[9] emphasize service-centricity in non-profit museums as a pathway to sustainable practice. Lastly, Link[10] offers an insightful historical perspective on the evolution of the sustainability concept within the museum sphere.

This burgeoning interest and diversified research clearly emphasize the multifaceted nature of sustainability in the museum domain. However, while a vast body of work exists, there still remains a palpable gap in understanding how these individual components synergize to shape a truly sustainable museum of the future. Motivated by this backdrop, our study aims to holistically analyze these individual facets, offering a cohesive understanding of sustainable museum practices and their broader implications. The background of the research revolves around sustainable design, with a specific focus on renewable energy systems. Sustainable design and construction play a crucial role in addressing environmental challenges and promoting a more sustainable future. Renewable energy systems are an essential component of sustainable design, as they offer a clean and renewable source of energy that can significantly reduce carbon emissions and dependence on fossil fuels[11,12].

The motivation behind this research stems from the growing recognition of the importance of sustainable design in mitigating the impacts of climate change and promoting energy efficiency. With the increasing global demand for energy and the urgency to transition to renewable sources, there is a need for innovative and effective design solutions that integrate renewable energy systems in buildings and infrastructure[13,14].

Smart design practices are vital for creating sustainable buildings with renewable energy systems. These practices involve optimizing the design of buildings to take full advantage of renewable energy sources like solar panels, wind turbines, and geothermal systems. By incorporating renewable energy systems into the design process, buildings can generate their own energy, reduce reliance on the grid, and contribute to a more sustainable energy future[15,16].

However, the scope of sustainable design in energy systems needs to be expanded beyond individual buildings. It is crucial to integrate standalone energy systems through multi-scale optimization, considering the interconnectedness of energy consumption and production at various levels, such as community grids and urban networks. This holistic approach to sustainable design ensures efficient energy distribution and minimizes waste[16,17].

Moreover, the implementation of sustainable design theory in business practices is also a significant aspect of this research. Companies need to embrace sustainable design principles, especially in product service system design literature. By adopting sustainable design practices, businesses can create products and services that are environmentally friendly, resource-efficient, and socially responsible[12,13].

The Karlskrona manifesto is an important resource that outlines key issues, goals, values, and principles of sustainable design for software-intensive systems. This manifesto provides guidance for integrating sustainability principles into the design and development of software and digital products, considering their significant environmental and energy impacts.

In summary, the research background and motivation revolve around the importance of sustainable design, particularly in the context of renewable energy systems. The research aims to explore various perspectives and approaches to sustainable design in different fields, including construction, architecture, engineering, manufacturing, and software development, with a focus on creating energy-efficient and environmentally conscious solutions. Through this research, we aim to contribute to the advancement of sustainable design practices and address the urgent need for a more sustainable and resilient future[12–14].

2. Literature review

The concept of sustainability within the museum sector has attracted considerable academic attention over the past few decades, with a diverse range of studies exploring various facets of this intricate nexus.

1) Educational Approaches: Kristinsdóttir[1] highlights the growing need for sustainable museum education practices. The research underscores the significance of supportive frameworks that pivot on existing museum learning theories. An essential aspect of Kristinsdóttir's work is the emphasis on the empowerment of museum educators, emphasizing the role they play in driving sustainable education.
2) Museums and Regional Development: Pop and Borza[2] delve into the relationship between sustainable museums and sustainable regional development. They posit that for museums to play a pivotal role in regional sustainability, they first need to embed sustainability within their operational and strategic frameworks.
3) Sustainability Metrics: Offering a more methodological approach, Pop and Borza[2] introduce factors that influence museum sustainability. Their work is vital for museums aiming to measure their sustainability initiatives, providing a comprehensive model that assesses sustainability levels across various institutions.
4) Museum Planning and Operations: A manual by King and Lord[4] offers a deep dive into sustainable museum planning, covering space utilization, facility management, and day-to-day operations. The work underlines the argument that museums ought to be frontrunners in showcasing sustainable living.

5) Cultural Equity: Besterman[5] provides a compelling perspective on the intersection of cultural equity and sustainability within museums. He argues about the cultural footprint of Western museums, suggesting that their approach, if not rectified, might be unsustainable in the long run.
6) Conservation Practices: The sustainability conversation also extends to the conservation of artifacts. Kampasakali et al.[6] focus on the use of biodegradable agents for the surface cleaning of contemporary art and design objects, reflecting the broader shift towards sustainable museum practices.
7) Museum Collections: Merriman[7] touches upon the socio-economic facets of sustainability within museums. His stance is that a genuinely sustainable museum doesn't view environmental, social, and economic aspects in isolation but considers them as interconnected domains.
8) Community Engagement: Brown et al.[8] provide insights on the role of community engagement in sustainable museums, emphasizing shared experiences and knowledge.
9) Sustainability in Service-Centric Museums: Alcaraz et al.[9] explore service-centricity in non-profit museums, identifying critical issues that can aid in establishing sustainability within these institutions.
10) Evolution of the Sustainability Concept: Lastly, Link[10] offers a historical viewpoint, tracing the evolution of sustainability within the museum sector and its ties to citizenship and the common good.

In a quest to fathom the multifaceted nature of sustainability in the museum sector, several studies have come to the fore, often intersecting in their areas of emphasis yet diverging in their methodologies and focal points. Kristinsdóttir[1] underscores the pivotal role that museum educators play in imparting sustainable education, building on extant learning theories. Yet, one wonders whether these existing paradigms are truly compatible with the sustainability ethos or if there's a need for radical paradigm shifts. This educational framework, while foundational, seems somewhat decoupled from the more strategic concerns voiced by Pop and Borza[2], who emphasize embedding sustainability within operational matrices for regional development. The later work in 2019[3] provides a methodological model for gauging museum sustainability, but juxtaposing this with King and Lord[4] hands-on approach to museum planning hints at a potential gap between theory and practice. Is the act of measuring sustainability inherently sustainable, or does it, paradoxically, divert resources from actionable sustainability endeavors? Besterman's[5] discourse on cultural equity brings forth a nuanced critique of Western museums, implying an ethnocentric bias. Still, the question arises: Are non-Western museums inherently attuned to sustainable practices, or are they subject to their own biases? Kampasakali et al.'s[6] innovative focus on artifact conservation, while novel, raises concerns about the long-term efficacy of biodegradable agents. Merriman[7], in his holistic perspective on museums, seems to touch upon an integrated vision that resonates with Brown et al.'s[9] emphasis on community engagement. But can shared experiences truly catalyze sustainability, or do they inadvertently foster echo chambers? Alcaraz et al.'s[9] exploration of service-centric museums provides a refreshing non-profit perspective, but the broader implications for their profit-driven counterparts remain shrouded. Finally, Link's[10] historical tracing of sustainability's evolution seems to suggest a teleological progression, but is the trajectory of sustainability linear, or are there cyclic patterns and recurrences? This intricate tapestry of studies, while offering rich insights, beckons for an integrated, holistic, and perhaps more self-critical approach to truly fathom and further sustainability in the museum domain.

Collectively, these studies showcase the multi-faceted nature of sustainability in the museum sector, highlighting the importance of integrating sustainable practices across various operations and strategic initiatives. Sustainable design principles are gaining prominence across diverse sectors, as underscored in recent literature. The importance of sustainability is highlighted within supply chain networks, advocating for resource conservation. The emphasis on product safety and lifecycle sustainability is evident. The convergence of value engineering with building modeling could potentially refine sustainable building designs. Sustainable manufacturing, food packaging innovations, and designs for underground environments, warm mix asphalt, and natural fiber composites underline the need for eco-centric practices. Additionally, integrated sustainable supply chains and education tailored towards green recovery emphasize holistic sustainability[18,19].

Overall, these literature categories highlight the significance of sustainable design and its application in various fields, including supply chain management, product safety, building design, manufacturing, food packaging, transportation, and education. They provide valuable insights into the integration of sustainable practices across different sectors and emphasize the need to consider sustainability throughout the design process for a more environmentally friendly future[12,20].

3. Research method

In our exploration of the confluence of museums, educational strategies, and sustainable practices, we utilized the framework proposed by Kitchenham and Charters[21] to craft a coherent, clear, and thorough review of existing literature. This procedure, as outlined by Kitchenham and Charters[21], involves defining research questions, designing a review strategy, setting criteria for inclusion and exclusion, detailing the search and inclusion techniques, consolidating and interpreting data, and finally presenting the results. Further details of our methodology and the steps undertaken are discussed in the sections that follow.

The systematic review journey begins by defining a structured protocol rooted in the central research questions and the selected methodologies[21]. Such a structured approach is crucial to minimizing biases. Key components of this protocol include an initial exploration of the subject, framing the research questions, developing a research strategy, setting criteria for selection, mechanisms for data retrieval, and the eventual synthesis of the collected data. For this study, the foundational research and question formulation can be found in prior sections.

Our research considered publications in English from 2010 to 2022, spanning journals, conference papers, and workshop outputs. The time frame was selected for specific reasons. Primarily, we aimed to augment and extend the scope of previous analyses centered on museums, education, and sustainable practices in contemporary settings. Hence, our effort involved systematically assembling relevant studies from the said period to holistically analyze and deduce findings related to the roles of museums, their educational techniques, sustainable approaches, and instructional resources that might have been missed in previous scholarly works. Digital libraries such as ISI Web of Knowledge, ScienceDirect, IEEE Explore, and Springer Link were consulted. We refrained from incorporating editorials, article introductions, poster sessions, panels, abstracts, incomplete papers, non-reviewed works, or papers not in English.

Taking cues from Webster and Watson[22], our review encompassed diverse electronic databases, ensuring a comprehensive collection of literature rather than being restricted to specific journals. Thus, prominent databases like ISI Web of Knowledge, ScienceDirect, IEEE Explore, and Springer Link were tapped into, considering their relevance to themes of culture, education, and sustainability. Our search was steered using terms like "educational role of museums", "green museum initiatives", "learning through museums", and "sustainability in museums". Following the suggestions by Kitchenham[23], we employed the Endnote software for managing and sifting through the gathered literature, discarding duplicates. In alignment with Kitchenham and Charters[21], we also manually scanned references in the primary articles to ensure comprehensive coverage. This cycle continued until we identified no new relevant literature.

4. The pervasive power of sustainable design: A new era emerges

As society stands on the precipice of a new decade, sustainable design emerges as a beacon, illuminating the way forward across multiple disciplines. Its influence, broad and all-encompassing, touches everything from the concrete structures we inhabit to the very fabric of our digital world[11,13,14].

Central to this transformative wave is the fervent emphasis on renewable energy systems. In today's sustainable architectural and infrastructural designs, the integration of renewable energy is no longer an afterthought. It forms the very essence of blueprints, embodying an ethos where sustainability is foundational. Intelligent design principles accentuate this shift. The essence of "smart design" is not merely the incorporation of technologically advanced systems but fusing them seamlessly with renewable energy mechanisms to create edifices that are not only functional but also environmentally harmonious.

As we delve deeper into the realm of energy, it becomes evident that the spectrum of sustainable design is broadening. It's not just about one or two energy systems but an array that spans the gamut, from traditional solar and wind to more novel sources. And in this broader scope, the focus sharpens on the integration and optimization of these often-standalone systems. By leveraging multi-scale optimization, the goal is to weave these systems together, ensuring that they operate in symphony, magnifying their collective sustainability impact[12,13].

But sustainable design isn't confined to physical spaces or energy systems. It's making inroads into the world of business. Contemporary business practices are undergoing a green metamorphosis, with the tenets of sustainable design theory increasingly finding a place in boardrooms. Whether it's in product service system design literature or broader strategic decision-making, sustainability is becoming synonymous with sound business acumen.

The Karlskrona manifesto underscores the evolution of sustainable design into the domain of technology. With software now an intrinsic part of our daily lives, it's heartening to see the core principles of sustainable design being adapted and integrated into this digital realm. While on the topic of adaptation, optimization tools such as genetic algorithms are being fine-tuned to further the goals of sustainable design. The application of Warm Mix Asphalt (WMA) serves as a testament to the potential of these multi-objective optimization techniques[15].

The threads of sustainability extend further into the design of supply chains and transportation networks. Here, the narrative revolves around an integrated approach. No longer are supply chains seen in isolation but as part of a larger, interconnected web that includes transportation networks, especially when it comes to perishable products.

In an age where knowledge is paramount, education is not untouched by this green wave. Modern educational institutions are embedding sustainable and well-being aspects into curricula, weaving in positive psychology interventions. The objective? Cultivating a mindset that not only values knowledge but also sustainable happiness and well-being for future generations[16,17].

The COVID-19 pandemic, though disruptive, has further accelerated the pace of sustainable innovation. Online education, for instance, has seen a surge in sustainable models. These are not mere digital replicas of physical classrooms but thoughtfully designed learning environments that recognize and address the unique challenges and opportunities of online pedagogy[14,15].

In summary, sustainable design, once relegated to select fields, now permeates the entire fabric of society. From architecture and engineering to manufacturing and education, its influence is undeniable, marking the dawn of an era where design thinks green and acts sustainably.

Ten major trends in sustainable design can be identified:

1) Growing emphasis on renewable energy systems: Sustainable design is increasingly focused on integrating renewable energy systems into buildings and infrastructure.
2) Smart design for sustainable buildings: The use of intelligent design principles is gaining importance to create sustainable buildings with renewable energy systems.
3) Broadening the scope of sustainable design in energy systems: The concept of sustainable design is expanding to include a wider range of energy systems and their integration to optimize sustainability.
4) Integration of standalone energy systems through multi-scale optimization: The trend is towards the integration and optimization of standalone energy systems at different scales to enhance sustainability.
5) Implementation of sustainable design theory in business practices: There is a growing focus on incorporating sustainable design theory into business practices, particularly in product service system design literature.
6) Karlskrona manifesto for software-intensive systems: The Karlskrona manifesto outlines key principles of sustainable design for software-intensive systems, bringing the concept into the field of technology.
7) Multi-objective optimization for sustainable design[15]: Genetic algorithms and other multi-objective optimization techniques are being used to achieve sustainable design objectives, as seen in the case of Warm Mix Asphalt (WMA).
8) Integrated design of sustainable supply chain and transportation network: There is a trend towards integrating sustainable design principles in supply chain and transportation network design, particularly for perishable products.
9) Sustainable education and positive psychology interventions in schools: Education is increasingly focusing on sustainable and well-being aspects, aiming to achieve sustainable happiness and well-being in the 21st century.
10) Construction of online sustainable educational models: The COVID-19 pandemic has driven the construction of online sustainable educational models to adapt to changing learning environments.

These trends highlight the evolving landscape of sustainable design across various disciplines, including architecture, engineering, manufacturing, and education.

5. Discussion

The conversation around sustainability has transcended its original confines, notably entering spaces like the museum sector. Traditionally viewed as cultural vaults, museums are now redefining themselves as advocates for sustainability, encompassing more than just environmental considerations. Their approach touches on social, educational, and cultural facets of sustainability. Numerous researchers, including Kristinsdóttir[1], highlight the significance of educators in forwarding the agenda of sustainable museum education. This transformation is not just about the content being shared but also the methodologies and platforms facilitating it. Pop and Borza's[2] findings underscore that museums are integral to the broader sustainable ecosystem and not isolated entities. Drawing from the detailed guide by King and Lord[4], it's clear that sustainability is intricately woven into everyday operations and not just an overarching strategy. Parallel to these insights, cultural equity, as championed by Besterman[5], and conservation efforts, as per Kampasakali et al.[6], bring fresh perspectives to the table. Delving into socio-economic dimensions and community involvement, researchers like Merriman[7] and Brown et al.[8] bring to the fore the intricate mesh of sustainability that spans the environment, society, and economics. Alcaraz et al.'s[9] service-oriented approach, along with Link's[10] historical overview, charts the evolution of museums in the sustainability context. Beyond museum spaces, there's an evident push towards sustainable design in various domains, including infrastructure and energy. The universal emphasis on shifting to renewable energy sources, optimizing energy distribution, and ingraining sustainable design into varied facets of life signifies the crucial need to prioritize this approach.

6. Conclusion

As we critically analyze the wealth of information and delve into the findings presented, it becomes strikingly clear that we're on the cusp of an unprecedented transformative era. The realm of museums, which have long held the role of guardians and curators of our collective history, is undergoing a significant metamorphosis. No longer are they just silent observers of our past; they are dynamically positioning themselves as luminous beacons, heralding a vision for a sustainable future.

This shift, while profoundly evident in museums, is by no means confined to them. Indeed, the ethos of sustainable design has permeated various facets of our society, standing out as a binding force that seamlessly interlaces through diverse sectors. Whether it be the intricate world of business, the robust domain of infrastructure, or the ever-evolving fabric of community spaces, the principles of sustainability resonate with a clarion call. It's a call for thoughtful design, mindful consumption, and holistic development that respects both our heritage and our environment.

What lends credence to this transformative shift is the burgeoning body of research that champions a holistic approach to our future. Researchers, policymakers, and thought leaders from varied disciplines converge on the idea that sustainability cannot be compartmentalized or viewed in isolation. It's not just a fragment of our developmental narrative but rather forms the very bedrock of it. Sustainability, in this light, emerges as a comprehensive framework guiding our actions, decisions, and visions for the future.

In essence, as we navigate the complexities of our modern world, it's this commitment to sustainability that provides a beacon of hope. It's more than just a strategy; it's a philosophy, a way of life that strives for equilibrium between our needs and the planet's capacity. As we forge ahead, this commitment ensures that we leave behind not just a legacy of progress but also a blueprint for a balanced, harmonious world for all subsequent generations to cherish and sustain.

Author contributions

Conceptualization, THW; methodology, HCKL; software, CTL and HCKL; writing—original draft preparation, THW; writing—review and editing, HCKL; funding acquisition, CTL. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

All authors of this paper have no conflict of interest.

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Original Research Article

Physical comfort in Statiko Coffee Shop, Wonosobo, Indonesia

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ABSTRACT: This research aims to analyze the environmental conditions inside and outside the Statiko Coffee Shop, Wonosobo, Indonesia, with a focus on noise, light intensity, air temperature, and humidity. Measurements were carried out at certain time intervals starting from 15:00 to 23:00. The collected data shows significant variations in each observed parameter. Indoors, noise levels varied, light intensity was recorded, air temperature fluctuated, and humidity ranged from 78.0% to 85.0%. Outdoors, wider variations in noise, light intensity, air temperature, and humidity were seen. The results of this research show the importance of good understanding and design regarding ventilation and environmental management to create comfort for visitors in a coffee shop. This information can be used as a basis for designing an effective ventilation system and maintaining good indoor air quality, as well as considering external environmental influences such as noise and light intensity. Further research is needed to provide more specific recommendations for optimizing the environment at the Statiko Coffee Shop, Wonosobo, Indonesia.

KEYWORDS: thermal; voice; comfort; building; architecture

1. Introduction

Rising air temperatures are affecting many countries around the world. Global warming is getting higher and higher. Buildings contribute to worsening global warming through the use of cooling equipment. Buildings are infrastructure to accommodate human activities, so they require comfort. Global warming creates thermal discomfort for human activities. Thermal comfort in a building is related to the comfortable temperature for humans in each area. The comfortable temperature for humans in locations with low air temperatures is different from locations with high air temperatures[1]. Humans in low-temperature areas have a lower comfortable temperature than humans in high-temperature areas. Human adaptation to air temperature varies so that the comfortable temperature for humans in an environment also varies. Predicting comfortable temperatures is needed so that humans can predict thermal comfort needs in buildings[2]. Predicting comfortable temperatures can be done using various methods. Using statistical analysis can provide a prediction model for the air temperature that will occur. Predictive models can be used in building design. The prediction model will make it easier for architects to estimate thermal comfort needs from outside air temperature[3].

Uncomfortable buildings can cause people inside to become stressed and make people sick. Buildings that make occupants sick are called sick building syndrome (SBS). Indoor air is one of the essential factors in buildings that is related to sick building syndrome. Good indoor air exchange will maintain clean air in the room. Ventilation is an essential factor in meeting indoor air quality. Good ventilation can remove dirty air particles to create clean air[4]. Clean air quality will support the thermal comfort of buildings. Clean air makes the air cooler. Clean air will also maintain indoor humidity. Thermal comfort in a room is related to the air temperature and air humidity in the room. The wind factor in the room is not too influential because the wind conditions do not blow too hard. The relationship between outdoor air temperature, humidity, and wind is very close to creating thermal comfort. Environments with extreme conditions adapt buildings by creating additional elements to create thermal comfort[5].

Building elements have a role in creating thermal comfort. Research in high-temperature and high-humidity areas found that building layout influences creating thermal comfort for residents. Air temperature and air speed are analyzed using simulation methods, producing findings about building arrangement patterns that can create thermal comfort. Several layouts were analyzed and resulted in parallel layouts forming a ventilation corridor. The parallel layout can channel the wind well so that residents get fresh air[6]. The combination of architectural elements and adaptive thermal comfort is an essential factor in creating building thermal comfort. Wall material is one element in changes in air temperature and air humidity. Residents in the highlands and lowlands experience different air temperatures and air humidity in different seasons[7]. Differences in location make the air temperature and air humidity different, so building elements must be adapted to environmental conditions. An architectural element that is often discussed in thermal comfort research is the building envelope. Locality is one of the factors in determining the building envelope. The effect of using local building envelopes will create sustainability in architecture[8].

The relationship between indoor air temperature, air humidity, and the content of substances in the air is very close to creating thermal comfort indoors. Research conducted in naturally ventilated schools shows variations in the results of the three variables. The CO_2 content in the air is not very much, but air temperature and humidity have significant variations. Using VENSIM simulation software to analyze the data shows a high correlation between variables. CO_2 concentrations cannot be predicted when they reach 1500 ppm. Air temperature and humidity are variables that cannot be separated when discussing thermal comfort, although other factors add to the discussion[9].

The strategy for creating thermal comfort through variable air temperature and air humidity is one of the points in various thermal comfort research. Research in Beirut, Lebanon City, carried out a strategy of changing soil albedo, replacing old buildings with new ones, and adding vegetation to create thermal comfort. The strategy used will improve the urban environment to make it more comfortable. The research used a simulation method and found that vegetation was the best strategy compared to the other two. The decrease in air temperature occurs in the afternoon and radiation temperature during the day. The search for strategies for creating thermal comfort through research on air temperature and humidity is still relevant and essential[10].

The strategy to reduce air temperature will cause problems when using modern materials, which cause air temperature to increase. Extensive use of glass in a building gives the impression of a modern building, but also a need to pay attention to the structure of its adhesion to other materials. Research on the use of modern materials, which have problems with increasing temperatures in adhesion between materials, is one of the concerns in creating thermal comfort in buildings. Structural errors will also have an impact on the continuity of the building. Building structures need to pay attention to occupant safety to create occupant comfort[11].

Apart from thermal comfort, sound comfort is required by buildings used for learning activities. Learning activities require peace from noise, so building design also requires sound comfort. Visual, thermal, and acoustic factors can influence the psychology of building occupants. Research findings show that visual, thermal, and acoustic comfort influence 41.5% of human psychological recovery[12]. People who need room comfort related to these three factors are willing to pay for technology that can provide room comfort. The research results show that people under forty want comfort even though they have to provide compensation payments[13]. The three comfort factors can be called physical comfort, which is also related to the health of the interior. Gender differences influence responses to physical comfort. Designing buildings with certain functions related to gender needs to pay attention to differences in response[14].

Learning activities also require sufficient lighting, so the light intensity needs to be planned so that it is sufficient for carrying out learning activities. The function of the building influences the use of indoor lighting. Building functions that influence design require careful lighting planning so that the building can function well[15]. Building design is not only related to space design but also related to building elements such as windows. Current developing technology can provide additional features to Windows. The development of information technology can make building elements increasingly sophisticated. Using intelligent windows in buildings can create visual and thermal comfort for occupants[16]. Using windows to create visual and thermal comfort can create energy savings. Modelling is one way to research windows in energy-saving[17]. Lack of lighting in the room means it is not optimal for providing comfort for its occupants[18].

One building that requires sufficient lighting, low noise, and comfortable thermals is a cafe. Currently, using cafes as a place to study has become a trend for young people in Indonesia. Learning activities require a calm atmosphere, sufficient lighting, and comfortable thermal conditions. A calm atmosphere is not without sound, but some do not interfere with learning motivation. Calm sounds can be accompanied by certain music, increasing learning motivation. The research aims to investigate the physical comfort of the Statiko Coffee Shop, which consists of lighting, noise, and thermal in creating user comfort.

2. Method

The research was conducted at the Statiko Coffee Shop in Wonosobo Regency, Central Java, Indonesia. Statiko Coffee Shop is a two-story building on the side of a secondary road, so it is relatively quiet (**Figure 1**). Store opening hours are 15:00–23:00. There are more visitors at night. Visitors want a calm shop atmosphere and can chat with other visitors calmly. Some visitors also use the shop for learning activities.

Figure 1. Front view of Statiko Coffee Shop.

The method used in this research is divided into four stages: the research preparation stage, data collection stage, data analysis stage, and data analysis results presentation stage. At the research preparation stage, the researcher determines the research topic, chooses the research object, determines the appropriate theory for what he wants to research, and looks for references by conducting a literature study. This type of research is exploratory, descriptive research, namely measuring the thermal temperature conditions of a room in a coffee shop building. This measurement aims to measure, observe, and detect the room's temperature and natural lighting, which impact the comfort of coffee shop users.

The measurement time is once every 30 min from 15:00 (coffee shop opening hours) to 23:00 (coffee shop closing hours). The tools used for measurements include: 1) lux meter, also known as a light meter, is a tool for measuring light intensity (other than photometers). This equipment consists of a light sensor of photocell material and a screen; 2) multi-function Environment Meter brand Krisbow KW06-291, to measure temperature (℃) and humidity (%); 3) cell phone for clock timer detection on the cell phone to see the time of each measurement; and writing tools, which are used to record measurement results.

3. Results and discussion

The area in the Statiko Coffee Shop has a fish pond, which adds to the room's coolness. Plants are arranged along the pool's edge, and some are in the middle. The inner area around the pool has chairs and a dining table used for eating. The dining area by the pool is not too big, so there are few visitors along the pool. A larger dining area is located in the area after the pool. An area of around 20 m^2 can be used by more visitors (**Figure 2**).

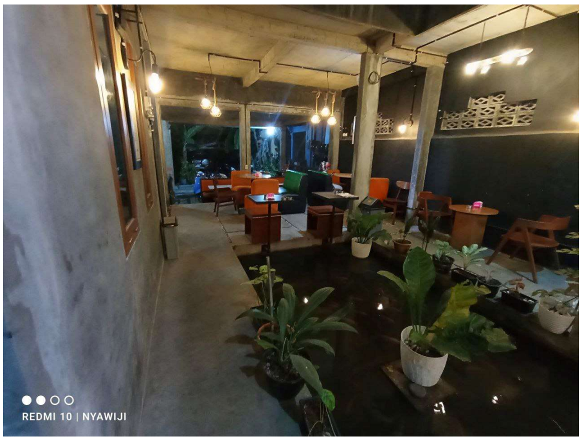


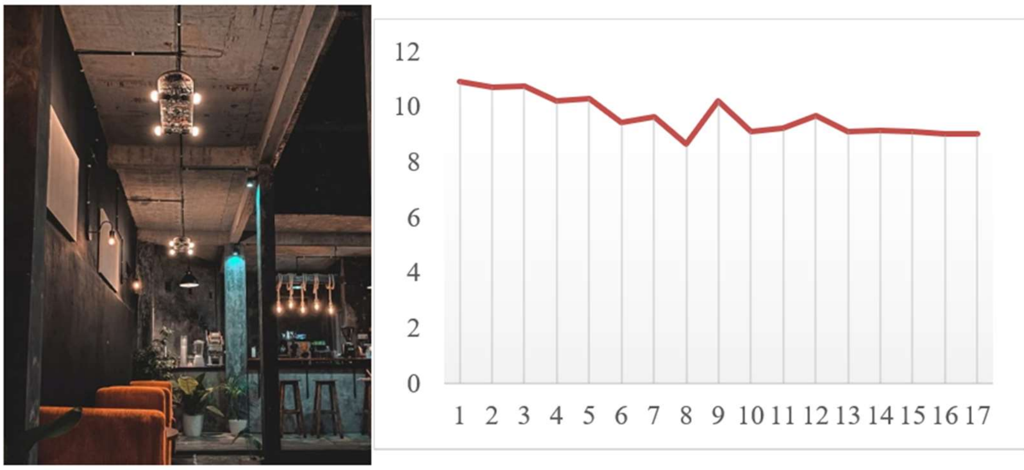
Figure 2. Statiko Coffe Shop indoor.

Noise levels in the room varied, with some hours showing higher noise levels while others were quieter than others. This condition can be influenced by outside traffic, equipment used, and customer visits. The light intensity is similar. Wind speed does not indicate movement because the inside area is protected from the outside area. Air temperature ranges between 24.2 ℃ and 26.1 ℃. The air temperature is relatively low, considering that Wonosobo is a mountainous area with cool temperatures. Air humidity is relatively low, ranging between 78% and 85% (**Table 1**).

Based on the recorded light intensity data, it can be concluded that the light intensity in the coffee shop varies during the hours observed (**Figure 3**). Although units are not given in the table, the data reflects differences in lighting levels in the room at certain times. The importance of light intensity in a coffee shop room can influence the atmosphere and comfort of visitors. Good lighting can create a pleasant atmosphere and improve the visitor's experience when enjoying coffee and the atmosphere in the coffee shop. Therefore, it is essential to pay attention to lighting arrangements in the design and management of a coffee shop in order to create a comfortable and attractive atmosphere.

Table 1. Indoor measurement.

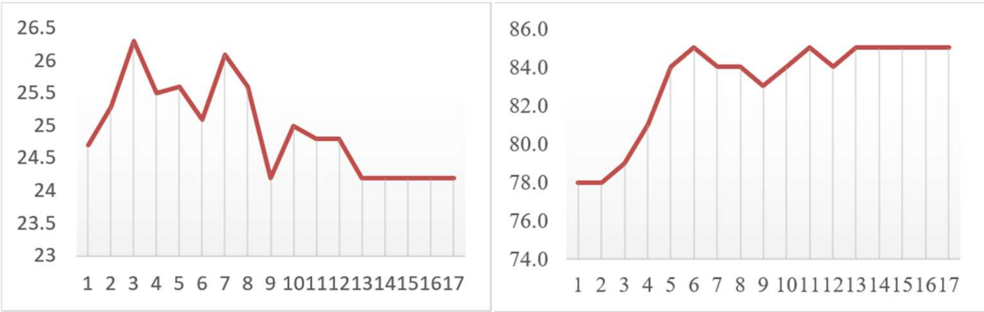
Hour	Noise	Light intensity	Wind velocity	Temperature	Humidity
15:00	Noisy	10.9	0	24.7	78
15:30	A bit noisy	10.7	0	25.3	78
16:00	Not noisy	10.7	0	26.3	79
16:30	Noisy	10.2	0	25.5	81
17:00	Not noisy	10.3	0	25.6	84
17:30	A bit noisy	9.4	0	25.1	85
18:00	Not noisy	9.6	0	26.1	84
18:30	Not noisy	8.6	0	25.6	84
19:00	Not noisy	10.2	0	24.2	83
19:30	Not noisy	9.1	0	25.0	84
20:00	Noisy	9.2	0	24.8	85
20:30	Noisy	9.6	0	24.8	84
21:00	A bit noisy	9.1	0	24.2	85
21:30	Not noisy	9.1	0	24.2	85
22:00	Not noisy	9.1	0	24.2	85
22:30	Not noisy	9.0	0	24.2	85
23:00	Not noisy	9.0	0	24.2	85



(a) **(b)**

Figure 3. (a) Indoor lighting; **(b)** indoor lighting measurement results.

The wind speed in the room shows a value of 0 at all measurement hours. This condition can be explained by wind speed being generally insignificant in closed spaces such as coffee shops. The indoor air temperature showed observable fluctuations, with a temperature range between 24.2 °C and 26.3 °C. These fluctuations may be influenced by external factors such as outdoor weather conditions and temperature regulation through indoor cooling or heating systems. Indoor air humidity also shows significant variations, with humidity values ranging from 78.0% to 85.0% (**Figure 4**). High humidity levels can be associated with weather conditions such as rain and cloudy skies, which can provide comfort for visitors, especially in areas with climates that tend to be dry.



(a) **(b)**

Figure 4. Indoor measurements, **(a)** air temperature; **(b)** air humidity.

The recorded weather information shows variations between rainy, cloudy and sunny weather. Outdoor weather conditions can affect indoor air conditions, and this factor needs to be considered in ventilation settings to maintain visitor comfort (**Table 2**).

Table 2. Outdoor measurement.

Hour	Noise	Light intensity	Wind velocity	Temperature	Humidity
15:00	Noisy	138.0	0	25.3	75
15:30	A bit noisy	115.0	0	25.5	79
16:00	Not noisy	116.0	0	25.1	80
16:30	Noisy	19.5	0	25.7	83
17:00	Not noisy	13.7	0	24.9	86
17:30	A bit noisy	9.5	0	24.6	89
18:00	Not noisy	9.2	0	24.2	85
18:30	Not noisy	7.2	0	24.2	85
19:00	Not noisy	7.0	0	24.0	86
19:30	Not noisy	7.1	0	23.8	86
20:00	Noisy	7.0	0	23.8	86
20:30	Noisy	5.5	0	22.7	87
21:00	A bit noisy	5.3	0	22.2	87
21:30	Not noisy	5.2	0	21.5	87
22:00	Not noisy	5.5	0	20.0	87
22:30	Not noisy	5.3	0	18.0	88
23:00	Not noisy	5.2	0	18.0	88

Noise levels around the outdoor area vary, with some hours showing higher noise levels, while at other times, it is quieter. Traffic, nearby activities, and equipment use can influence the noise level. Outdoor light intensity shows significant differences in observation hours **(Figure 5)**. Although the units are not mentioned in the table, the data reflects variations in lighting levels around the coffee shop at certain times. The right light intensity can influence the atmosphere and mood of visitors outside the room.

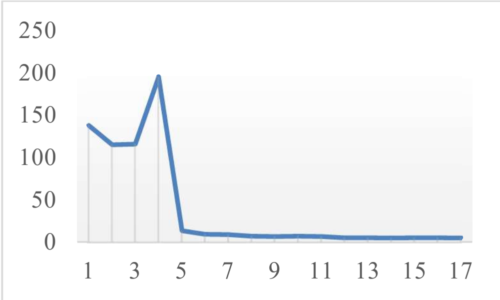
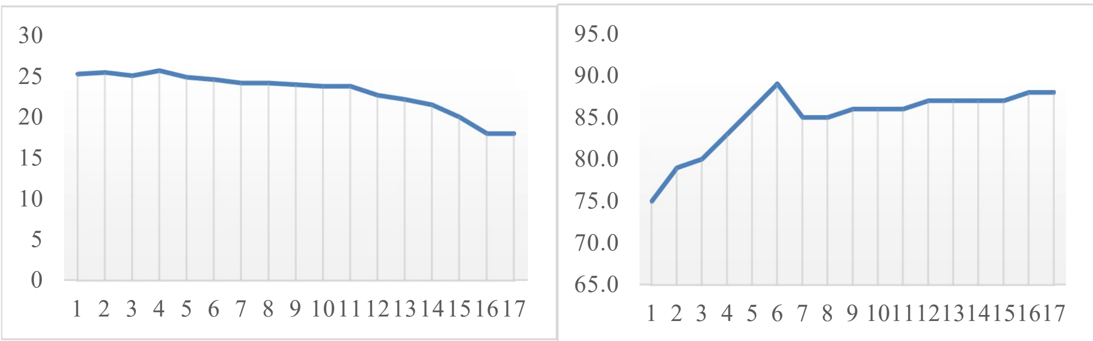


Figure 5. Outdoor light intensity.

The wind speed around the area is not recorded in the table, with all observation hours showing 0. This condition can be explained by outdoor wind speed being insignificant or unmeasurable at certain hours. Outdoor air temperature showed observed fluctuations, with a temperature range ranging from 18 °C to 25.7 °C. These temperature fluctuations can be influenced by factors such as season, weather, and the influence of the surrounding environment. Outdoor humidity also shows significant variations, with humidity values ranging from 75.0% to 89%. Different humidity levels can be associated with weather conditions, where higher humidity may occur during rain or overcast conditions (**Figure 6**).



(a) **(b)**

Figure 6. Outdoor measurement, **(a)** air temperature; **(b)** air humidity.

The relationship between noise and air temperature measurements differs between indoor and outdoor spaces. Noise has nothing to do with air temperature but can influence the thermal sensation of building users[19]. Using fewer lights will result in significant energy usage and hotter temperatures. The energy used becomes more wasteful. Using more lighting will make the building look attractive but will waste energy. Lighting control system strategies can reduce energy savings due to visual comfort[20].

4. Conclusion

Based on observations, there are variations in noise, light intensity, air temperature, and humidity inside and outside the Statiko Wonosobo Coffee Shop. Indoors, noise levels varied, light intensity was recorded, air temperature fluctuated, and air humidity ranged from 78.0% to 85.0%. Outdoors, we also see variations in noise, light intensity, air temperature, and humidity over a broader range. These changing environmental conditions show the importance of good understanding and design regarding ventilation and environmental management in creating comfort for visitors in coffee shops. This information can be a basis for designing an effective ventilation system, maintaining good indoor air quality, and considering external environmental influences such as noise and light intensity. In this context, further research and in-depth analysis are needed to provide more specific recommendations for optimizing the environment at the Statiko Wonosobo Coffee Shop.

Author contributions

Conceptualization, HH and NAA; methodology, HH and NAA; validation, HH, SRPM and DAM; formal analysis, HH, SRPM and DAM; investigation SRPM and DAM; resources, SRPM and DAM; data curation, SRPM and DAM; writing—original draft preparation, HH and NAA; writing—review and editing, HH; visualization, NAA; supervision, HH and NAA; project administration, NAA; funding acquisition, HH. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

The authors declare no conflict of interest.

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Original Research Article

Total illiteracy in construction—The tragic retribution for this will be very heavy and sorrowful: Seismic isolation strategies are the way to overcome such consequences

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ABSTRACT: Frequent earthquakes of medium and high intensities in different countries of the world constantly testify that engineers, in most cases, are illiterately solving the problem of the interaction of load-bearing and non-load-bearing structures in the buildings. As a result, the mass destruction of non-load-bearing walls and damage in load-bearing structures take place, and they are illustrated in the paper for various buildings in different countries. We must always remember the quote of Galileo Galilei: "*Ignorance is the mother of malice, envy, greed and all other low and gross vices, as well as sins*". Therefore, this paper points to the total illiteracy and corruption that reign in the construction industry of Armenia in all cycles, starting with design, project expertise, issuing construction permits, and ending with construction and its technical and author's supervision. It shows that the people employed in the construction complex have completely forgotten about the lessons of the devastating Spitak earthquake and completely ignored the high seismic danger in the territory of Armenia. Design organizations envisage old, unreliable methods for mass construction, where the dilemma of how to simultaneously minimize inter-story drifts and floor accelerations along the height of the buildings cannot be solved. This quite obviously leads to a significant increase in the cost of construction, which fully satisfies corrupt builders and corrupt state bodies. In the second part of the paper, the author states that one of the ways to overcome the current situation is the widespread application of the seismic isolation systems created by him and largely implemented in Armenia. In terms of the number of seismically isolated buildings per capita, the author brought Armenia to the second place in the world after Japan. The advantages and reliability of structures with seismic isolation systems both in the construction of new buildings and in the retrofitting of existing buildings are clearly illustrated. A comparative analysis of deformed states and values of accelerations along the height of buildings with and without seismic isolation systems is given. The paper also demonstrates the high economic efficiency obtained from the use of seismic isolation systems. It is shown that in the construction of new seismically isolated buildings, savings reach 40%, and the retrofitting of existing buildings by application of seismic isolation costs up to 5 times less, compared to traditional methods of strengthening. At the same time, the retrofitting of existing buildings by means of seismic isolation is carried out without interruption of their operation.

KEYWORDS: total illiteracy in construction; unreliable methods in mass construction; corrupt construction and state bodies; modern and cost-effective seismic isolation systems; advantages of structures with seismic isolation systems; reliability and low-cost; comparative analysis; deformed states; inter-story drifts; accelerations; newly constructed seismic isolated buildings; retrofitting of the existing buildings by seismic isolation

1. Total illiteracy in construction—The tragic retribution for this will be very heavy and sorrowful

Armenia is located in an earthquake-prone zone. What is expected if a strong seismic event occurs in our country? This will definitely take place, as evidenced by the 1988 Spitak earthquake. At that time, according to our research, in a matter of seconds, we lost 52,000 people and had many cities and villages destroyed[1]. In order not to be unfounded, I will refer to the World Bank Working Paper Series No.9 of 2004[2], where it is mentioned: "*The Spitak earthquake took the lives of 50,000 people, and a total of 1,400,000 people suffered serious physical and material damage*". The results of material damage and destruction of buildings are given in[3].

We must finally learn lessons from our own experience as well as from the world's experience. How much longer should our population remain uninformed because of the criminal negligence of semiliterate officials? How much longer will the brains of our people be brainwashed by idiotic serials, programs on cooking all kinds of dishes and advertising their recipes, low-grade, so-called "humorous" programs, low-grade music, and other useless, moreover, and hostile to the spirit of the people information? At the same time, no information is given to people by the government propaganda about the hazardous situation with the existing building stock, schools, hospitals, etc., which, practically, do not have the required level of earthquake resistance. Also, no information is given about the extremely low quality and illiterate construction of new buildings. The photos below in **Figure 1** are clear evidence of this.

(a)

(b)

Figure 1. (*Continued*).

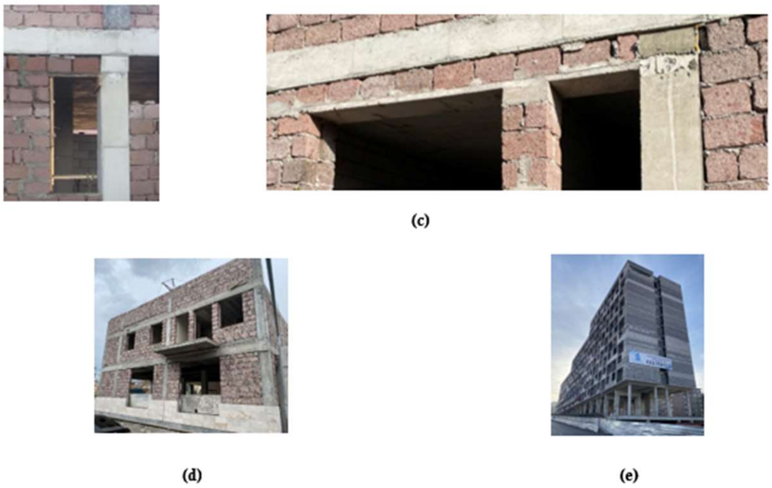


Figure 1. Examples of illiterate construction currently going on in Armenia. **(a)**. Reinforced concrete frames in these buildings have unreinforced masonry infills constructed without soft joints with columns and beams; **(b)**. The same as for the above examples plus the unacceptably small width of the piers between two doors or between a door and a window aperture; **(c)** The same as for the above examples plus unacceptable execution of the windows lintels; **(d)** This building includes all possible deficiencies and violations of the Armenian Seismic Code in force; **(e)** This building also includes all possible deficiencies and violations of the Armenian Seismic Code in force plus it has a soft ground floor which is prohibited for use in Armenia.

In a few seconds, for example, in Yerevan (the capital of Armenia), in the event of an estimated earthquake of intensity 9, the nation will lose 300,000 people, and 80% of existing buildings will be destroyed or damaged by such a state that their restoration will become impossible. About 500,000 people will become disabled, and the number of people left homeless will be incalculable[1]. As the author or coauthor of many scientific papers, the author of the given paper has written about this many times in his books and articles, spoken at press conferences, and during his interviews on various channels and in the press.

In such conditions, will a very limited number of government rescue units be able to achieve tangible positive results in rescuing people from the 32,000–33,000 buildings and structures destroyed in the capital? Of course not. Let's recall, for example, the sad experience of rescue operations on a small recently exploded building in Yerevan, where 200 (!) rescuers worked, and as a result, they did not even temporarily fix one of the façade walls, which posed a threat of collapse. As a result, in a couple of days, this wall collapsed and brought new hardships.

Thus, we can unequivocally state that, by and large, we have not learned anything after the Spitak earthquake. Moreover, we have simply forgotten this tragedy! Based on the above mentioned, it should be stated that there is a danger that our people living in the territory of present-day Armenia will be wiped off the face of our earth by strong earthquakes. Of course, it may be objected to by the author that we have long been considered "builder people". And this is true. We know what a magnificent construction culture our ancestors had. And we are proud of that. We are proud of the constructed churches, monasteries, castles, and fortresses. However, this does not mean that everyone, with or without the appropriate education, has the right to consider himself a builder and disgrace this noble and high title. We know that total illiteracy reigns now in the construction industry of Armenia, from the design and expertise of projects to construction and supervision.

Why is this happening? Mainly because the construction industry is now flooded with people who have completely forgotten the tragedy of 1988, who, due to their own illiteracy, do not even want and do not try to learn lessons from past disasters. These are also those who, at one time, used money to purchase term and diploma projects and in the same manner "delivered" these works, "defended" these projects, not caring at all about future crimes that are now taking place in construction. These people do not read anything and practically do not know the requirements of the current Standards for the Design and Construction of Earthquake-Resistant Buildings and Structures. And why should they do this if the state bodies responsible for the mandatory observance of these norms and for the policy in the construction industry, as well as the regulatory authorities, are practically inactive due to their corruption?

The author has repeatedly explained in writing, as well as in his numerous television appearances, interviews on various channels, and in the press, that the seismic resistance and reliability of buildings depend on the competent design and construction of all structural load-bearing and non-load-bearing elements. However, the above photos prove that today's "would-be designers" and "would-be builders" know nothing about this and do not want to know. If the author's worldwide fame infuriates these people who reject prudence and literacy, then look at what the famous professor from Switzerland Hugo Bachmann writes in his book[4]: *"It is necessary to abandon the construction of walls that fill the frame structures using the methods shown in the photographs. They are bound to be damaged and destroyed, resulting in death or injury".* Two of the relevant illustrations are presented in **Figure 2**. Other examples of destruction of walls in different countries are shown in **Figure 3**.

Figure 2. Damage and collapse of illiterately constructed non-load-bearing walls in frame buildings.

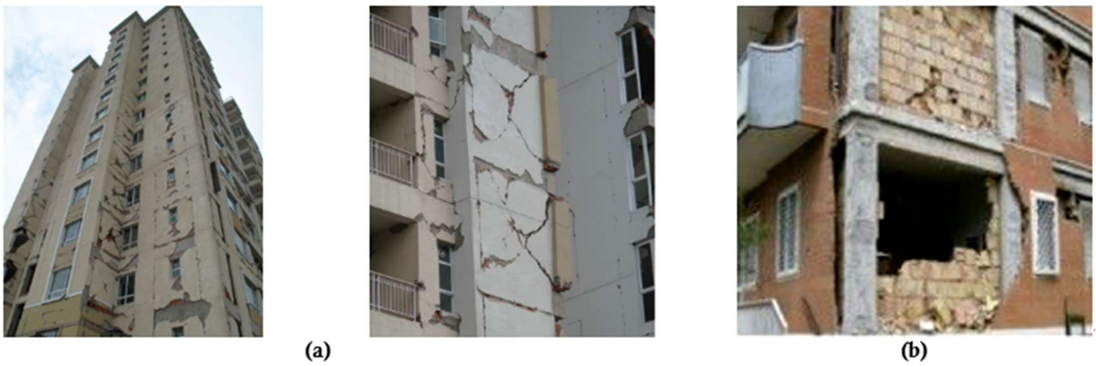


Figure 3. (*Continued*).

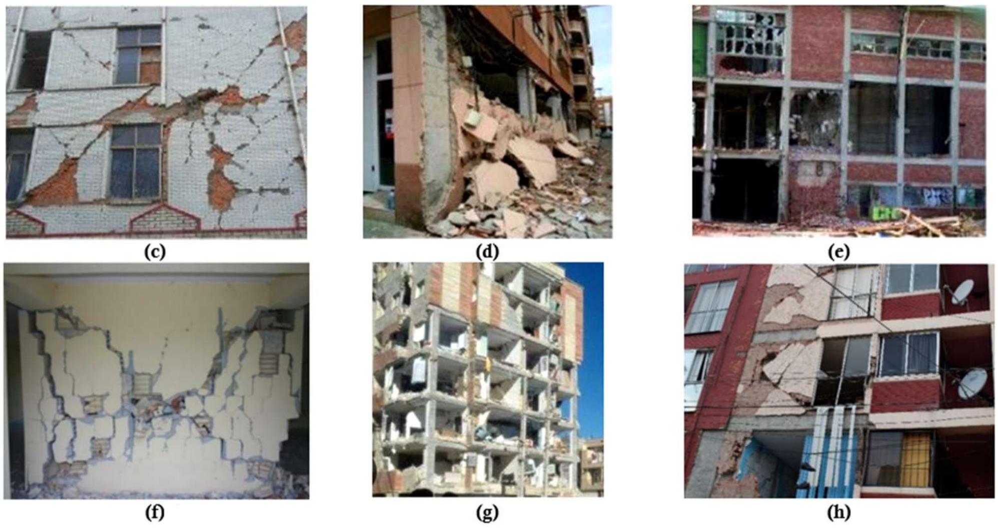


Figure 3. Examples of destruction of the infill walls in frame buildings during earthquakes in different countries. **(a)** Portugal; **(b)** Italy; **(c)** China; **(d)** Spain; **(e)** New Zealand; **(f)** Nepal; **(g)** Iran; **(h)** Mexico.

It is interesting that the current (as well as in the previous editions of the Armenian norms) unambiguously indicate the methods of competent construction of walls in frame buildings. However, our illiterate officials, designers, builders, and regulatory authorities do not know them, as they do not read literature and normative documents. I do not hope that they will be able to draw the necessary conclusions from the past, as well as from the above examples of disgusting construction. But they must do this in order to stop the inept and criminal construction. Yes, we need to put an end to this! You can't play with people's lives for the sake of your own enrichment. We don't have the right to do that...

In the territory where we live, we are simply doomed to observe the well-known postulates, namely, to prepare for future strong earthquakes by all possible preparatory means and measures to prevent massive damage and destruction of buildings. Constantly inform the population about the impending danger, discarding the false thesis that such information can cause panic. This thesis is needed only by officials in order to continue to squander public funds without doing anything, uselessly rubbing their pants on bureaucratic chairs and conducting an "ostrich policy". However, people should always be told the truth! This should be done at the state level by specialists with a high educational level and strong spirit and will. This must be done everywhere: in public and private institutions, in schools, hospitals, courtyards, etc.

Among the priority buildings to be strengthened should be the buildings of schools, hospitals, and government offices from which officials are to carry out all necessary control actions during and after the action of the earthquake. The big question here is whether these unprepared officials know what they should do. The author is sure they don't. In Tokyo, the author had the opportunity to personally participate in a large exercise held right on the streets in the capital of Japan. A large number of the capital's population (several thousand people) took part in these well-prepared exercises, along with the employees of the governing bodies and rescuers. It is obvious that our arrogant officials would not agree to lie in the streets, pretending to be seriously wounded or killed. After all, they are only used to being saluted on the parade ground by the commanders of rescue teams, and, they say, everyone is ready to perform their tasks. The above-mentioned explosion in Yerevan showed quite the opposite. The buildings themselves, where rescuers or unfortunate officials are located, do not have the necessary level of seismic resistance. They will collapse in an earthquake of the design level and even below the design level in a matter of seconds.

How many more times must we be punished by the Lord God in order to finally understand that it is impossible to turn a blind eye to the most important problems under consideration, to the high seismic danger and the high risk of destruction of the buildings of the existing stock? We have to understand that we must avoid a new genocide of our people. Wake up, gentlemen officials and false builders! Why was the author, and not "you", able to make possible the implementation of the program of strengthening and rebuilding schools in Armenia, thereby fulfilling my duty as a specialist and my moral duty? Not being a government official, it took me about 4 years of unpaid work to finally convince and make it clear to the Asian Development Bank (ADB) about the need and importance of such a program for Armenia. Thank God that there are noble and grateful people who, unlike semi-literate officials, were able to highly appreciate my work! Here is what the director of the ADB Armenia Resident Mission wrote to me in this regard:

"*Dear Professor Melkumyan,*
…I am very grateful for your generous help and advice on seismic safety and school rehabilitation over the past 3-4 years. I can honestly and sincerely give you 100% of the credit for introducing this topic to ADB and helping ADB to understand its importance. You can rest assured that due to your efforts many generations of children in Armenia will attend schools that are safe from earthquakes.
…I will always be ready to help you in your noble and vital efforts to improve the safety of schools in Armenia…
Sincerely,
David Dole
Country Director, Armenia Resident Mission
Asian Development Bank, January 10, 2016"

As can be seen from the letter, Mr. David Dole assures me that thanks to my efforts, many generations of children in Armenia will attend earthquake-resistant schools. But, alas, as is evidenced by the material I have cited above, illiterate officials and designers, pseudo-specialists in the examination of projects, in technical supervision, and the pseudo-builders themselves have defiled this magnificent program in such a way that cracks in the walls of the already built and strengthened existing schools are practically abundant. And this is the case even with small oscillations! It is not difficult to imagine what will happen during the design or close to its level of seismic impact.

Similar programs related to improving the seismic resistance of hospitals, residential, and other civilian buildings should be immediately thought about by such state structures as the Ministry of Territorial Administration and Infrastructure, the Ministry of Internal Affairs, and the Urban Development Committee of Armenia. Officials need to abstract from existing stereotypes in order not to allow future strong earthquakes to engulf our nation. We need to think outside the box and act outside the box. The mentioned state bodies, as well as the Hayastan All-Armenian Fund and the Territorial Development Fund, are not only the bearers of urban planning policy but are also responsible for the high-quality implementation of construction programs in our country. Unfortunately, I can say with confidence that in their activities and programs, these bodies have lagged behind the progress in modern construction for decades and have completely forgotten about the protection of the population from the threat of seismic hazards and the risk of destruction of existing buildings. As a result, state resources are senselessly squandered, as well as sums collected by the Diaspora or provided by donors, but in return, unreliable, non-earthquake-resistant buildings and structures are built, and existing buildings are allegedly strengthened by the oldest inefficient "old-fashioned" methods, spending five times more resources and time. This suits the above-mentioned corrupt state bodies acting with impunity and without control.

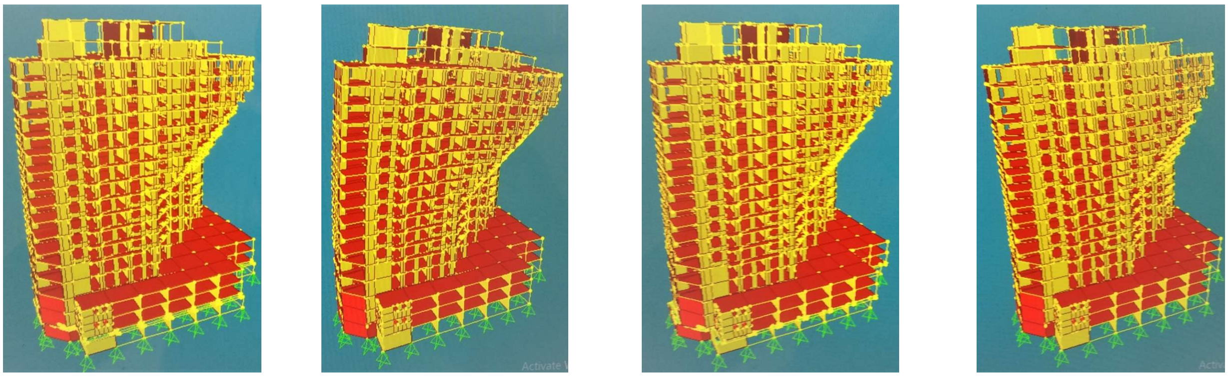
All this is also negatively condoned by the State Supervision Service of Armenia, to which the author has repeatedly appealed with demands to inspect the disgraceful and illiterate construction. However, no action was taken by this state organization, and the author did not receive any written responses to his appeals. What can be said, the author's conscience is clear. He has a better chance of surviving the coming devastating earthquake because he lives in a base-isolated house. Then, after the devastating earthquake, the author will be able to show the people and the judiciary all his programs, publications, speeches, and letters, with which he has warned illiterate and corrupt state actors and builders of the dangers and hell in which our nation will find itself. Then all of them, as well as various controlling organizations, will be held accountable to the people for what happened in the course of numerous court hearings.

2. Seismic isolation strategies are the way to overcome the heavy and sorrowful consequences of strong earthquakes

The author is absolutely confident that seismic isolation strategies are the way to overcome the above-described consequences. Due to his huge efforts, Armenia is now the second country in the world after Japan by the number of seismically isolated buildings per the number of residents. This is evidenced in "Recent Worldwide Application of Seismic Isolation and Energy Dissipation and Conditions for Their Correct Use"[5], where it is stated: "*It is worthwhile stressing that Armenia remains second, at worldwide level, and has the largest number of building applications of seismic isolation per number of residents, in spite of the fact that it is still a developing country*". Currently, there are more than 60 base- or roof-isolated buildings designed by the author that are newly constructed or retrofitted in Armenia. Some of these buildings constructed by different local construction companies are shown in **Figure 4**.

Figure 4. Some of the base or roof-isolated buildings are newly constructed or retrofitted in Armenia. **(a)** 5-story existing stone apartment building in Vanadzor retrofitted by base isolation for the first time in the world without interruption of the use of the building; **(b)** 11-story building of the multifunctional residential complex "Cascade"; **(c)** 20-story business center "Elite Plaza"; **(d)** 16- and 14-story buildings of the multifunctional residential complex "Arami"; **(e)** 18-story buildings of the multifunctional residential complex "Northern Ray"; (f) 16- and 13-story buildings of the multifunctional residential complex "Dzorap"; **(g)** 17-story building of the multifunctional residential complex "Baghramian"; **(h)** 17-story building of the multifunctional residential complex "Sevak"; **(i)** 9-story existing frame building protected by the roof isolation system—Additional Isolated Upper Floor—acting as a tuned mass damper.

Why does the author consider seismic isolation as the way to reliably protect buildings from the impact of strong earthquakes? The matter is that seismic isolation solves the problem of reducing simultaneously inter-story drifts and floor accelerations at each level of the buildings. This is easy to understand looking at the deformations of the buildings along their height. Time history analysis was carried out using the record of the 1988 Spitak earthquake. A comparison of the deformed states of the same building with and without seismic isolation is clearly proving this statement (**Figure 5**).



(a) **(b)** **(c)** **(d)**

Figure 5. Limit deformed states of the 18-story buildings of the residential complex "Northern Ray" with **(a,c)** and without **(b,d)** seismic isolation systems.

Results of calculations show that inter-story drifts in base-isolated buildings are smaller than in fixed base buildings by 2.6 times on average and horizontal shear forces are smaller by 2.3 times on average. The other example (**Figure 6**) shows that in a base-isolated building, reduction of 0.4 g input acceleration takes place along the height of the superstructure by 2.6 times on average, but in a fixed base building, vice versa, amplification of 0.4 g input acceleration takes place along the height of the structure by 2.25 times. Similar results were received by the author when carrying out comparative analyses for many other base-isolated and fixed-base buildings.

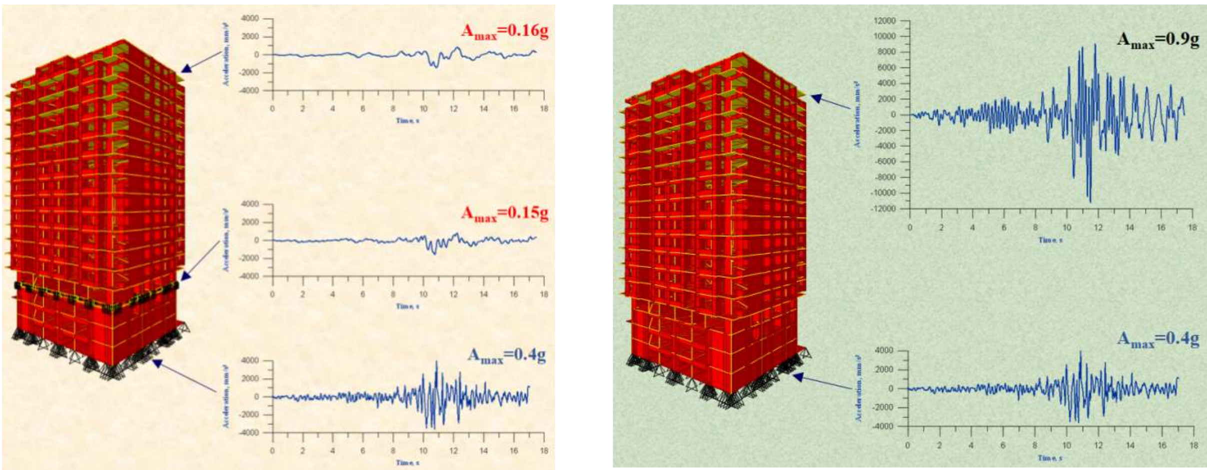


Figure 6. Reduction of input acceleration in 17-story base-isolated building of residential complex "Sevak" (left) and amplification of input acceleration in fixed base building (right).

That is why the experience of strong earthquakes shows and confirms that seismicly isolated buildings demonstrate high resilience and excellent behavior while conventional fixed-base buildings get huge damages and destructions[6]. In seismically isolated buildings, people feel earthquakes from 8 to 10 times less, and no damage takes place to sensitive internal equipment. Therefore, the only practical way to overcome the negative consequences described above in Part 1 is to use seismic isolation systems. They provide the necessary flexibility, with the displacements concentrated at the isolation level[7].

It must be especially emphasized that seismic isolation brings not only highly reliable construction but also, in Armenia, this system significantly reduces the cost of construction of new buildings and the cost of retrofitting existing buildings[1]. As an example, let us consider the newly constructed Yerevan residential complex consisting of one 16-story and two 10-story base-isolated buildings (**Figure 7**). These buildings were designed by the author with the application of seismic isolation systems, but it is necessary to underline that previously these buildings, having the same architectural solutions, were designed by other engineers with fixed base structural systems. This made it possible to directly compare the consumption and cost of the concrete and steel in the structural elements of the fixed-base and base-isolated R/C frame buildings with shear walls.

(a) **(b)**

Figure 7. Design **(a)** and completed **(b)** views of the 16- and 10-story base isolated buildings in the residential complex "Our Yard".

In the multifunctional multistory residential base isolated complex, "Our Yard" the reduction of consumption of the construction materials takes place due to changes in the cross sections of structural elements and a significant decrease in stories' drifts, namely:

- Foundations changed from the 1500mm thick solid slab to the strip beams with a cross-section of 900 mm × 1500 (h) mm;
- Cross sections of columns in the superstructure changed from 600 mm × 600 mm to 500 mm × 500 mm;
- Cross sections of beams in the parking floors changed from 700 mm × 600 (h) mm to 700 mm × 500 (h) mm;
- Cross sections of beams in the superstructure changed from 600 mm × 520 (h) mm to 500 mm × 350 (h) mm;
- The thickness of the floors' slabs changed from 200 mm to 150 mm;
- The thickness of shear walls in the parking floors changed from 400 mm to 300 mm;
- The thickness of shear walls in the superstructure changed from 300 mm to 160 mm;
- Consumption of steel per 1 m^3 of concrete changed from 150 kg to 90 kg.

As a result of the changes due to the application of the seismic isolation strategy to the considered buildings, the total saving was revealed and given in **Table 1**.

Table 1. Comparison of consumption and cost of the concrete and steel in the structural elements of the 16- and 10-story fixed base and base-isolated buildings of the multifunctional residential complex "Our Yard".

Structural elements		Fixed base buildings	Base isolated buildings
Consumption of concrete	Foundation	3131 (B25)	1648 m^3 (B25)
	Columns	3148 m^3 (B25)	1499 m^3 (B20)
	Beams	4254 m^3 (B25)	2488 m^3 (B20)
	Shear walls	2715 m^3 (B25)	1939 m^3 (B20)
	Slabs	4308 m^3 (B25)	3282 m^3 (B20)
	Beams below seismic isolators	-	334 m^3 (B25)
	Beams above seismic isolators	-	705 m^3 (B25)
Total consumption of concrete		17556 m^3	11895 m^3
Total consumption of steel		2635 t (150kg/m^3)	1071 t (90 kg/m^3)
Total cost	of concrete	$1,773,156	$1,179,500
	of steel	$2,239,750	$910,350
	of seismic isolators	-	$270,200
Total cost of construction materials for the complex		$4,012,906	$2,360,050

Comparing the values of the total cost of construction materials for the complex, it can be stated that savings due to the application of seismic isolation comprise 41%. From **Table 1**, one can see that for the fixed base building, the grade of the concrete is B25, but for the isolated base, it is mainly B20. This means that a huge amount of cement will also be saved. Thus, the actual savings will be higher than 41%.

In relation to the existing buildings, it can be stated that retrofitting cost and time, due to the application of the invented by the author seismic isolation technology, are reduced to a much higher extent. As an example, let us consider the existing old 9-story large panel apartment building (**Figure 8**) constructed in Stepanakert many decades ago in the Soviet era[8].

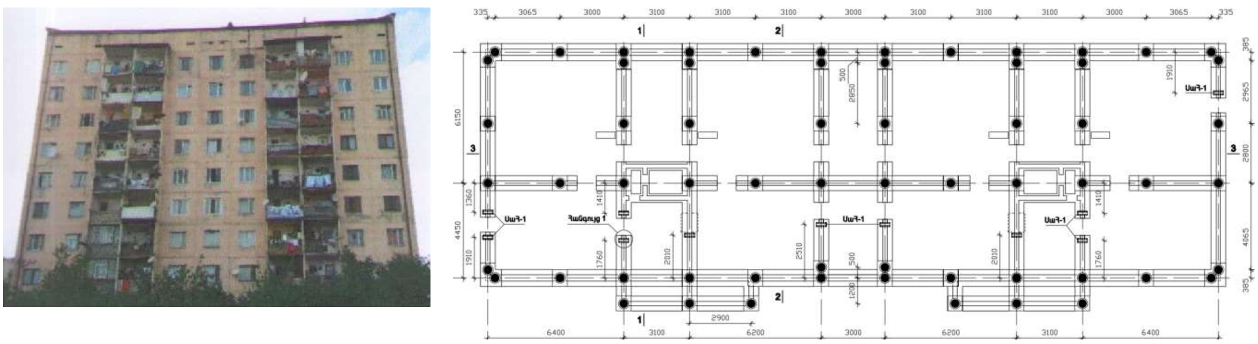


Figure 8. View of the existing 9-story large-panel apartment building and plan of the location of rubber bearings in the seismic isolation interface at the level of its basement.

The building has a symmetric rectangular plan with main dimensions of 34.6 m × 11.2 m. It has two exterior (300 mm thick) and one interior (200 mm thick) longitudinal load-bearing walls as well as two exterior and six interior transverse load-bearing walls. All walls in the transverse direction have a thickness equal to 200 mm. The floors' slabs consist of precast reinforced concrete hollow-core panels.

Before the customer approached the author with the request to develop the base isolation retrofitting design for this existing 9-story large-panel apartment building using innovative technology, he had ordered earlier to another company to develop a design for strengthening the same building using one of the known conventional methods. Obviously, conventional strengthening requires the eviction of tenants from the building. Construction cost calculated based on the design for conventional strengthening was about $1,000,000, and the time estimated for execution of conventional strengthening was about 2.5 years. After receiving and approving the author's base isolation retrofitting design, the cost and time estimation were accomplished by the customer, and it appeared that the earlier received figures were significantly decreased to $185,000 and 6 months, respectively. Also, during the application of this new technology, there is no need to move people out of their apartments, and, on the other side, the cost and time of retrofitting decrease by 5 times on average.

3. Afterword

In the end, the author would like to stress that illiterate construction and corruption in the construction industry encouraged by some corrupt governmental bodies in Armenia must stop. The tragic consequences of the Spitak and other devastating earthquakes in the world must never be forgotten, and lessons must be learned. The population of Armenia deserves to live in resilient buildings and should not become the victim of the future strong earthquakes and of illiterate, irresponsible dregs who lack a moral compass and overlook the problem of national security.

To overcome the current poor situation in the construction industry of Armenia, the old conventional methods of construction must be left away and replaced by modern and highly reliable construction technologies and materials. One such technology is seismic isolation, which, as evidenced by the consequences of the strong earthquakes in different countries, proves to be the most reliable technology, providing an incomparably high extent of increase in earthquake resistance of newly constructed and retrofitted buildings and structures. Moreover, the seismic isolation strategy leads to huge savings in construction costs and improves the quality of life for people who live in such buildings.

Conflict of interest

The author declares no conflict of interest.

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Original Research Article

Assessing seismic risk in the built environment of Istanbul: High-resolution hazard mapping and ground motion analysis in the sea of Marmara region

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ABSTRACT: This research scrutinizes the seismic threat looming over Istanbul, potentially subject to a substantial earthquake. We analyze six plausible earthquake scenarios, utilizing six ground motion prediction equations (GMPEs), to forge high-resolution seismic hazard maps. These maps reveal not only peak horizontal ground accelerations but also spectral acceleration values across varying temporal frames, integrating the amplification effects of softer sediments. Our approach delineates that Istanbul's western shoreline faces heightened risk, with median spectral accelerations at 0.3 s approaching 1 g, signifying intense shaking potential. In contrast, the area encompassing the financial district exhibits lower values, around 0.3 g. The granularity of these findings lays bare the seismic vulnerabilities of the region, offering a window into the risks and potential damages facing this bustling metropolis. This enhanced understanding paves the way for strategic urban planning and risk mitigation efforts aimed at safeguarding Istanbul's populace and infrastructure. This article succinctly condenses our study's pivotal conclusions, presenting a clarion call for proactive measures to diminish earthquake impacts on this dynamic urban landscape.

KEYWORDS: deterministic seismic hazard analysis; Istanbul metropolis; seismic design; site amplification; hazard; earthquake; risk; insurance; sea of Marmara; seismic risks in the building environment; seismic design; seismic-resistant construction

1. Introduction

Istanbul's historical significance is unparalleled, having been the epicenter of several empires, from the Roman to the Ottoman. Its unique geographical positioning along a 30 km strait, which serves as a conduit between the Black Sea and the Sea of Marmara, has long been strategic. Modern-day Istanbul covers an area of 1830 km^2, with its metropolitan expanse reaching 6220 km^2, supporting a dense population of approximately 16 million individuals. However, its illustrious history is marred by a legacy of seismic volatility due to its location within one of Eurasia's most active seismic belts, as evidenced by over ten notable seismic events since 1509, depicted in **Figure 1**.

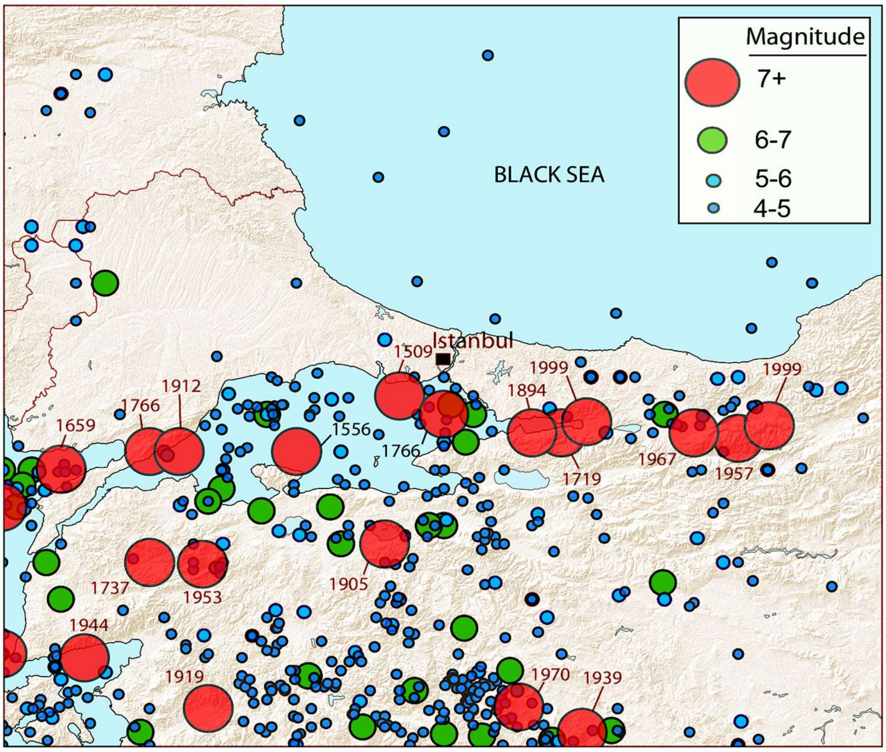

Figure 1. Map of Sea of Marmara (Turkey) region showing historic seismicity. More than ten damaging quakes have occurred since 1509. Within last century, seven earthquakes with M ≥ 7 took place. The earthquake magnitudes are indicated by the size of the circles.

The region's seismicity, particularly illuminated by the 1999 Kocaeli (M7.4) and Düzce (M7.2) earthquakes along the North Anatolian Fault Zone (NAFZ), has had a profound impact on the city's seismic risk profile, as documented in **Figure 2**. The NAFZ, a prominent strike-slip fault system, facilitates right-lateral slip movement between the Anatolian and Eurasian plates and has been characterized by a sequence of significant earthquakes, with magnitudes exceeding 6.7 (**Figure 3**).

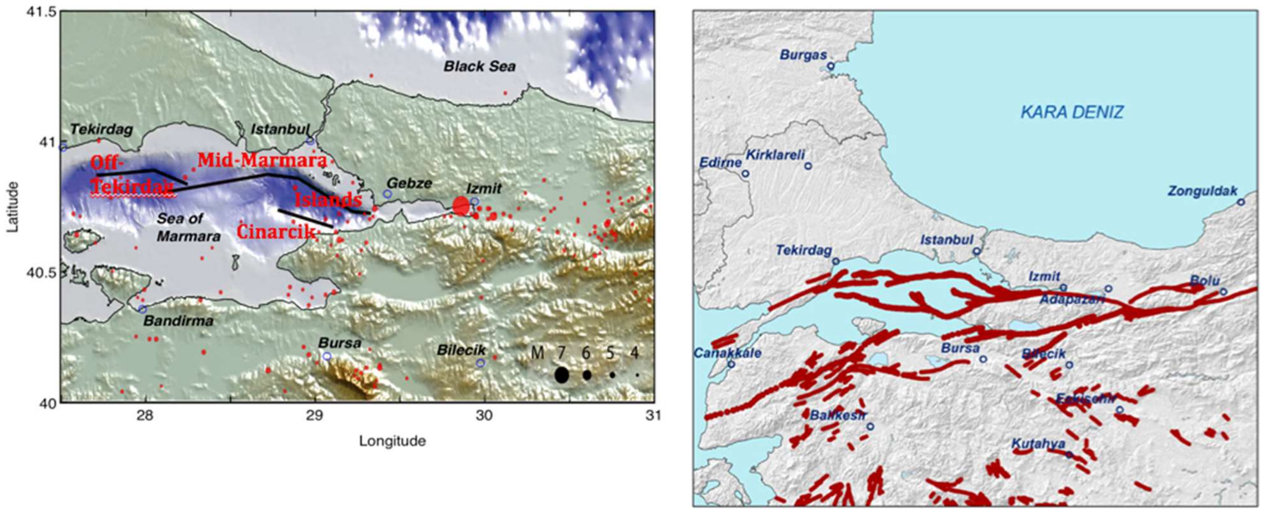

Figure 2. Map of Sea of Marmara (Turkey) region showing instrumental seismicity for the time period 1973–2010. The earthquake magnitudes are indicated by the size of the circles. Also shown are the submarine fault segments (Off-Tekirdağ, Mid-Marmara, Islands, and Çınarcık) under the Sea of Marmara floor; these fault segments may nucleate an M ≥ 6.9 event that may strongly shake the Istanbul Metropolitan Area. Nearest fault segments lie within 10 to 15 km offshore from the city's southern coastline.

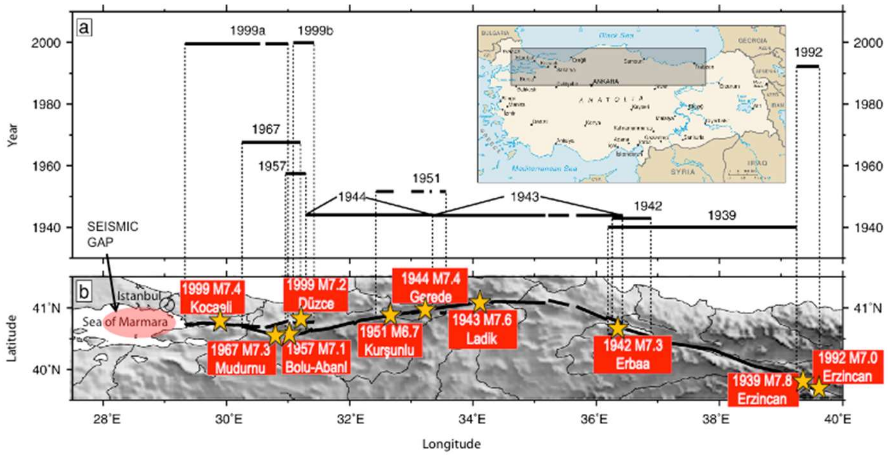

Figure 3. Sequence of westerly propagating ten large (M ≥ 6.7) earthquakes on the North Anatolian Fault Zone (NAFZ), shown with thick black line. Potential seismic gap in the Sea of Marmara is highlighted; also shown are the fault rupture length for each event along the NAFZ; the most recent events of this sequence are the 1999 M7.4 Kocaeli (Izmit) and M7.2 Duzce earthquakes.

This study addresses the critical need for a detailed seismic hazard and risk assessment for Istanbul tailored for earthquake engineering applications. The western extension of the NAFZ, particularly the submarine fault system comprising the Islands, Çınarcık, Mid-Marmara, and Off-Tekirdağ fault segments, poses a pronounced seismic threat to the Istanbul metropolitan area. These segments harbor the potential to generate earthquakes with magnitudes of 7 or greater, which could inflict considerable damage upon the city's infrastructure.

The seismic vulnerability of Istanbul is further exacerbated by its dense population, extensive infrastructure, and the prevalence of high-rise structures. The metropolis hosts numerous essential services, including healthcare, education, and transportation systems, and stands as a pivotal economic center with myriad commercial and industrial operations. Notably, the earthquake exposure concentrated around the Marmara Sea region constitutes 58% of the total regional exposure, with commercial enterprises being the most affected sector, as illustrated in **Figure 4**.

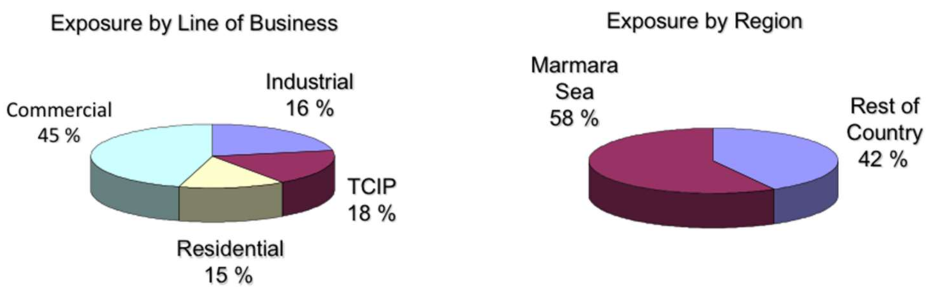

Figure 4. The majority of earthquake exposure, which accounts for 58% of the total, is located around the Marmara Sea region. The largest portion of this exposure is related to commercial lines (Credit: Risk Management Solutions Inc., Newmark, CA).

In light of these findings, the imperative to devise and implement comprehensive seismic risk mitigation strategies for Istanbul cannot be overstated. This research endeavors to fill the existing gap by providing high-fidelity seismic hazard maps and risk assessments, enabling the development of informed engineering solutions and urban planning strategies. By doing so, we aim to enhance the seismic resilience of the Istanbul metropolitan area, ensuring the protection of its inhabitants, the continuity of critical services, and the preservation of its economic vitality in the face of potential seismic catastrophes.

Our work is not only academic in nature but also a foundational piece aimed at guiding the revision of building codes, informing strategic development, and influencing policy-making towards a seismically resilient urban future. It is anticipated that the application of our research findings will lead to a tangible decrease in potential earthquake-induced casualties and property loss, thereby safeguarding the heritage and future prosperity of this historic urban hub.

2. Objective

Seismic hazard assessment is conducted through both probabilistic and deterministic methodologies. Probabilistic Seismic Hazard Analysis (PSHA), which generates maps and related products, plays a critical role in risk evaluation for building codes, earthquake insurance, and the seismic design of essential infrastructure. Prior PSHA endeavors for the Sea of Marmara region, which encompasses Istanbul, were reliant on general descriptions of submarine faults and ground motion prediction equations (GMPEs) from the 1990s. In a pivotal update, Kalkan et al.[1] revisited the region's seismic hazards using a probabilistic approach, adopting the methodology established for the U.S. national seismic hazards maps, with a specific focus on California. These modernized PSHA maps drew from then-available global and local GMPEs and incorporated data on regional faults and both historical and instrumental seismicity.

Conversely, deterministic seismic hazard analysis, often referred to as the 'scenario' method, offers a straightforward and traceable strategy for seismic hazard computation. This approach involves estimating ground motions from a selected subset of potential earthquakes, occasionally representing a single seismic event. For the Sea of Marmara, prior research utilized hybrid simulations to predict peak ground motion values. In this current study, we adopt a deterministic method, employing a range of six local and global GMPEs in a combinatorial manner to address epistemic uncertainty. We've delineated six earthquake scenarios for this task, encompassing single and multiple ruptures on the Islands, Mid-Marmara, Çınarcık, and Off-Tekirdağ fault segments along the NAFZ's western stretch beneath the Sea of Marmara.

The GMPEs are objectively weighted based on their precision in predicting the peak ground motions recorded during the 1999 M7.4 Kocaeli earthquake on the Izmit segment of the NAFZ, just east of Istanbul province. This leads to varied but consistent weights for each GMPE, differing across spectral periods.

The resultant seismic hazard for the region is depicted in high-resolution deterministic hazard maps. These maps, which factor in site effects, detail peak horizontal ground acceleration (PGA) and spectral acceleration (SA) at spectral periods of 0.2, 0.3, 0.5, 1, 1.5, 2, 3, and 4 s with 5-percent damping. The spectral periods of 0.2 and 1 s are particularly significant, often employed as key corner periods for the creation of a smooth design spectrum in structural engineering.

3. Seismotectonics of the Marmara region

Seismic reflection surveys, as explored by Smith et al.[2] and Parke et al.[3], have shed light on the intricate and diverse fault system beneath the Sea of Marmara, extending west from the North Anatolian Fault Zone (NAFZ). While the NAFZ is primarily characterized by right-lateral strike-slip faults near the Marmara Sea's eastern conjunction, a shift occurs beneath the sea. Here, the plate boundary transitions into a trans-tensional system, giving rise to a deep basin as noted by Okay et al.[4] (**Figure 1**). This subsea fault system is not merely a single, uninterrupted strike-slip fault but a series of segmented faults, each with significant normal faulting components. Although the geometry of these faults is well-documented up to a depth of 5 km, uncertainties prevail at greater depths. For this analysis, these segments are presumed to have a vertical dip.

Historically, this zone has witnessed a sequence of powerful earthquakes that have sequentially ruptured along the NAFZ. Notably, the Kocaeli and Düzce earthquakes continued a westward earthquake progression that was initiated with the M7.9 Erzincan earthquake in 1939 along this fault (depicted in **Figure 3**). Considering the 1912 event west of the Sea of Marmara as detailed by Kalkan et al.[1] a seismic gap emerges that has remained inactive for over two centuries (highlighted in **Figure 3**). This gap, spanning roughly 150–160 km, harbors the potential to unleash an earthquake exceeding magnitude 7, as indicated by Hubert-Ferrari et al.[5]. Post-1999 Kocaeli earthquake analyses, such as those by Parsons[6] and Parsons et al.[7], suggest increased shear stress on these fault segments, hinting at their heightened rupture potential.

The region's seismic hazard assessment is complicated by the complexity and variability of the fault system, particularly the vertically dipping segments poised to influence the seismic gap's rupture potential beneath the Sea of Marmara. Recognizing the imminent risk of a significant earthquake, a comprehensive grasp of the fault geometry and rupture dynamics is paramount for a more accurate seismic hazard evaluation.

4. Incorporating site effects for improved seismic hazard assessment

For enhanced precision in ground motion predictions across Istanbul's metropolitan regions, it's crucial to factor in the spatial variation of Vs30 values and their corresponding site effects[8]. Illustrated in **Figure 5** is the Vs30 proxy map, developed following the methodology of Wald and Allen[9], which involves computing topographic slope from a 1-km grid dataset. This map reveals that Vs30 values, indicative of stiff soil to hard rock, span from 400 to 760 m/s along the Sea of Marmara's southern coastline. In contrast, the northern coastlines, abutting the metropolitan areas, exhibit Vs30 values ranging from 200 to 400 m/s.

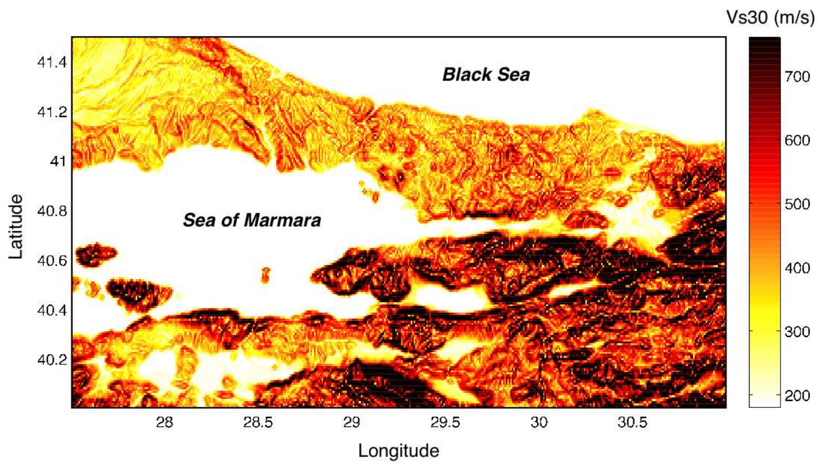

Figure 5. Map of Sea of Marmara (Turkey) region showing a proxy for the shear-wave velocity averaged over the top 30 m of the ground (Vs30) derived from the topographic slope. Dark color = rock site, light color = soft soil site, white color = water. Most of the population in the Istanbul metropolitan area resides on soft-soil deposits, prone to amplified ground shaking during earthquakes (Vs30 data was taken from the USGS).

Particularly noteworthy are the soft sediments, characterized by Vs30 values below 300 m/s, located in the southwestern locales of Istanbul's European side. These areas are more prone to significant ground-shaking amplifications, potentially up to 2.5 times greater than those experienced on the hard rock sites. Therefore, incorporating the spatial variability of Vs30 is indispensable for accurate ground motion estimations pertinent to each specific site within the Istanbul metropolitan expanse.

5. Earthquake scenarios

In the seismic evaluation of the greater Istanbul metropolitan area, our analysis delineated six earthquake scenarios based on potential singular and combined ruptures of the Islands, Mid-Marmara, Çınarcık, and Off-Tekirdağ fault segments. These hypothetical situations, as depicted in **Figure 6**, were informed by historical seismic data and the empirical relationships established by Wells and Coppersmith[10], detailing rupture lengths and anticipated maximum magnitudes (Mmax). For these scenarios, the fault segments in question are presumed to experience strike-slip faulting to their full extent. It is important to note that the earthquakes' hypocenter locations were not considered as variables; the Ground Motion Prediction Equations (GMPEs) employed in this study use specific definitions of distance, such as the closest distance to the co-seismic rupture plane (Rrup) or the closest distance to the surface projection of the causative fault (Rjb). These measures of distance are reliant on the fault's geometry rather than the hypocenter's position.

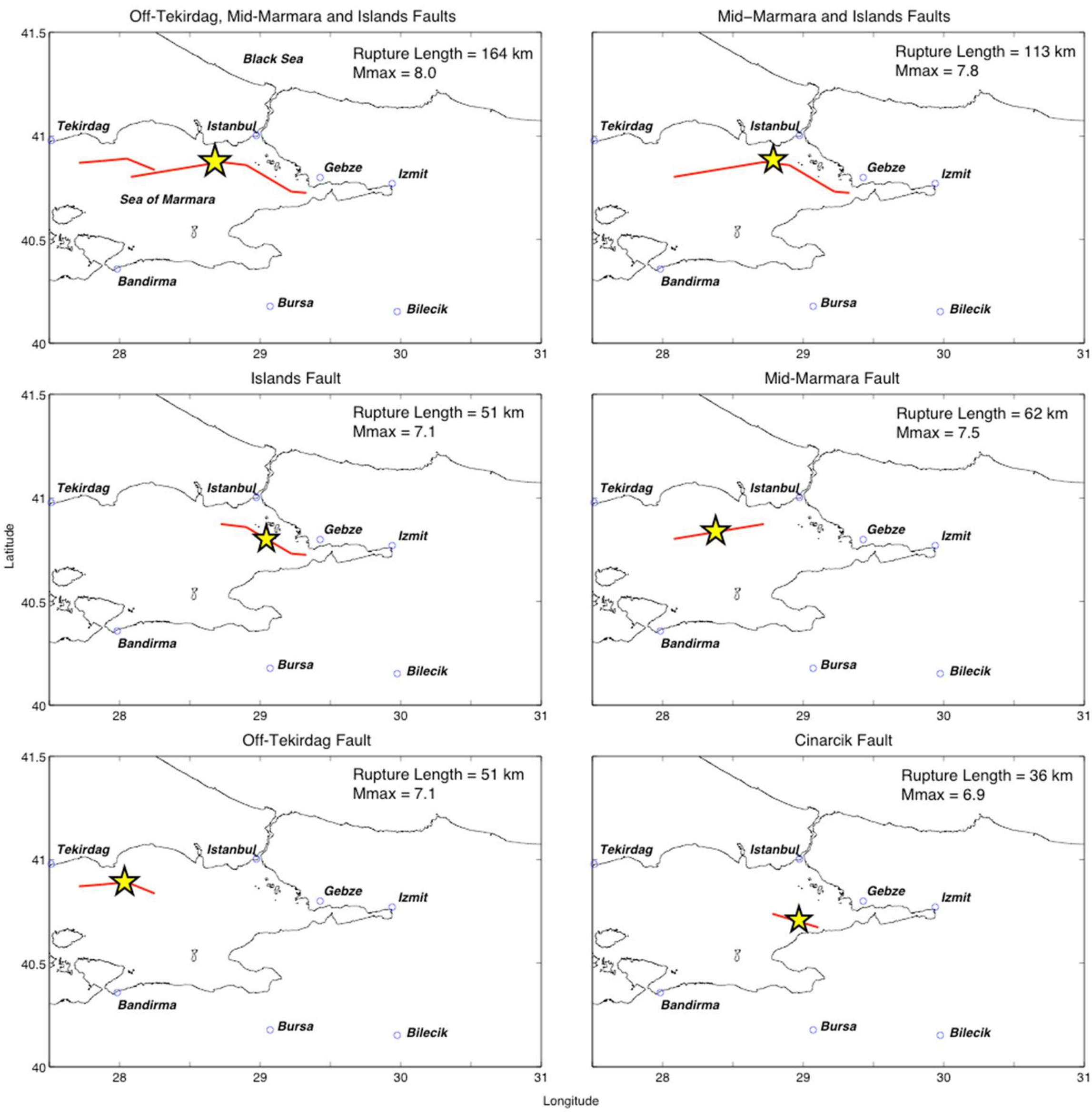

Figure 6. Six earthquake scenarios were defined for the greater Istanbul metropolitan area considering the individual and multiple rupturing of the Islands, Mid-Marmara, Çınarcık and Off-Tekirdağ fault segments. For each scenario, rupture length and expected magnitudes (Mmax) computed according to the historic seismicity and Wells and Coppersmith's[10] empirical equation are shown.

The scenarios outlined herein represent the most significant seismic events that could impact Istanbul, drawn from the understanding that the North Anatolian Fault Zone (NAFZ) is a continuous structure below the Sea of Marmara, as supported by Okay et al.[4] Armijo et al.[11,12], and Le Pichon et al.[13,14]. This continuity suggests that there are no substantial fault offsets that would impede a rupture's progression. While the considerable bends between the Islands and Mid-Marmara, as well as between the Mid-Marmara and Off-Tekirdağ, might theoretically arrest a fault rupture, dynamic faulting models and empirical evidence, such as from the Kocaeli earthquake, indicate that significant fault bends do not invariably halt fault ruptures[15–18]. This understanding is fundamental in recognizing the potential for widespread rupture and its implications for Istanbul's seismic risk assessment.

6. General methodology for hazard computation

The Deterministic Seismic Hazard Analysis (DSHA) methodology is employed to leverage geological and seismic data for identifying potential earthquake sources and calculating the largest conceivable earthquake that each source might generate, given current or theorized tectonic conditions. This hypothetical maximum quake, termed the Maximum Credible Earthquake (MCE), is projected to induce the most significant impact at a specified location. The determination of the MCE incorporates historical seismic records and utilizes the empirical relationship established by Wells and Coppersmith[10], which correlates fault lengths with earthquake magnitudes. By harnessing this data alongside a selection of suitable Ground Motion Prediction Equations (GMPEs) arranged in a logical tree framework, we can derive estimates for Peak Ground Acceleration (PGA) and Spectral Acceleration (SA) across various spectral periods, including 0.2, 0.3, 0.5, 1, 1.5, 2, 3, and 4 s.

6.1. Ground-motion estimation

In our study to quantify seismic hazards while accounting for epistemic uncertainty, we incorporated a suite of six ground-motion prediction equations (GMPEs), which were a blend of global models and those developed specifically for local conditions. The global GMPEs were carefully chosen from the Next Generation of Attenuation (NGA) project, including contributions by Abrahamson and Silva[19], Boore and Atkinson[20], Campbell and Bozorgnia[21], and Chiou and Youngs[22], all of which have been validated for their applicability in Europe and the Middle East, as per the findings of Stafford et al.[23].

Further augmenting our selection, the Graizer and Kalkan[24,25] model, which assimilates data from the NGA project alongside Turkish strong-motion records, was also employed. This model, according to Akkar et al.[26], has demonstrated its efficacy in estimating local ground motions with a precision comparable to its NGA counterparts. For ease of reference within our analysis, the global GMPEs are denoted as AS08, BA08, CB08, CY08, and GK07, respectively. Additionally, the GMPE founded on local data by Kalkan and Gülkan[27] is referred to as KG04.

6.2. Logic tree weighting

To address epistemic uncertainty in hazard analysis, a logic tree approach was utilized. Rather than relying on the subjective weighting of the GMPEs, their expressions were weighted based on the relative accuracy of their performance in predicting peak motions during the 1999 M7.4 Kocaeli earthquake when it ruptured the İzmit segment of the NAFZ up to the eastern reaches of Istanbul, as shown in **Figure 3**. The weighting approach involved assigning a higher weight to a GMPE that demonstrated a smaller overall standard deviation of prediction among other GMPEs. To calculate the relative weights of the GMPEs for each intensity measure (e.g., PGA or spectral accelerations at selected periods), residual analysis was used using the following method:

1) Compute the residuals for the *i*-th GMPE; residuals correspond to the difference between the observations and predictions in natural-log space,
2) Compute the standard deviation of residuals, σ_i for the i^{th} GMPE,
3) Relative weight, W_i, for the *i*-th GMPE is computed as

$$W_i = [1/\sigma_i^2] / \left[\sum_{i=1,n} (1/\sigma_i^2)\right]$$

where *n* is the total number of GMPEs selected and $\sum_{i=1,n}(W_i) = 1$.

Figure 7 illustrates the results of the de-facto segregation showing consistent but varying weights assigned to each GMPE at different spectral periods. Among the six GMPEs, KG04 local GMPE demonstrates the best performance for predicting PGA and spectral acceleration at 0.2, 0.3, 0.5, 1, and 1.5 s, with predictions limited to 2 s. For longer periods (i.e., 3 and 4 s), the remaining five global GMPEs were utilized. AS08 was assigned the highest weight as it has shown superior accuracy in predicting the peak ground motions recorded during the Kocaeli earthquake compared to other GMPEs.

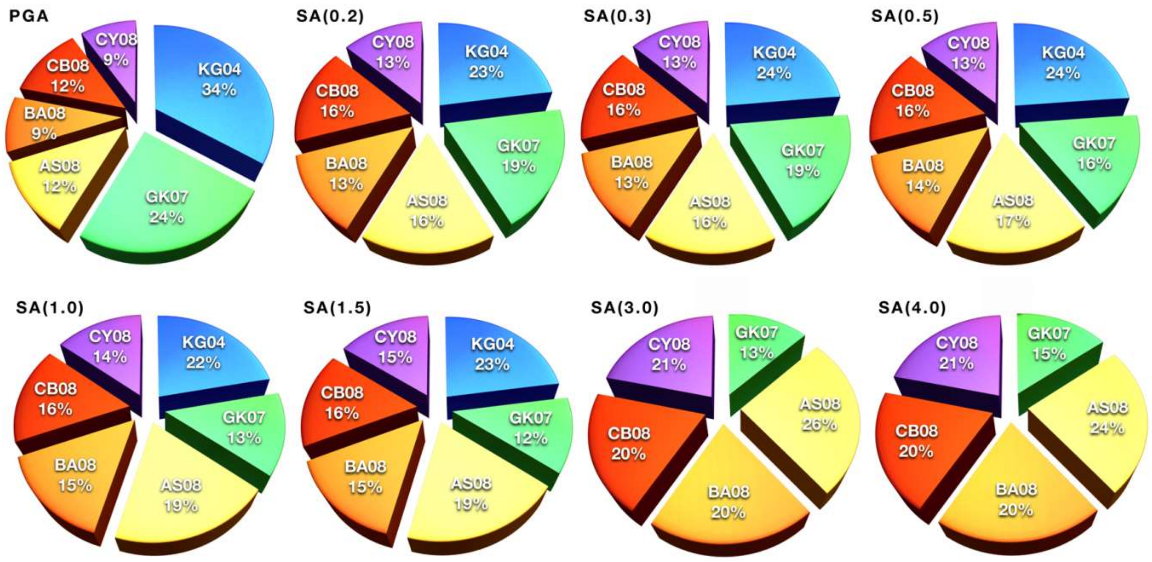

Figure 7. Logic tree weights of GMPEs computed according to their relative performances in predicting the peak motions of the 1994 M7.4 Kocaeli earthquake for PGA and spectral accelerations at 0.2, 0.3, 0.5, 1, 1.5, 2, 3 and 4 s; (local GMPE is KG04[27]; and global GMPEs are GK07[24,25]; AS08[19]; BA08[20]; CB08[21]; CY08[22]).

7. Seismic hazard results

For each earthquake scenario, the following set of maps (with a resolution of 0.002° by 0.002°, or approx. 250 m by 250 m) were generated:

- Median value of peak horizontal ground acceleration (PGA),
- Median value of spectral accelerations (SA) at 0.2, 0.3, 0.5, 1, 1.5, 2, 3, and 4 s for 5%-damping,
- Ratio comparing the shaking level of the 1999 M7.4 Kocaeli event with those in the scenarios for PGA and spectral accelerations,
- Spectral amplification.

Figure 8 displays the median value of PGA for the region for each earthquake scenario, and similarly, **Figures 9** and **10** display the median values of SA at 0.2 and 1.0 sec. These maps incorporate site effects by assigning a Vs30 value corresponding to each grid point by using the map in **Figure 5** as a proxy.

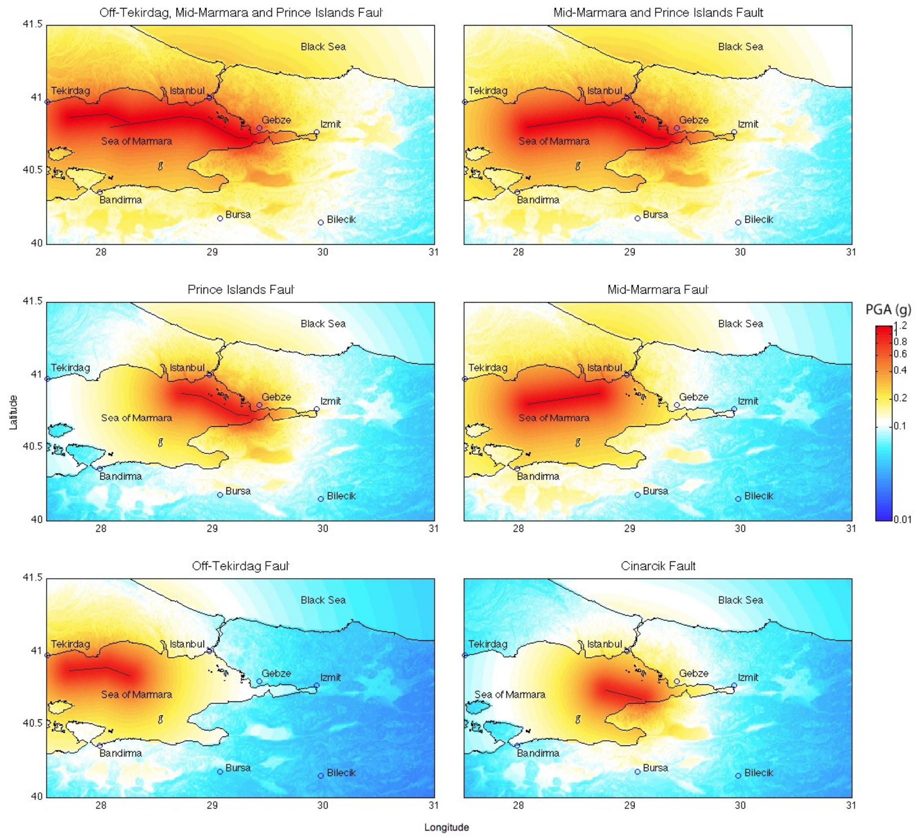

Figure 8. Peak ground acceleration (PGA) estimates for the Sea of Marmara region considering six plausible earthquake scenarios.

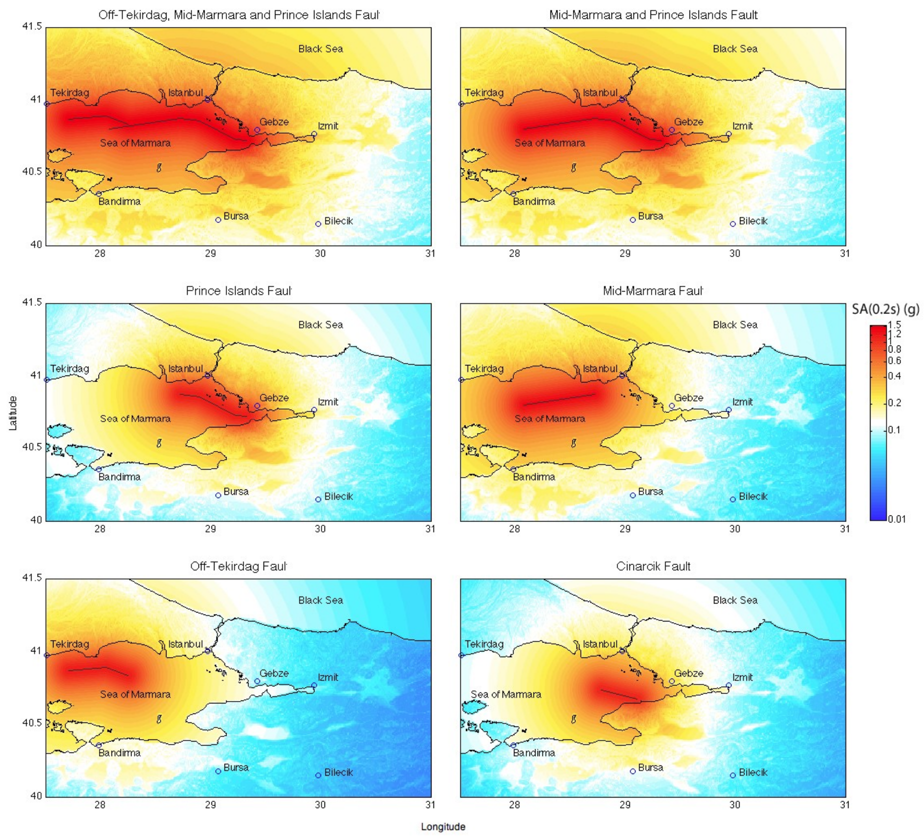

Figure 9. 5%-damped spectral acceleration (SA) at 0.2 sec estimates for the Sea of Marmara region considering six plausible earthquake scenarios.

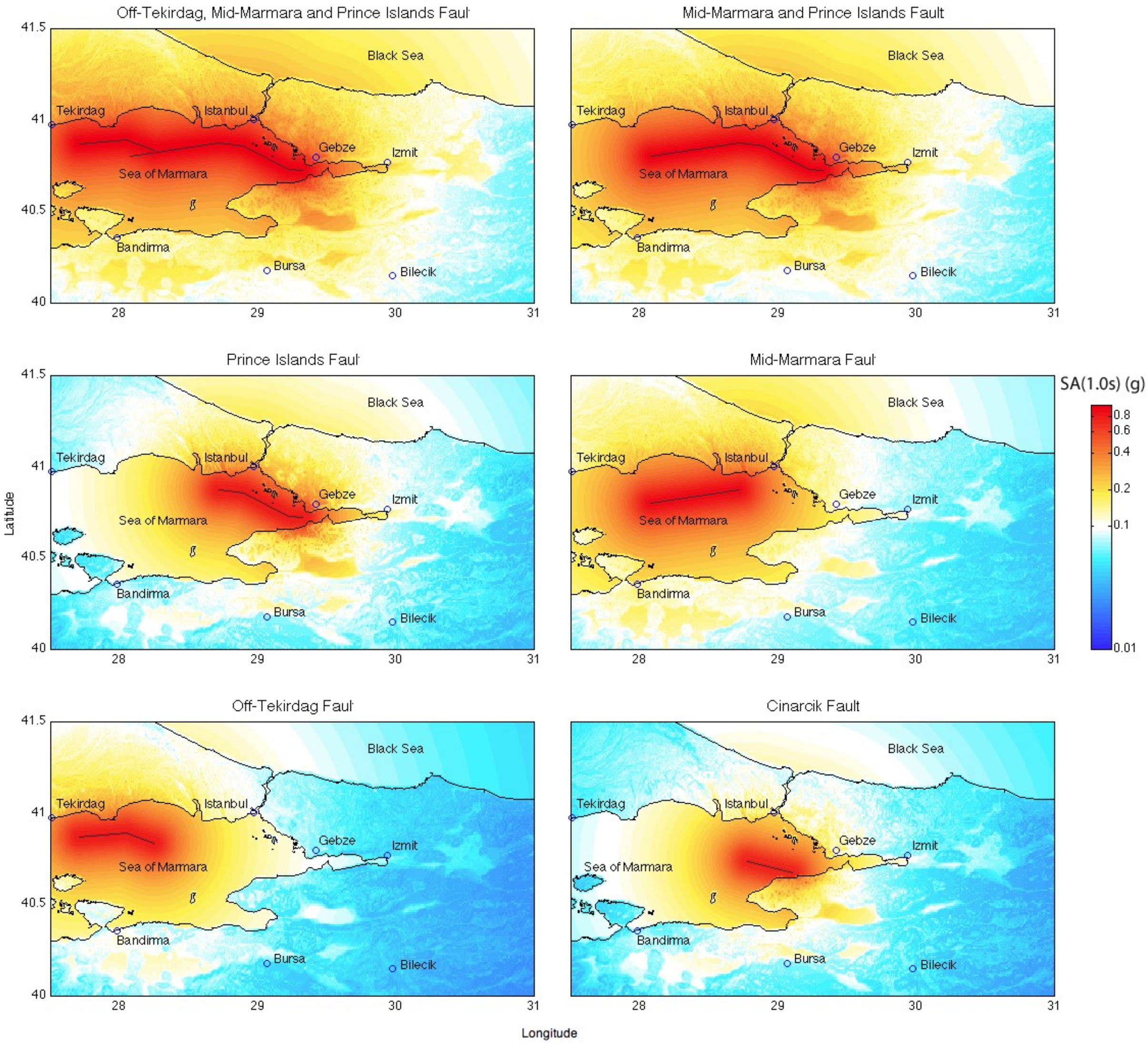

Figure 10. 5%-damped spectral acceleration (SA) at 1.0 sec estimates for the Sea of Marmara region considering six plausible earthquake scenarios.

In **Figure 11**, close-up views of the median values of PGA for the Istanbul metropolis are shown. The distribution of PGA values, shown by the color gradient, indicates a higher shaking level along the coastline of Istanbul, where Off-Tekirdağ, Mid-Marmara, and Islands faults are about 10–15 km offshore. Multiple rupturing of these fault segments is expected to shake the coastal districts of the city on the European side (these are Avcılar, Bahçeşehir, Bakırköy, and Beylikdüzü) with a PGA of 0.5–0.7 g. Intense PGA levels are also expected at the Istanbul Strait, where it opens to the Sea of Marmara. The level of shaking gradually diminishes toward the north. The median PGA ranges between 0.4 g and 0.6 g in the coastal districts of the city on the Asian side (these are Kadıkoy, Maltepe, Kartal, Pendik, and Tuzla). The estimated PGA increases to as much as 0.65 g in Adalar district (Marmara Islands).

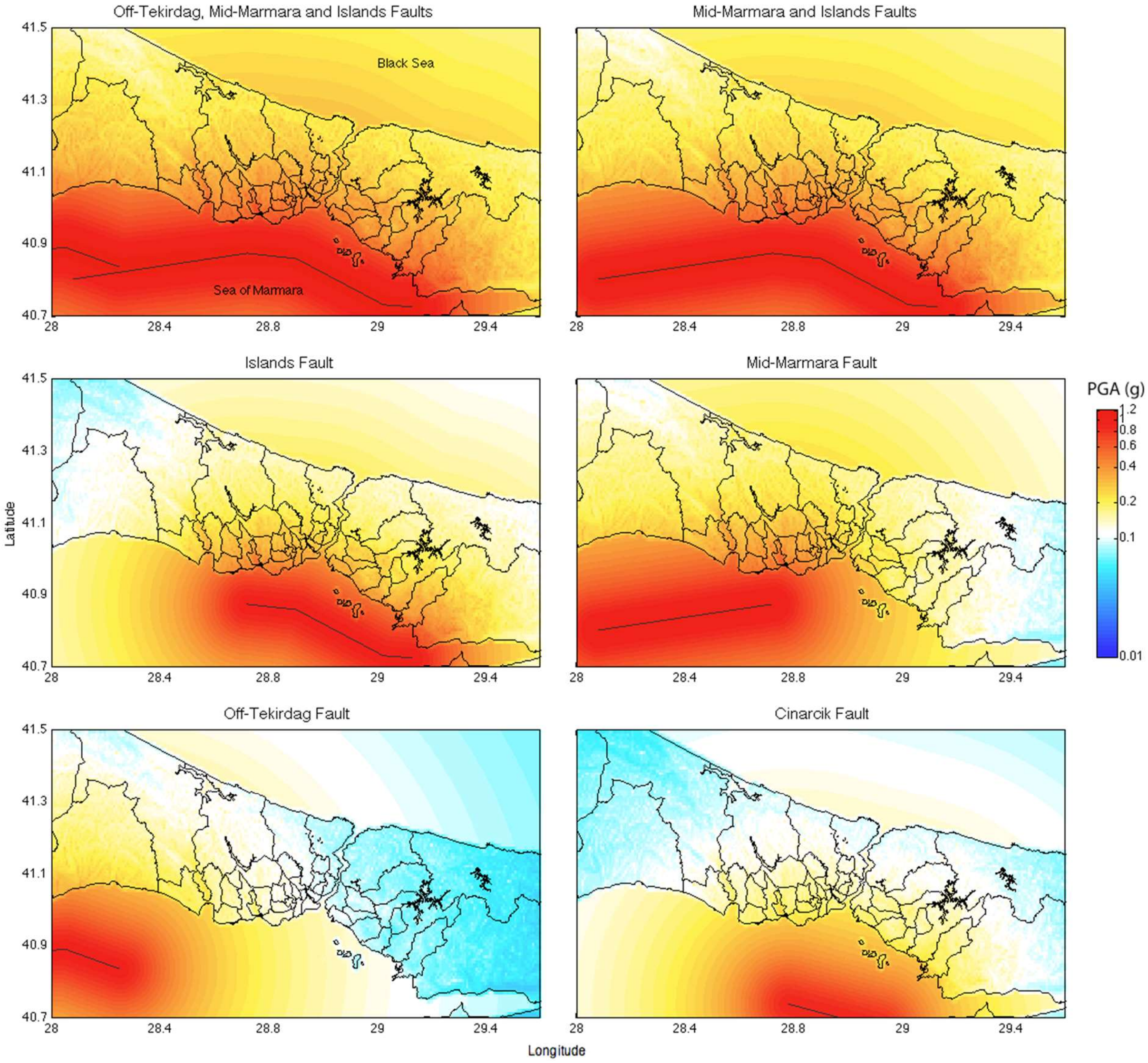

Figure 11. Close-up to peak ground acceleration (PGA) estimates for the Istanbul metropolitan area considering six earthquake scenarios. The median computed PGA is 0.65 g along the shoreline to the west of Istanbul (Bakırkoy district) and at Marmara Islands (Adalar discrict) as a result of multiple rupturing of Off-Tekirdağ, Mid-Marmara, and Islands faults; map (top panel) shows districts of the Istanbul Metropolitan Area.

Figure 12 shows the districts of the Istanbul metropolitan area, and **Table 1** lists the PGA and SA values at 0.2, 0.3, 0.5, 1, 1.5, 2, 3, and 4 s computed at the central point of each district considering the worst-case earthquake scenario (that is, multiple rupturing of Off-Tekirdağ, Mid-Marmara, and Islands fault segments). In this table, the districts expected to experience the highest shaking are also highlighted. This table shows that the largest expected spectral acceleration at short periods (0.3 s) that are close to the fundamental vibration period of 3- and 4-story reinforced concrete buildings is close to 1 g along the shoreline to the west of Istanbul and at the Sea of Marmara islands. The majority of the building stock in these parts of the city, including those at Avcılar, Bakirkoy, Bahçeşehir, and Adalar districts, are 3–5 story heights, which are the most vulnerable. At the city's financial district (Sarıyer), which has mostly mid- and high-rise buildings (5- to 30-story), the largest expected spectral acceleration at 0.5, 1, and 3 s are 0.24, 0.2, and 0.07 g, respectively. This level of shaking indicates that the financial district of the city will be shaken in much less intensity than its shoreline.

Table 1. Peak ground acceleration (PGA) and spectral acceleration (SA) values (at 0.2, 0.3, 0.5, 1, 1.5, 2, 3, and 4 s for 5%-damping) computed at central point of districts in the Istanbul metropolitan area considering the worst-case earthquake scenario (that is, multiple rupturing of Off-Tekirdağ, Mid-Marmara and Islands fault segments). The districts, expected to experience the highest shaking, are highlighted.

District name	Population	Area	Population density		Spectral accelerations (g)							
		(km^2)	(people/km^2)	PGA (g)	(0.2 s)	(0.3 s)	(0.5 s)	(1 s)	(1.5 s)	(2 s)	(3 s)	(4 s)
Adalar	10,460	11.05	947	0.65	0.91	0.95	0.71	0.59	0.37	0.28	0.20	0.15
Arnavutköy	148,419	506.5	293	0.27	0.36	0.37	0.27	0.24	0.16	0.12	0.09	0.07
Ataşehir	345,588	25.87	13,359	0.42	0.57	0.57	0.41	0.36	0.23	0.17	0.13	0.10
Avcılar	322,190	41.92	7686	0.55	0.77	0.78	0.57	0.48	0.29	0.22	0.16	0.12
Bağcılar	719,267	22.4	32,110	0.38	0.53	0.53	0.39	0.33	0.21	0.15	0.11	0.08
Bahçelievler	571,711	16.57	34,503	0.56	0.74	0.77	0.55	0.48	0.32	0.24	0.19	0.14
Bakırköy	214,821	29.65	7245	0.65	0.87	0.90	0.65	0.56	0.37	0.28	0.21	0.16
Başakşehir	193,750	104.5	1854	0.37	0.50	0.51	0.37	0.32	0.21	0.15	0.11	0.08
Bayrampaşa	272,196	9.5	28,652	0.41	0.56	0.56	0.41	0.36	0.23	0.17	0.13	0.10
Beşiktaş	191,513	18.04	10,616	0.34	0.47	0.48	0.35	0.30	0.20	0.15	0.11	0.08
Beykoz	241,833	310.4	779	0.23	0.32	0.32	0.24	0.21	0.13	0.10	0.07	0.05
Beylikdüzü	186,847	37.74	4951	0.52	0.72	0.73	0.53	0.45	0.28	0.20	0.15	0.11
Beyoğlu	247,256	8.96	27,596	0.49	0.68	0.69	0.50	0.42	0.26	0.19	0.14	0.10
Büyükçekmece	151,954	157.7	964	0.45	0.62	0.63	0.46	0.40	0.26	0.19	0.15	0.11
Çatalca	61,566	1040	59	0.25	0.35	0.35	0.26	0.22	0.14	0.10	0.07	0.05
Çekmeköy	135,603	148	916	0.23	0.31	0.30	0.22	0.19	0.12	0.09	0.06	0.05
Esenler	468,448	18.51	25,308	0.37	0.51	0.52	0.38	0.33	0.21	0.16	0.12	0.09
Esenyurt	335,316	43.12	7776	0.49	0.65	0.67	0.48	0.43	0.28	0.22	0.17	0.13
Eyüp	317,695	228.1	1393	0.26	0.35	0.35	0.26	0.22	0.15	0.11	0.08	0.06
Fatih	455,498	15.93	28,594	0.50	0.67	0.68	0.49	0.44	0.29	0.22	0.17	0.13
Gaziosmanpaşa	464,109	11.67	39,769	0.34	0.47	0.48	0.35	0.30	0.19	0.14	0.10	0.08
Güngören	318,545	7.17	44,427	0.50	0.68	0.69	0.50	0.44	0.29	0.22	0.17	0.13
Kadıköy	550,801	25.07	21,971	0.46	0.63	0.64	0.46	0.41	0.27	0.20	0.16	0.12
Kağıthane	418,229	14.83	28,202	0.31	0.44	0.44	0.32	0.27	0.17	0.12	0.09	0.06
Kartal	427,156	38.54	11,083	0.52	0.70	0.72	0.52	0.45	0.29	0.22	0.17	0.12
Küçükçekmece	662,566	37.25	17,787	0.46	0.65	0.65	0.47	0.40	0.25	0.18	0.13	0.10
Maltepe	415,117	53.06	7824	0.41	0.56	0.57	0.42	0.36	0.23	0.17	0.12	0.09
Pendik	520,486	180.2	2888	0.43	0.61	0.61	0.44	0.37	0.23	0.17	0.12	0.09

Table 1. (*Continued*).

District name	Population	Area	Population density		Spectral accelerations (g)							
		(km²)	**(people/km²)**	**PGA (g)**	**(0.2 s)**	**(0.3 s)**	**(0.5 s)**	**(1 s)**	**(1.5 s)**	**(2 s)**	**(3 s)**	**(4 s)**
Sancaktepe	223,755	61.87	3617	0.26	0.36	0.36	0.27	0.23	0.15	0.11	0.08	0.06
Sarıyer	276,407	151.3	1827	0.23	0.32	0.31	0.24	0.20	0.13	0.09	0.07	0.05
Silivri	118,304	869.5	136	0.31	0.43	0.43	0.32	0.27	0.17	0.12	0.09	0.07
Sultanbeyli	272,758	28.86	9451	0.33	0.46	0.46	0.34	0.29	0.18	0.13	0.10	0.07
Sultangazi	436,935	36.24	12,057	0.34	0.46	0.47	0.34	0.30	0.20	0.16	0.12	0.09
Şile	25,169	781.7	32	0.18	0.24	0.24	0.18	0.16	0.11	0.08	0.06	0.04
Şişli	314,684	34.98	8996	0.42	0.56	0.58	0.42	0.37	0.25	0.19	0.16	0.12
Tuzla	165,239	123.9	1334	0.57	0.78	0.80	0.58	0.50	0.31	0.24	0.18	0.13
Ümraniye	553,352	45.3	12,215	0.40	0.54	0.55	0.40	0.36	0.24	0.19	0.15	0.11
Üsküdar	529,550	35.34	14,984	0.34	0.48	0.48	0.35	0.30	0.19	0.14	0.10	0.07
Zeytinburnu	288,743	11.31	25,530	0.53	0.73	0.74	0.54	0.46	0.30	0.22	0.17	0.13

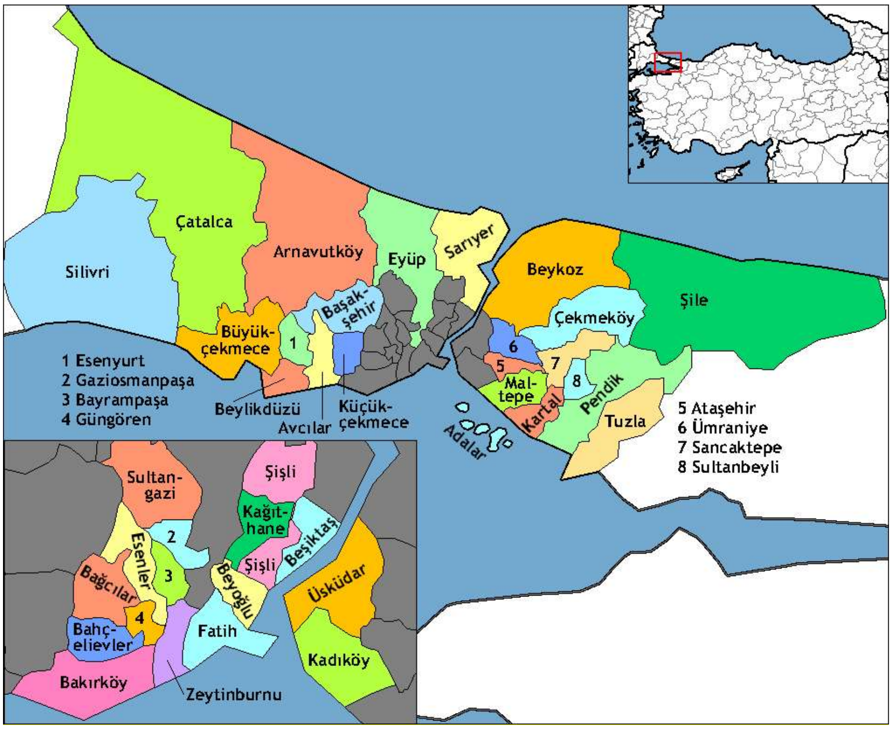

Figure 12. Districts of the Istanbul metropolitan area.

8. Comparing ground shaking with the 1999 M7.4 Kocaeli earthquake

Figure 13 showcases the comparative analysis where the Peak Ground Acceleration (PGA) ratio is calculated, contrasting the projected outcomes referenced in **Figure 11** with the actual PGA values recorded during the 1999 M7.4 Kocaeli earthquake in Istanbul. This analysis reveals that the western part of the Istanbul Metropolitan area could encounter ground-shaking intensities that exceed, by more than threefold, the levels experienced in the 1999 Kocaeli tremor.

9. Conclusions

In this study, we delved into the seismic hazards threatening Istanbul, a city on the cusp of a potential major earthquake. Our goal was to establish a robust scientific foundation for seismic design applications, evaluating the intensity of ground shaking across six well-defined earthquake scenarios. These plausible scenarios were constructed based on a rich blend of geological, tectonic, historical, and instrumental evidence, ensuring a comprehensive risk assessment.

We employed an objective approach in choosing logic-tree weights for Ground Motion Prediction Equations (GMPEs) and factored in the site-specific amplification effects of near-surface soils. This dual consideration allowed us to paint a more detailed picture of the seismic shaking hazards across the Sea of Marmara region.

The tangible outcome of our research is a set of deterministic seismic hazard maps that not only provide a granular view of potential risks but also serve to enhance the probabilistic seismic hazard maps introduced by Kalkan et al.[1]. These maps are primed for integration into the risk assessment and structural design processes within the Istanbul metropolitan area, serving as a crucial tool for both new constructions and the evaluation of existing structures. They underscore the need for improved design and construction methodologies aimed at mitigating loss of life and property in the face of seismic events.

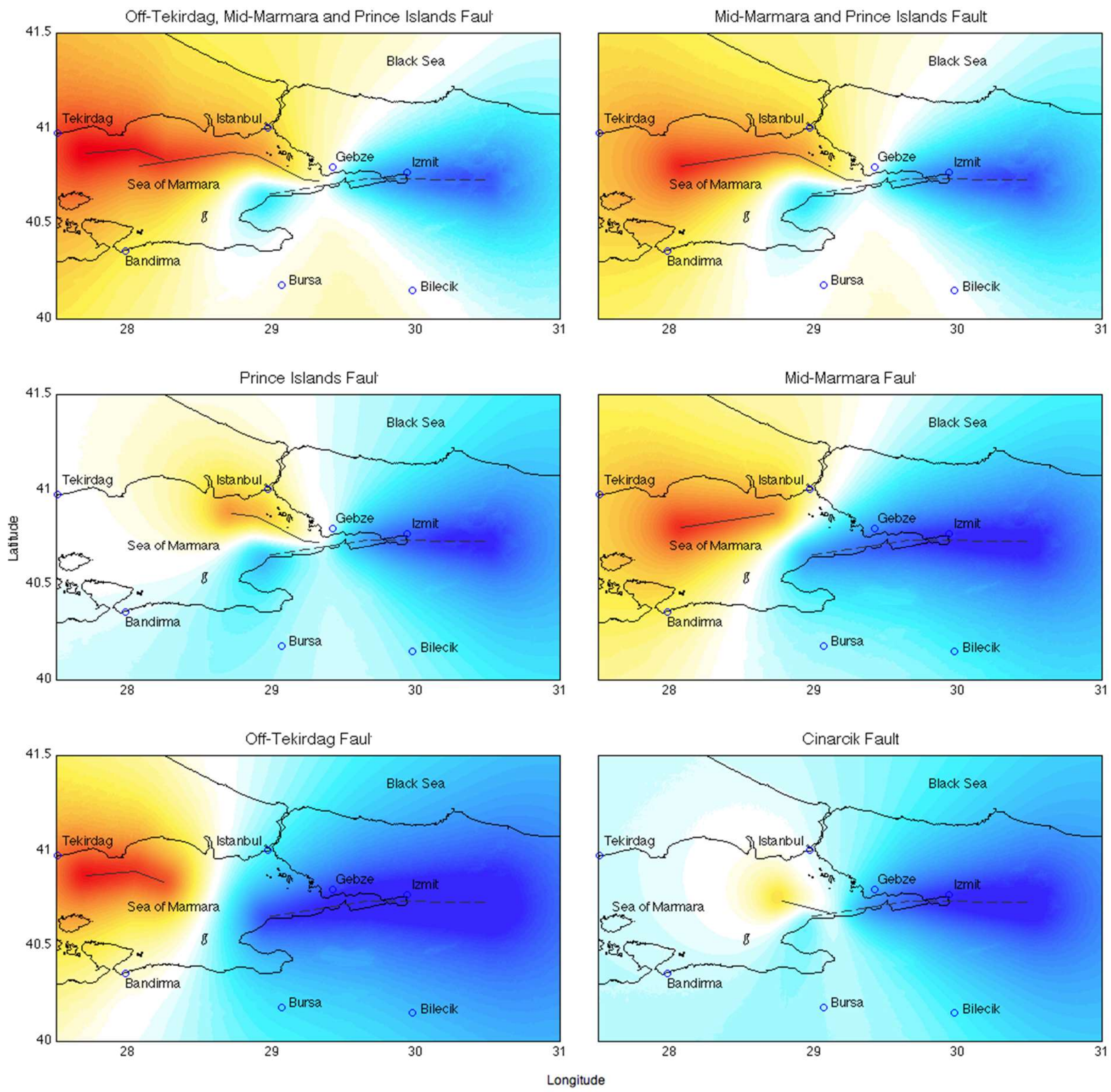

Figure 13. Ratio of PGA values of scenario earthquakes to the 1999 Kocaeli Earthquake shows that the west of the Istanbul Metropolitan area is expected to be shaken more than three times as it did during the Kocaeli Earthquake.

Moreover, our methodology has broader applications, extending to other seismically active regions such as eastern Turkey, which suffered from devastating earthquakes in 2023. Our findings offer a supplementary perspective to the Global Seismic Hazard Assessment Project, with our approach providing a more refined scale of analysis.

The study also addresses the potential integration of our methods into current design and construction regulatory frameworks, including the Turkish Seismic Design Code. This discussion underscores the practical implications of our findings and paves the way for their institutional implementation.

Lastly, we contemplate the strategic development of Istanbul, proposing rational zoning strategies informed by our seismic assessments. This element of the conclusion emphasizes the value of our research in supporting urban planning and the proactive mitigation of earthquake risks in Istanbul and similar urban environments.

Through these multifaceted conclusions, our study serves as a reminder of the power of informed, data-driven decision-making in enhancing structural resilience and public safety.

Author contributions

Conceptualization, EK and PK; methodology, EK and PK; software, EK; validation, EK and PK; formal analysis, EK and PK; investigation, EK and PK; resources, EK; data curation, EK; writing—original draft preparation, EK; writing—review and editing, EK and PK; visualization, EK; supervision, EK and PK; project administration, EK. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

The authors declare no conflict of interest.

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Original Research Article

Dynamic vibration control of non-linear buildings using multiple tuned mass dampers

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ABSTRACT: In the field of civil engineering, tuned mass dampers (TMDs) serve as passive devices designed for dynamic vibration control of structures. When dealing with buildings exhibiting nonlinear behavior under dynamic loads, the effectiveness of TMDs may be affected by detuning due to the degradation of the building's strength. Therefore, addressing the non-linear behavior requires a unique strategy involving the tuning of TMDs to specific time periods following the onset of non-linearity. The proposed approach in this study entails a pushover analysis to establish the pushover capacity curve. The regions between the origin and a target drift of 1/150 are then represented using an idealized trilinear form, with the initial segment corresponding to linearity and subsequent segments capturing non-linear behavior. The second segment spans from the onset of non-linearity to a target drift of 1/400, and the third segment covers the drift range from 1/400 to 1/150. Examining this strategy involves calculating time periods for each segment. Subsequently, three single TMD (STMD) scenarios and one multiple TMD (MTMD) scenario with 3 TMDs, each tuned to time periods corresponding to specific segments of the idealized trilinear, are compared in this study. The evaluation includes non-linear dynamic analysis of 7-story and 25-story reinforced concrete buildings equipped with these TMD scenarios. The floor maximum displacement and peak acceleration results indicate that the STMDs tuned to the time periods corresponding to the non-linear segments exhibit robustness, surpassing the performance of the STMD tuned to the fundamental period. Remarkably, the MTMD scenario demonstrates superior robustness compared to all three STMD scenarios. Further analysis under wind load on the same 25-story building confirms the effectiveness of the MTMDs and STMD tuned to the nonlinearity segment compared to the STMD tuned to the fundamental period. This research provides valuable insights into TMD design for enhanced building performance under non-linear conditions.

KEYWORDS: dynamic vibration control; multiple tuned mass dampers; non-linear building; control strategy; pushover capacity curve; modal effective mass

1. Introduction

The application of TMDs for controlling the nonlinear behavior of buildings has been the focus of attention in recent times. Numerous research efforts have been dedicated to investigating the efficacy of employing TMDs in addressing the challenges posed by nonlinear behaviors in buildings as the field of structural engineering continues to evolve. This reflects a growing interest in minimizing structural vibrations and enhancing overall stability.

Boccamazzo et al.[1] suggest employing a TMD featuring a spring exhibiting hysteretic behavior with pinching designed to regulate the response of nonlinear structures under seismic forces. The authors conduct two optimizations: the first involves stationary harmonic loading, and the second utilizes seismic records in the time domain, with both approaches yielding comparable results. In comparison to traditional TMDs, the newly proposed device exhibits increased resilience across various seismic intensities and greater efficacy in managing the nonlinear response of the primary structure. Huang et al.[2] propose employing a TMD with a restitutive force generated by an element made of shape memory alloy, allowing the device to prevent detuning through thermal control, consequently adjusting the frequency of the TMD. Lu et al.[3] investigate analytically and experimentally the application of a TMD in which the mass consists of particles colliding with each other, resulting in energy dissipation and a more resilient response compared to the conventional version.

Elias and Matsagar[4] conducted a thorough examination of the installation of multiple tuned vibration absorbers (MTVAs) positioned across both the height and plan of a building. Their primary objective was to mitigate the nonlinear behavior exhibited by the structure. Notably, they emphasized the importance of targeting the first few modes with a modal mass contribution of 90% or more, and all installed devices were conventionally tuned to the time period of each corresponding mode. The findings from their study revealed the efficacy of MTVAs when adhering to optimal placement criteria for multimode dynamic response control.

Domizio et al.[5] addressed potential stiffness and strength degradation during the control device's design. Their proposed TMD configurations include the classical single-degree-of-freedom TMD and the two-degree-of-freedom TMD with parallel and series arrangements, designed to control nonlinear responses in seismic scenarios. An objective function was introduced to sustain the control device's robustness against stiffness degradation. Calculations of the infinity norm of the frequency response magnitude were conducted for two stiffness reduction levels (75% and 50%), representing moderate and severe degradation in reinforced concrete structures. The results highlight that the configuration with two TMDs in series, tuned to 50% of the fundamental frequency of the healthy structure, demonstrated optimal effectiveness when the ductility demand exceeded 5. In short, numerous other studies have also been conducted to explore the application of TMDs in structures with non-linear behavior[6–9].

Distinguished from existing research, this study introduces an innovative approach and specifically focuses on addressing non-linear behavior by tuning TMDs to specific time periods following the initiation of non-linearity. The proposed strategy involves a thorough process, beginning with a pushover analysis to derive the pushover capacity curve. Then it is transformed into a trilinear form covering a region between the origin and a target drift of 1/150. This form outlines the linearity and subsequent non-linear segments of the building's behavior. The tow nonlinear segments span from the onset of nonlinearity to a target drift of 1/400, and the drift ranges from 1/400 to 1/150. Following the calculation of the time periods corresponding to each segment, three STMD scenarios and one scenario featuring MTMDs with three TMD, each precisely tuned to those time periods, are subjected to comparison. Importantly, the total mass ratios of the MTMD scenario are equivalent to those of the STMD scenarios. The efficacy of these strategies is rigorously examined through non-linear dynamic analyses conducted on 7-story and 25-story RC buildings, utilizing frame models. The results, encompassing floors' maximum displacement and peak acceleration, affirm the robustness of the STMDs tuned to the time periods corresponding to the non-linear segments, surpassing conventional STMDs tuned to the fundamental period. Notably, the MTMD scenario exhibits superior robustness when compared to all three STMD scenarios. Furthermore, a comprehensive analysis under wind load conditions on the same 25-story building reaffirms the effectiveness of the MTMDs and STMD tuned to the nonlinearity segment compared to the STMD tuned to the fundamental period. This research contributes valuable insights into the TMD design to effectively mitigate the impact of non-linear behavior in buildings.

2. Control strategy

Traditionally, TMDs are designed to align with a building's fundamental period, with the goal of controlling its primary mode of vibration. As illustrated in **Figure 1**, the pushover capacity curve vividly illustrates the building's response. Notably, nonlinear behavior becomes apparent when the base shear force exceeds 733 kN resulting in a displacement of 0.8 cm at the top floor of this specific structure. Accordingly, during dynamic events like earthquakes and strong wind loads, buildings transition into a nonlinear range. In such circumstances, TMDs, initially tuned to the fundamental period, lose their efficacy. This is attributed to the building's diminishing stiffness as it yields, causing an increase in its period or decrease in its frequency. In response to this challenge, this study proposes an innovative approach: incorporating TMDs tuned to longer time periods than the fundamental period to effectively control non-linear buildings. The pushover capacity curve is idealized using a trilinear representation divided into three regions, as illustrated in **Figure 1**. The first region, denoted by segment $\overline{OA}$, signifies the linear range of the structure, while segments $\overline{AB}$ and $\overline{BC}$ represent the nonlinear segments covering a region between the onset of nonlinearity and a target drift of $1/150$. Rather than opting for a STMD tuned to the fundamental period, this research recommendation advocates for the installation of three smaller TMDs, each precisely tuned to the time periods corresponding to the stiffness characteristics of the three identified regions. This approach is proposed to enhance the overall effectiveness of the damping system and better address the dynamic response of the building throughout various stages of nonlinearity.

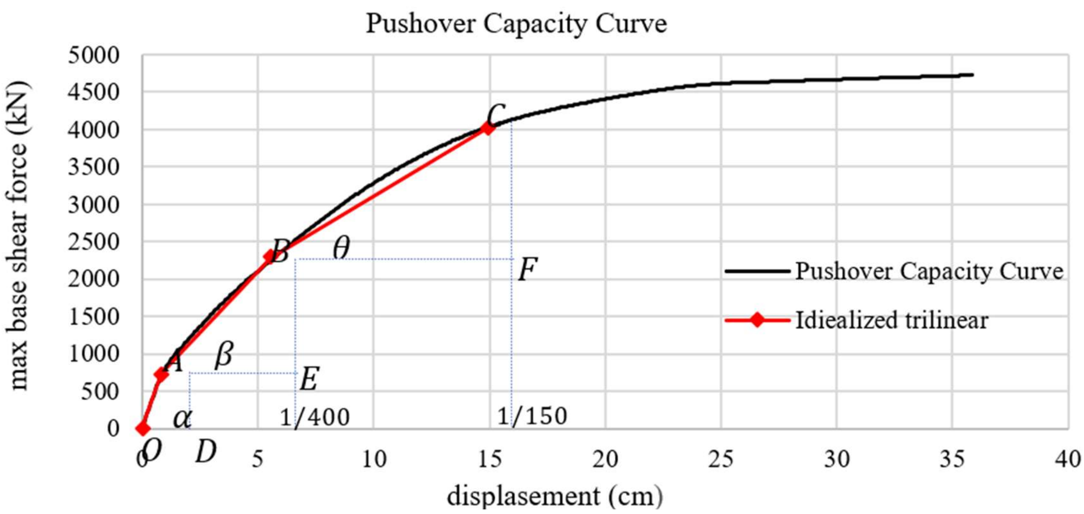


Figure 1. Illustration of an Idealized trilinear on pushover capacity curve of an RCC building in the X-direction.

As depicted in **Figure 1**, the stiffness of the building in regions $\overline{OA}$, $\overline{AB}$, and $\overline{BC}$ can be determined by taking the tangent of α, β and θ, respectively. A detailed step-by-step calculation procedure is outlined in **Table 1** for clarity and reference.

Table 1. Corresponding stiffness and time period calculation methods for each segment of the idealized trilinear.

Stiffness (K_i)	$T_i = 2\pi\sqrt{\frac{m_{eff}}{K_i}}$
$\tan\alpha = \overline{AD}/\overline{OD} = K_1$	T_1 (Fundamental period)
$\tan\beta = \overline{BE}/\overline{AE} = K_2$	T_2
$\tan\theta = \overline{CF}/\overline{BF} = K_3$	T_3

While m_{eff} represents the effective mass of the first dominant mode which is supposed to be controlled and calculated by the Equation (1)[10].

$$m_{eff} = \frac{(\emptyset^T M\zeta)^2}{\emptyset^T M\emptyset} \tag{1}$$

where $\emptyset$ is the mode shape, M is the mass matrix, and ζ is a unit vector. It is noteworthy that the modeling and comprehensive analyses, including eigenvalue analysis, were conducted utilizing the STERA_3D software[10,11].

Tuning a STMD solely to the fundamental period of the building, corresponding to linear range, proves insufficient. Post-yielding, such a TMD would fall out of tune due to the diminishing strength of the structure. Therefore, in addition to conventional TMD, complementary TMDs, specifically tuned to the nonlinearity range of the building, become imperative. The introduction of these additional TMDs is crucial to address the evolving dynamic characteristics of the structure as it progresses from linear to nonlinear behavior, ensuring sustained efficacy in vibration control measures.

3. TMD optimal parameters

In this study, the optimal frequency ratios, and damping ratios of TMDs are calculated using the Equations (2) and (3), respectively[12].

$$f_i = \left(\frac{\sqrt{1-0.5\mu_i}}{1+\mu_i} + \sqrt{1-2\zeta_i^2} - 1\right) - \left[2.375 - 1.034\sqrt{\mu_i} - 0.426\mu_i\right]\zeta_i\sqrt{\mu_i} - \left(3.73 - 16.903\sqrt{\mu_i} - 20.496\mu_i\right)\zeta_i^2\sqrt{\mu_i} \tag{2}$$

$$\zeta_{d\,i} = \sqrt{\frac{3\mu_i}{8(1+\mu_i)(1-0.5\mu_i)}} + \left(0.151\zeta_i - 0.17\zeta_i^2\right) + \left(0.163\zeta_i + 4.98\zeta_i^2\right)\mu_i \tag{3}$$

where μ_i: Mass ratio of i^{th} TMD and ζ_i: Damping ratio of i^{th} mode.

Finally, the damping coefficient and stiffness of each TMD is calculated using Equations (5) and (6) respectively[13].

$$\omega_{di} = f_{opti}\omega_i \tag{4}$$

$$c_{di} = 2\zeta_{di}\omega_{di}m_{di} \tag{5}$$

$$k_{di} = \omega_{di}^2 m_{di} \tag{6}$$

4. Selected ground motion records (GMRs)

In this research, four distinct Ground Motion Records (GMRs) are selected to be applied in example buildings. These records span a moment magnitude scale ranging from 6.1 to 7.5 Mw and exhibit a focal depth variation between 6 and 66 km, details of which are comprehensively presented in **Table 2**[14,15].

Table 2. Detail of input earthquake ground motions.

No	Record name	location	Date (yy/mm/dd)	Depth (km)	Magnitude (Mw)	Duration (sec)	PGA (gal)	
							Component	PGA
1	El Centro	El Centro, California, USA	1940/05/19	8.8	6.9	53.8	East-West	210.1
							Up-Down	−206.3
2	Kobe	Kobe, Japan	1995/01/17	17	6.9	50	East-West	617.1
							Up-Down	332.2
3	Taft	Kern County, California, USA	1952/07/21	16	7.5	54.4	East-West	175.9
							Up-Down	102.9
4	Tohoku	Tohoku, Japan	1978/02/20	60	6.1	41	East-West	202.6
							Up-Down	153.0

The acceleration response spectrum of the selected GMRs is visually represented in **Figure 2**. It is established using the data obtained by ViewWave Software[16]. The numerical examples included in this study involve two reinforced concrete buildings: one with 7 stories and the other with 25 stories. These structures are characterized by restricted movement along the horizontal Y direction. Consequently, only the east-west and up-down components of the GMRs are applied to obtain the dynamic response characteristics of the buildings under consideration.

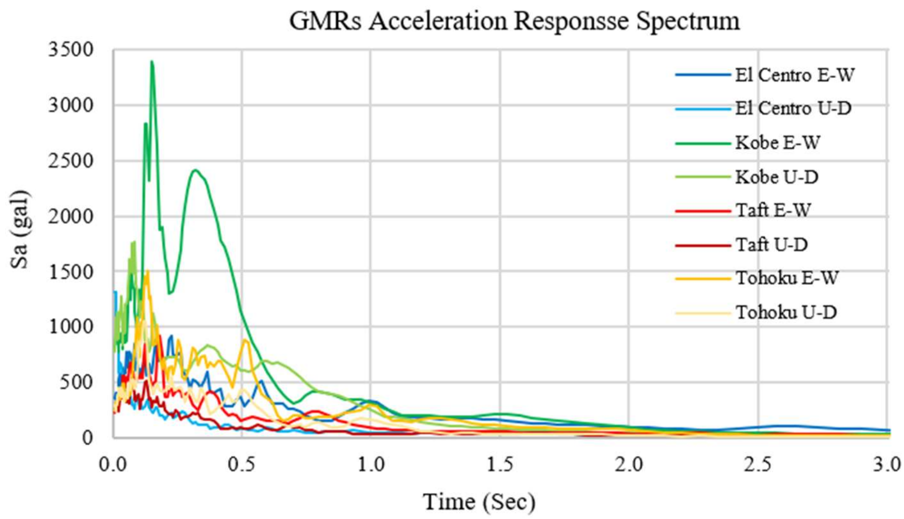
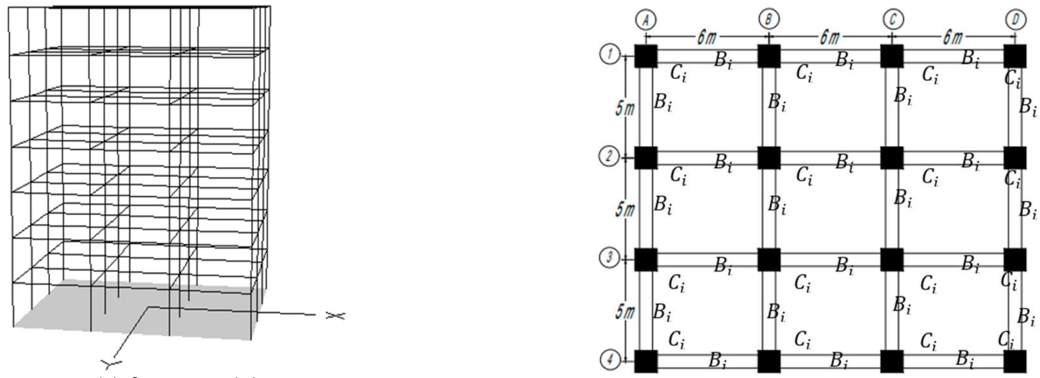


Figure 2. GMRs acceleration response spectrum (2% damping).

5. Numerical Example 1 (7-story building)

5.1. Model information and TMD design

A 7-story reinforced concrete building, depicted in both its 3D frame model and plan in **Figure 3**, is under consideration. The assumed load weight per unit is 12 $kN/m2$, resulting in a calculated weight of each story equaling 3.24×10^3 kN. The height of each story is set at 3200 mm. The building has no basement floor, and the foundation structure is assumed to be sufficiently rigid, and the analysis assumes that the first-floor columns of the frame model are fixed to the foundation. The building's fundamental damping ratio is 0.02.



(a) frame model **(b)** Typical plan

Figure 3. 7-Story model.

For a more comprehensive understanding of the building's members, **Table 3** provides detailed information about the columns and beams.

Table 3. Element properties of 7-story building.

Floors	Members	$Dimensions\ (mm)$	Longitudinal rebars		$F_c(N/mm^2)$	$F_y(N/mm^2)$
1–2	C1	500 × 500		24 ∅25	24	390
3–7	C2	500 × 500		20 ∅25	24	390
1–2	B1	b = 400, h = 550	Top	5∅22	24	390
			Bottom	5∅22		
3–7	B2	b = 400, h = 550	Top	4∅22	24	390
			Bottom	4∅22		

By conducting pushover analysis of the non-controlled building, the pushover capacity curve is established as shown in **Figure 4**. Based on the explanation in Section 2, the capacity curve is idealized by a trilinear, which the segment $\overline{OA}$ represents the linear behavior of the building and segments $\overline{AB}$, and $\overline{BC}$ represents the nonlinear range of the building.

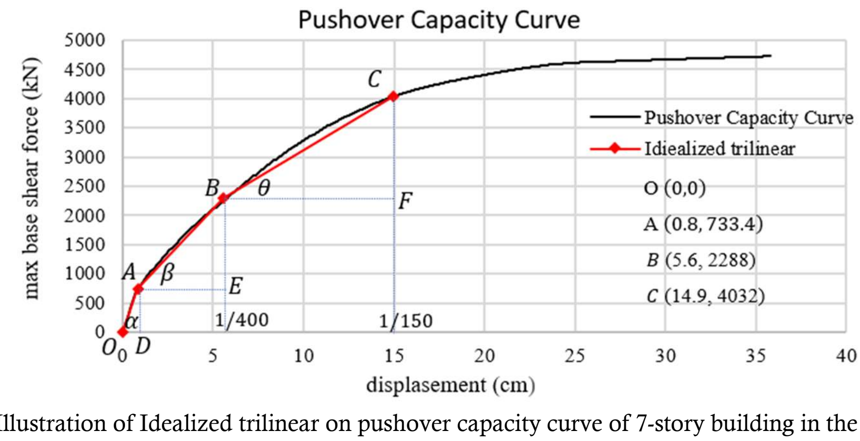


Figure 4. Illustration of Idealized trilinear on pushover capacity curve of 7-story building in the X-direction.

Furthermore, by conducting eigenvalue analysis, the mode shape of the first dominant mode will be derived. Consequently, in Equation (1), the effective mass of the first mode is calculated to be 1.938 $^{kN.s^2}/_{mm}$. Referring to **Figure 3**, and considering the value of the first mode's effective mass, the three time periods are calculated as presented in **Table 4**.

Table 4. Time periods corresponding to three segments of idealized trilinear pushover capacity curve of 7-story building.

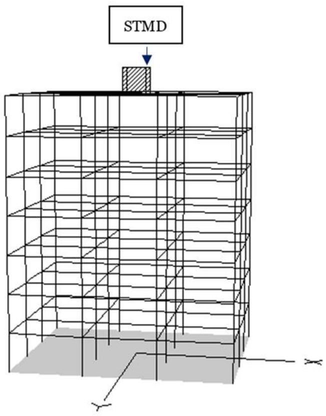
angle	Stiffness (K)	$K_i(kN/cm)$	$T_i = 2\pi\sqrt{\frac{m_{eff}}{K_i}}$ (sec)	Hereinafter referred as
$\tan\alpha$	$K_1 = \overline{AD}/\overline{OD}$	$K_1 = 874.0$	$T_1 = 0.935$	Fund T
$\tan\beta$	$K_2 = \overline{BE}/\overline{AE}$	$K_2 = 328.6$	$T_2 = 1.526$	$\mathrm{N-LT_1}$
$\tan\theta$	$K_3 = \overline{CF}/\overline{BF}$	$K_3 = 186.1$	$T_3 = 2.027$	$\mathrm{N-LT_2}$

Taking into account the decided mass ratio (here, 3%) and utilizing Equations (2)–(6), the stiffness and damping coefficients for each TMD are computed, as outlined in **Table 5**.

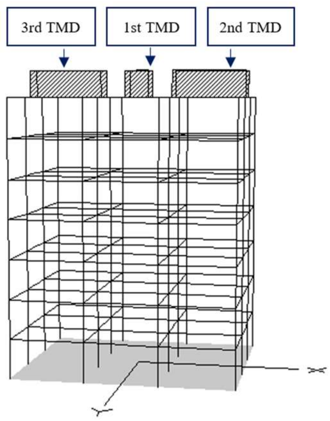
Table 5. Parameter values and information of TMDs designed for 7-story building.

TMD Scenarios			$K_{di}(kN/mm)$	$C_{di}(kN.s/mm)$	$W_i(kN)$	μ_i	details
STMD	STMD Fund-T		2.939	0.098	680.4	0.03	Three STMD scenarios with 3% mass ratio each
	STMD N-L T1		1.075	0.059	680.4	0.03	
	STMD N-L T2		0.609	0.045	680.4	0.03	
MTMD	1st TMD	TMD Fund-T	1.008	0.020	226.8	0.01	One MTMD scenario with a total 3% mass ratio; each carry 1% mass ratio
	2nd TMD	TMD N-L T1	0.379	0.012	226.8	0.01	
	3rd TMD	TMD N-L T2	0.215	0.009	226.8	0.01	

To optimize control of the first dominant mode, each TMD scenario will be placed atop the building, where the first mode exhibits the maximum amplitude. The controlled models are visually represented in **Figure 5**, showcasing the installation of STMD and MTMDs.



(a) Model wit STMD

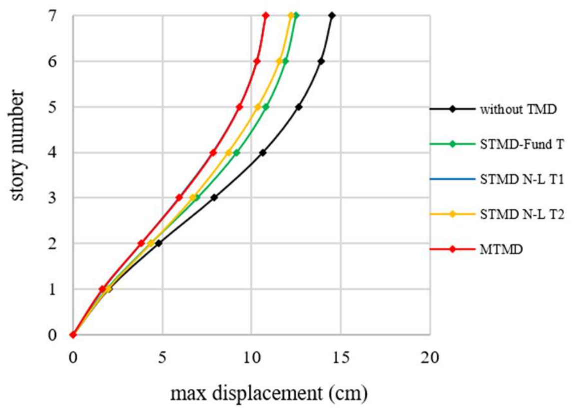


(b) Model wit MTMD

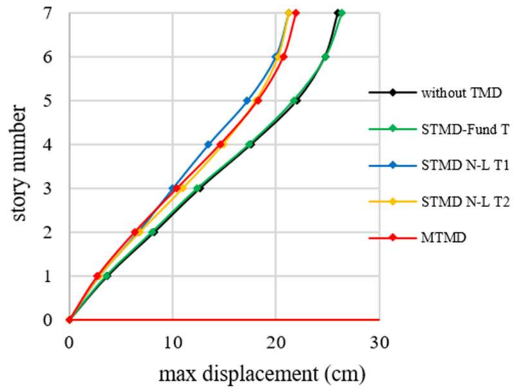
Figure 5. 7-story controlled frame models.

5.2. Seismic response

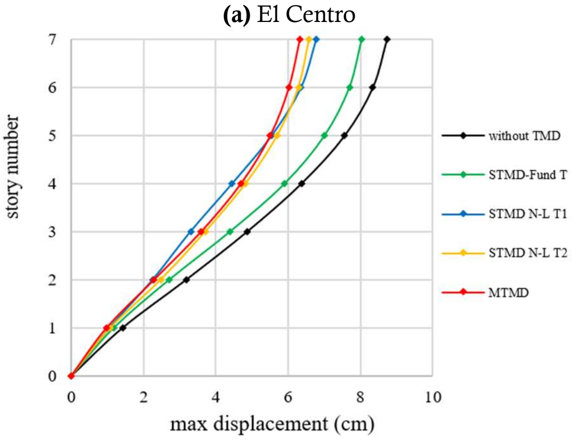
Following the dynamic nonlinear analysis of the building against four GMRs detailed in Section 4, a comprehensive assessment of maximum displacements is conducted across various scenarios. These scenarios include cases non-controlled (without TMD), with STMD tuned to the fundamental period (STMD-Fund T), STMD tuned to the time period corresponding to the second segment of the idealized trilinear (STMD N-L T1), STMD tuned to the time period corresponding to the third segment of the idealized trilinear (STMD N-L T2), and MTMDs with each tuned to time periods corresponding to three different segments of the idealized trilinear. The graphical representation of the maximum floor displacement for each of these distinct scenarios is presented in **Figure 6**.



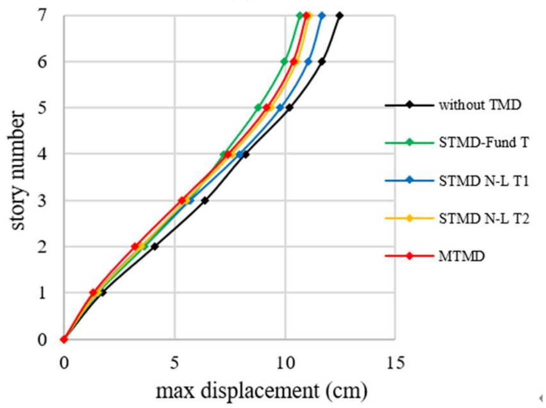
(a) El Centro



(b) Kobe



(c) Taft



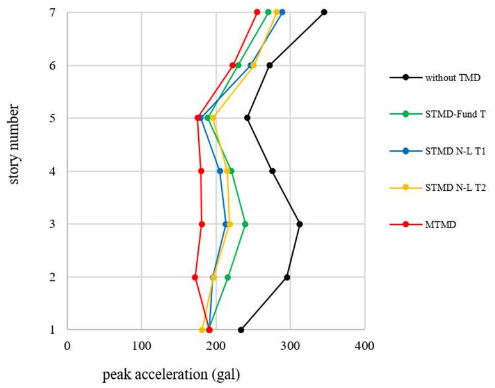
(d) Tohoku

Figure 6. Maximum displacement response of 7-story building against.

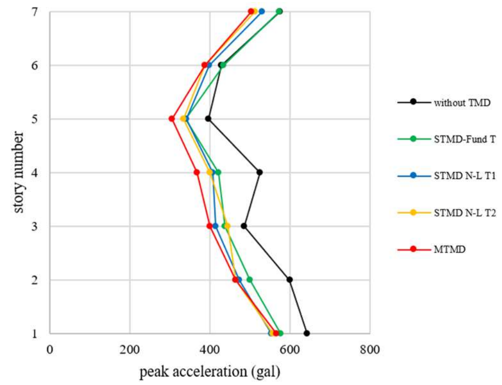
As depicted in **Figure 6**, the conventional “STMD-Fund T” demonstrates a relatively modest reduction in maximum floor displacement across three earthquake records, with the exception of the Tohoku earthquake, where it exhibits slightly improved performance compared to other scenarios. In this particular case, the difference is minimal, showcasing a 14.6% reduction in the maximum displacement of the top floor compared to a 13.3% reduction in the MTMDs scenario. Notably, among the three STMD scenarios, “STMD N-L T1” and “STMD N-L T2” generally outperform “STMD-Fund T”, except in the case of the Tohoku earthquake. In a comprehensive comparison, MTMDs consistently demonstrate higher effectiveness than STMD scenarios, apart from the Kobe earthquake, where “STMD N-L T1” exhibits a slight advantage. The MTMDs have effectively reduced the maximum displacement of the top floor by 25.8%, 15.4%, 27.6%, and 12.1% under the influence of the El Centro, Kobe, Taft, and Tohoku earthquakes, respectively. In contrast, the corresponding reductions for the “STMD-Fund T” are 14.1%, −1.5%, 7.9%, and 14.6%, following the same order.

Apart from assessing maximum floor displacements, the peak floor acceleration response is also regarded as a crucial performance objective for comparison. As illustrated in **Figure 7**, STMD scenarios exhibit nearly identical performance. Nevertheless, the MTMD scenario surpasses the STMD scenarios overall, except for the 6th floor against Taft and the 5th and 6th floors against Tohoku, where “STMD-Fund T” demonstrates a slightly better performance.

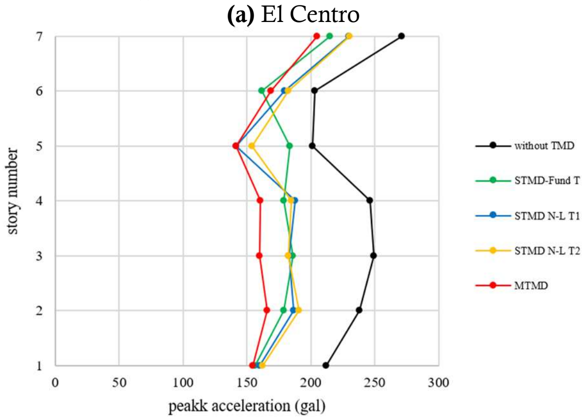
To visualize the temporal evolution of acceleration, **Figure 8** presents the acceleration time history experienced by the top floor during the El Centro earthquake. The findings for the Kobe, Taft, and Tohoku earthquakes are outlined in **Figures 9–11**, respectively. This dual evaluation offers a comprehensive insight into the structural performance under diverse seismic records.



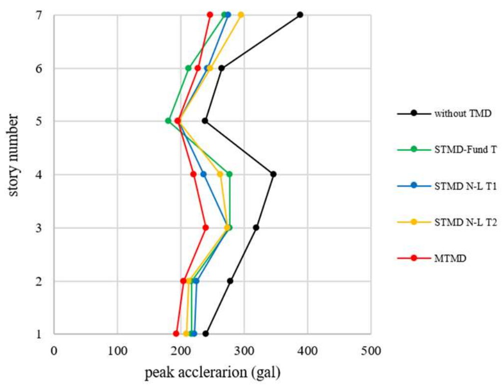
(a) El Centro



(b) Kobe



(c) Taft



(d) Tohoku

Figure 7. Peak floor acceleration response of 7-story building against.

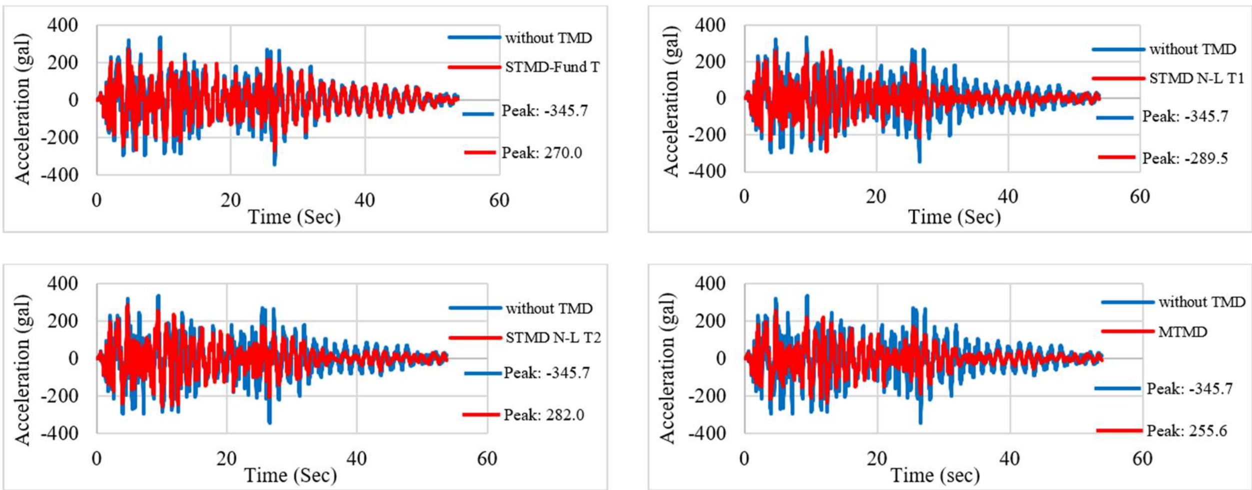


Figure 8. Top floor acceleration time history of non-controlled and controlled 7-story building with different TMD scenarios against El Centro.

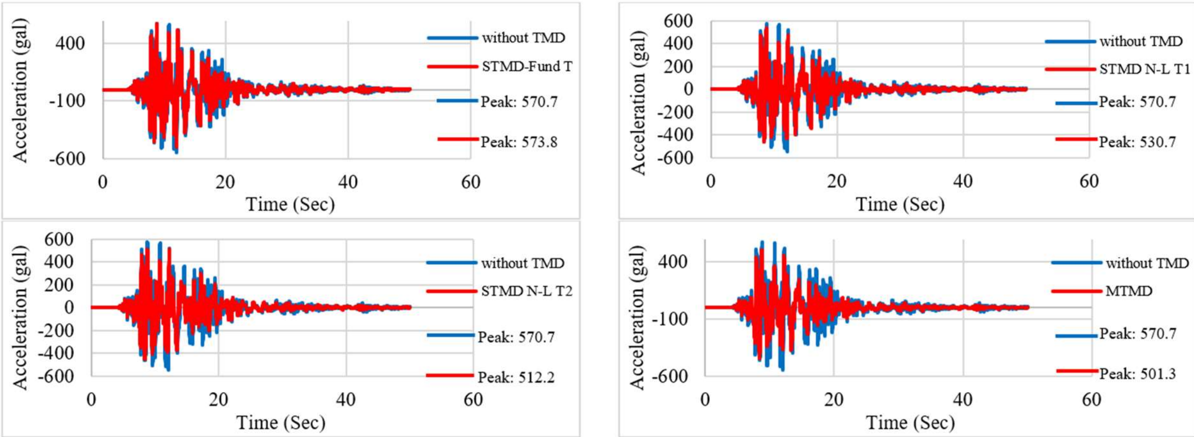


Figure 9. Top floor acceleration time history of non-controlled and controlled 7-story building with different TMD scenarios against Kobe.

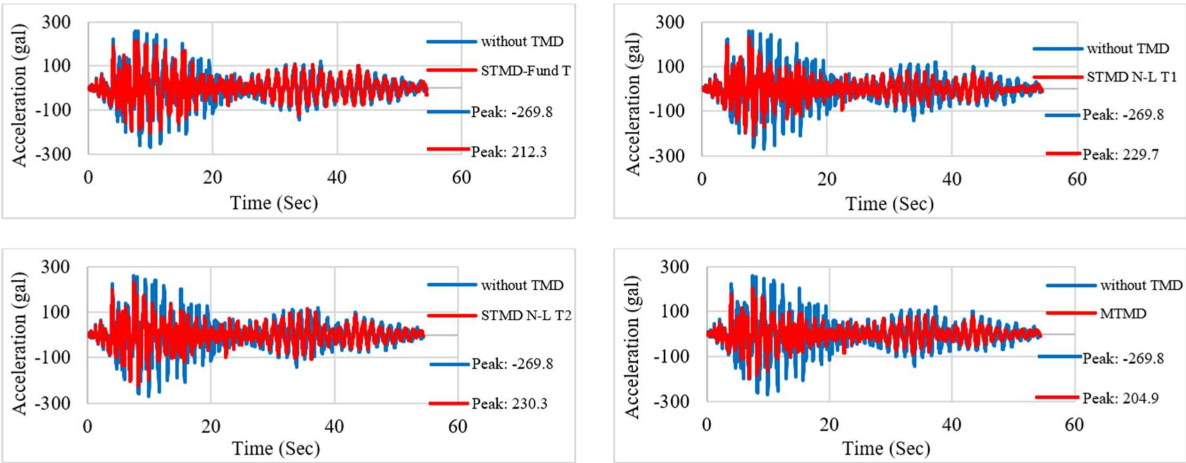


Figure 10. Top floor acceleration time history of non-controlled and controlled 7-story building with different TMD scenarios against Taft.

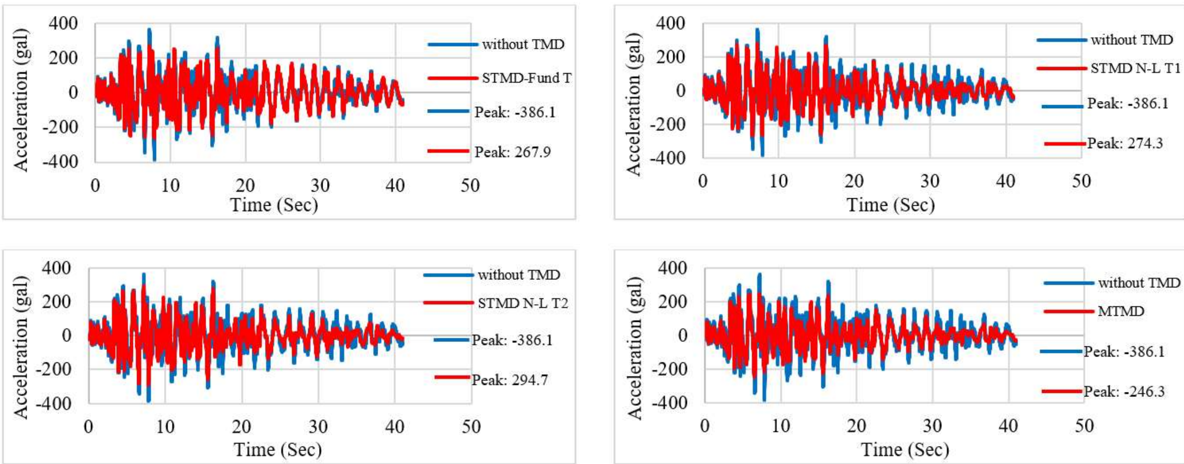


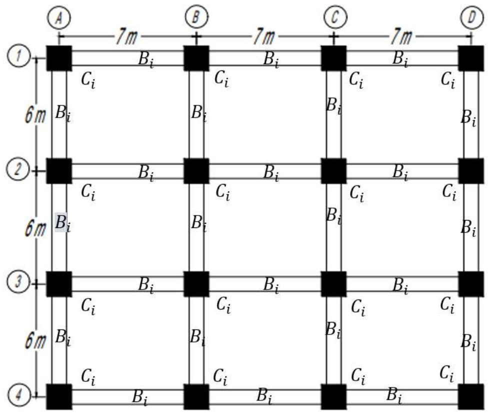
Figure 11. Top floor acceleration time history of non-controlled and controlled 7-story building with different TMD scenarios against Tohoku.

Upon observing the plotted results, it is evident that MTMDs overall outperform STMD scenarios, leading to a substantial reduction in the top-floor acceleration during the El Centro earthquake, as illustrated in Fig. 8. MTMDs resulted in a 26.1% reduction in peak acceleration, followed by the "STMD-Fund T" scenario with 21.9%, "STMD N-L T1" with 16.3%, and "STMD N-L T2" with 18.4%. Among the STMD scenarios, while the peak acceleration values indicate the efficacy of "STMD-Fund T," an observation visually of acceleration time histories reveals the overall effectiveness of the other two STMD scenarios. This effectiveness hierarchy holds true across three additional earthquake records, emphasizing the significance of considering the nonlinear characteristics of the building in the TMD tuning process, as demonstrated in **Figures 9–11**.

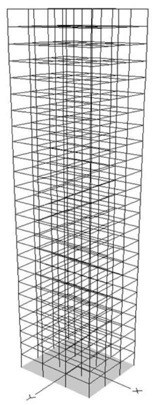
6. Numerical Example 2 (25-story building)

6.1. Building information and TMD design

In addition to the 7-story RC building, the investigation extends to a 25-story RC building, portrayed in both its 3D frame model and plan in **Figure 12**. The assumed load weight per unit is set at 12 kN/m^2, resulting in a calculated weight of 4.536×10^3 kN for each story. The initial story stands at a height of 4200 mm, while the subsequent upper stories maintain a typical height of 3800 mm. Additionally, the fundamental damping ratio of the building is 0.02.



(a) Typical plan



(b) Frame model

Figure 12. 25-Story model.

To gain thorough insight into the building's structural elements, **Table 6** provides detailed information regarding the columns and beams.

Through pushover analysis of the non-controlled model, the resultant pushover capacity curve is illustrated in **Figure 13**. As detailed in Section 2, the capacity curve is idealized by a trilinear representation.

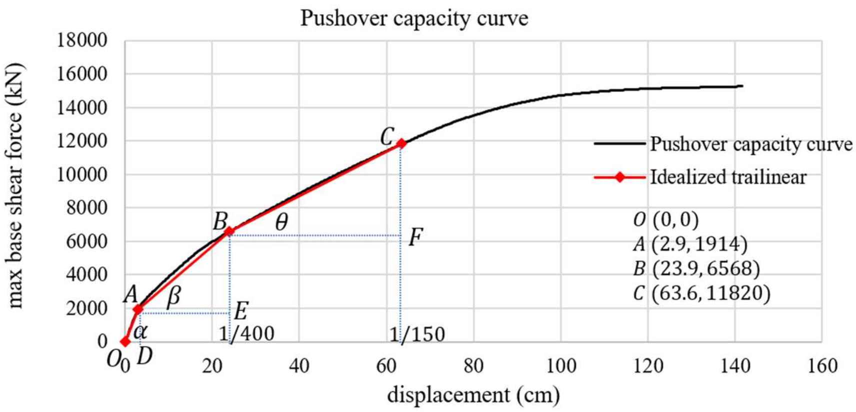


Figure 13. Illustration of Idealized trilinear on pushover capacity curve of 25-story building in the X-direction.

Table 6. Element properties of 25-story building.

Floors	Members	dimensions(mm)	Longitudinal rebars		$F_c(N/mm^2)$	$F_y(N/mm^2)$
1	C_1	900 × 900	24∅35		34	390
2–5	C_2	900 × 900	20∅35		34	390
6–10	C_3	850 × 850	20∅35		34	390
11–14	C_4	850 × 850	16∅35		34	390
15–19	C_6	750 × 750	20∅32		34	390
20–22	C_7	750 × 750	16∅32		34	390
23–55	C_8	750 × 750	16∅29		34	390
1–5	B_1	b = 600, h = 850	Top	8∅32	34	390
			Bottom	8∅32		
6–10	B_2	b = 550, h = 800	Top	8∅32	34	390
			Bottom	8∅32		
11–14	B_3	b = 550, h = 750	Top	7∅32	34	390
			Bottom	7∅32		
15–19	B_4	b = 500, h = 750	Top	7∅29	34	390
			Bottom	7∅29		
20–23	B_5	b = 500, h = 750	Top	6∅29	34	390
			Bottom	6∅29		
23–25	B_6	b = 500, h = 700	Top	6∅29	34	390
			Bottom	6∅29		

By performing eigenvalue analysis of non-controlled buildings, the mode shape corresponding to the first dominant mode was obtained. Utilizing Equation (1), the effective mass of the first mode is computed to be 8.449 $kN.s^2/mm$. Considering **Figure 13**. and the calculated value of the effective mass for the first mode, the corresponding three time periods are computed, as presented in **Table 7**.

Table 7. Time periods corresponding to three segments of idealized trilinear pushover capacity curve of 25-story building.

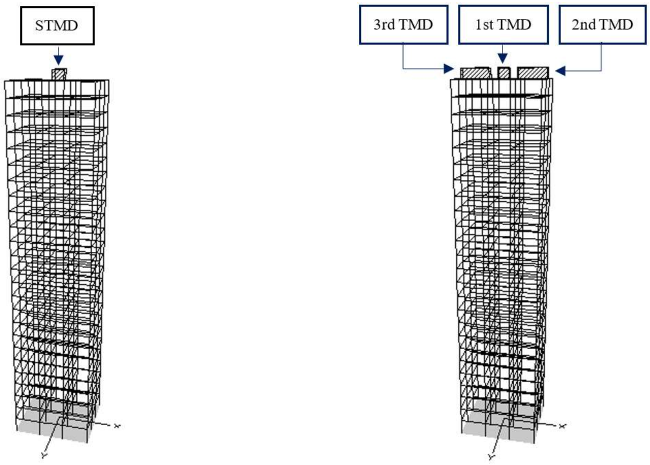
angle	Stiffness(K)	$K_i(kN/cm)$	$T_i = 2\pi\sqrt{\frac{m_{eff}}{K_i}}$(sec)	Hereinafter referred as
$\tan\alpha$	$K_1 = \overline{AD}/\overline{OD}$	$K_1 = 650.6$	$T_1 = 2.264$	Fund T
$\tan\beta$	$K_2 = \overline{BE}/\overline{AE}$	$K_2 = 222.6$	$T_2 = 3.871$	$\mathrm{N-LT_1}$
$\tan\theta$	$K_3 = \overline{CF}/\overline{BF}$	$K_3 = 132.1$	$T_3 = 5.025$	$\mathrm{N-LT_2}$

Considering the decided mass ratio (in this case, 3%) and employing Equations (2)–(6), the stiffness and damping coefficients for each TMDs are computed, as outlined in **Table 8**.

To enhance the control of the first dominant mode, each TMD scenario, along with its calculated parameters, will be strategically positioned at the top of the building, precisely targeting the floor where the first mode demonstrates the maximum amplitude. The controlled frame models are visually depicted in **Figure 14**, illustrating the installation of STMD and MTMDs.

Table 8. Parameter values and information of TMDs designed for 25-story building.

TMD Scenarios			$K_{di}(kN/mm)$	$C_{di}(kN.s/mm)$	$W_i(kN)$	μ_i	Detail
STMD	STMD Fund-T		2.616	0.207	3402	0.03	Three STMD scenarios with 3% mass ratio each.
	STMD N-L T1		0.835	0.117	3402	0.03	
	STMD N-L T2		0.495	0.090	3402	0.03	
MTMD	1st TMD	TMD Fund-T	0.860	0.040	1134	0.01	One MTMD scenario with a total 3% mass ratio; each carry 1% mass ratio
	2nd TMD	TMD N-L T1	0.294	0.024	1134	0.01	
	3rd TMD	TMD N-L T2	0.175	0.018	1134	0.01	



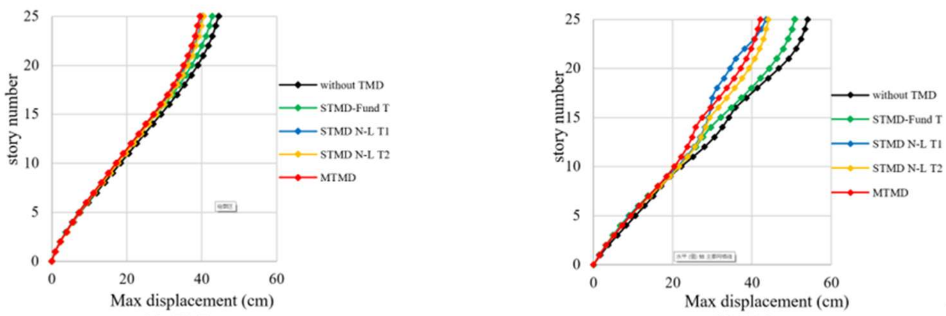
(a) Model wit STMD **(b)** Model wit MTMD

Figure 14. 25-story controlled frame models.

6.2. Seismic response

Similar to the 7-story building, dynamic nonlinear analysis was performed on the 25-story structure using four selected GMRs, as outlined in Section 4. A comprehensive assessment of maximum displacements was then performed across various scenarios, aligning with those discussed for the 7-story building in Section 5.

As depicted in **Figure 15**, "STMD-Fund T" shows the least reduction in maximum floor displacement compared to all other scenarios. The effectiveness, ranked from less effective to more effective, is followed by "STMD N-L T2" in the second position and "STMD N-L T1" in the third position. This emphasizes the importance of considering the middle segment of the idealized trilinear form in controlling tall non-linear buildings.



(a) El Centro **(b)** Kobe

Figure 15. (*Continued*).

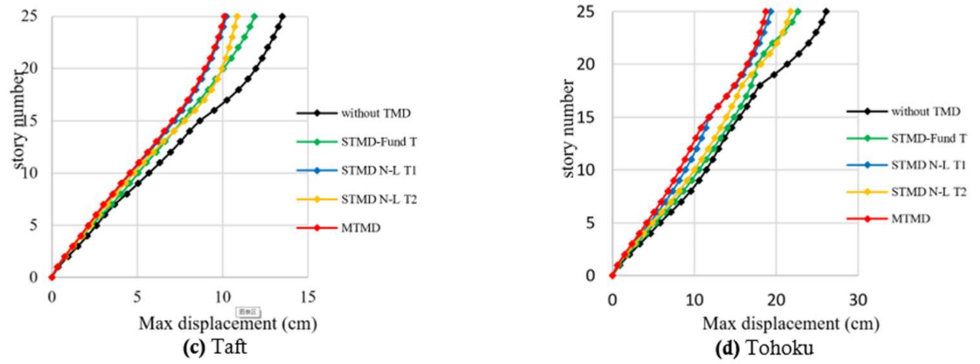


Figure 15. Maximum displacement response of 25-story building against.

Furthermore, the MTMDs demonstrate robustness compared to all STMD scenarios except for the Kobe earthquake, where "STMD N-L T1" exhibits slightly superior performance only on the 17th to 22nd floors. The conventional STMD tuned to the fundamental period reduces the top floor's maximum displacement by about 3.7%, 5.9%, 12.1%, and 13.3% against El Centro, Kobe, Taft, and Tohoku, respectively. However, for MTMDs, these values in the same order are 11.1%, 22.1%, 25.1%, and 28.2%.

In addition to evaluating maximum floor displacements, the peak acceleration response is also considered as a vital performance objective for comparison. As the results are illustrated in **Figure 16**, it is evident that the STMD tuned to the time periods corresponding to the non-linearity of the building exhibited superior performance when compared to the conventional STMD tuned to the fundamental period. However, the MTMD configuration consistently outperformed all the STMD scenarios, with the exception of the Taft earthquake, where "STMD N-L T2" demonstrated slightly better performance.

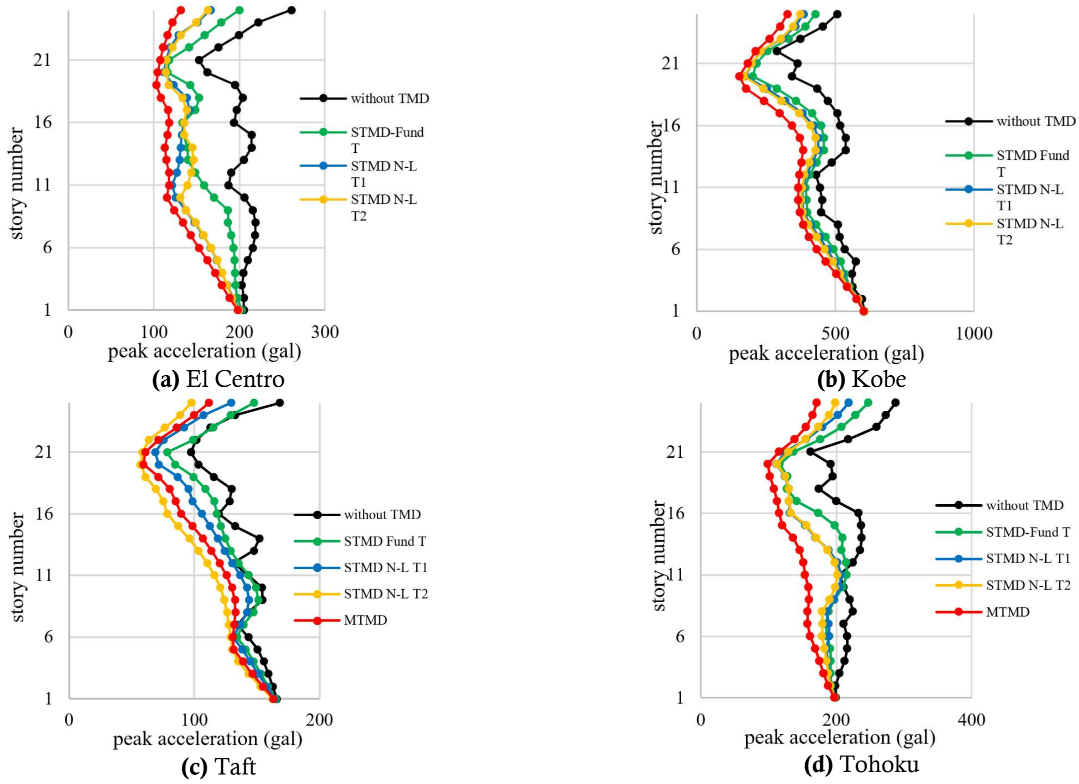


Figure 16. Peak floor acceleration response of 25-story building against.

To depict the acceleration over time, **Figure 17** illustrates the acceleration time history of the top floor during the El Centro earthquake. The results for the Kobe, Taft, and Tohoku earthquakes are detailed in **Figures 18–20**, respectively.

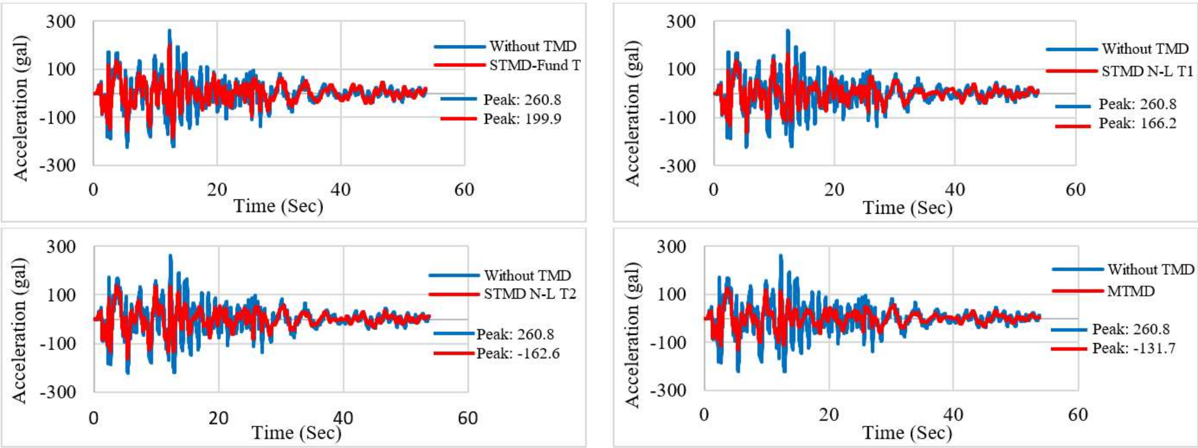


Figure 17. Top floor acceleration time history of non-controlled and controlled 25-story building with different TMD scenarios against El Centro.

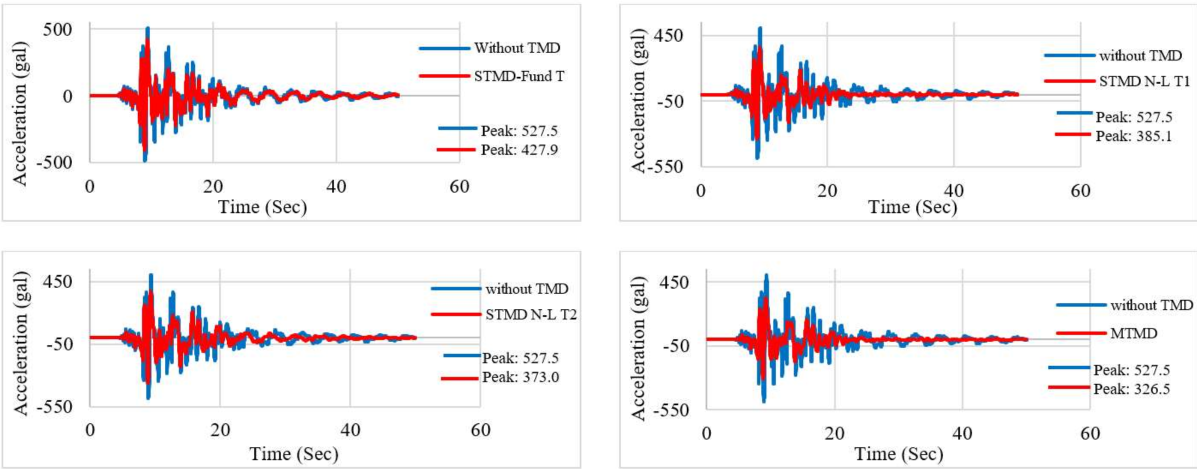


Figure 18. Top floor acceleration time history of non-controlled and controlled 25-story building with different TMD scenarios against Kobe.

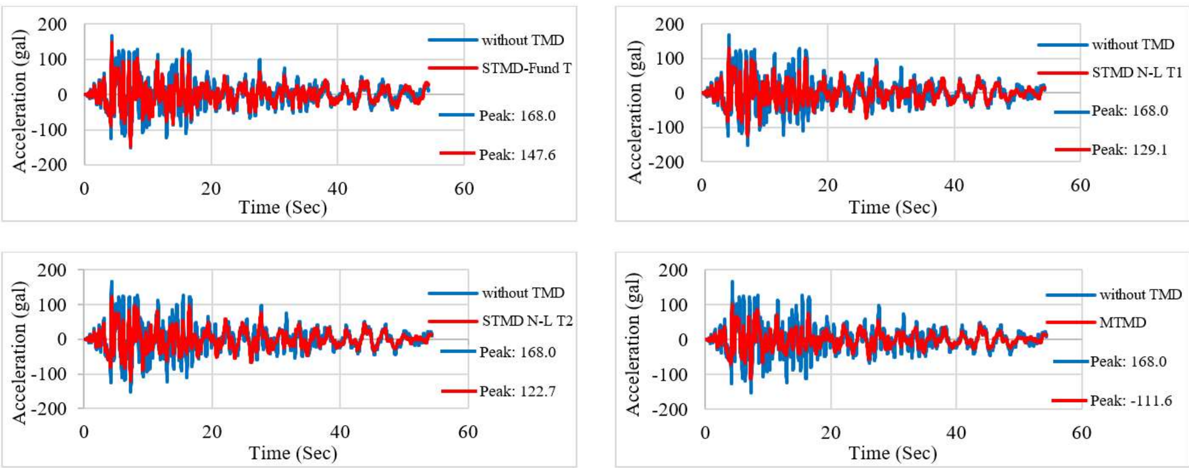


Figure 19. Top floor acceleration time history of non-controlled and controlled 25-story building with different TMD scenarios against Taft.

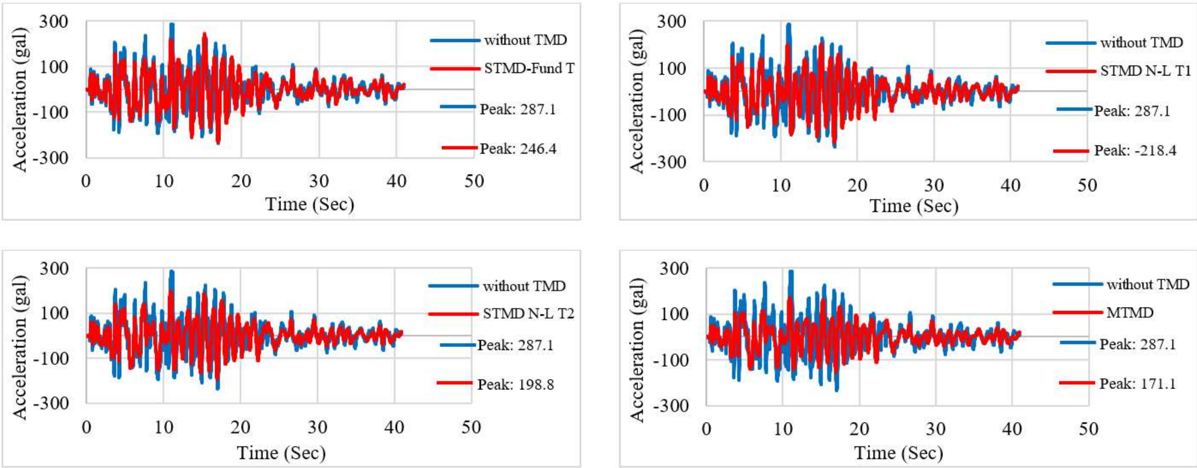


Figure 20. Top floor acceleration time history of non-controlled and controlled 25-story building with different TMD scenarios against Tohoku.

As demonstrated in **Figure 17**, the conventional "STMD Fund T" exhibited a comparatively smaller reduction in the acceleration of the top floor during the El Centro earthquake compared to other scenarios. The effectiveness increased with the installation of "STMD N-L T1," followed by "STMD N-L T2," and MTMDs demonstrated the highest level of robustness. The MTMD configuration achieved a significant reduction, approximately 49.5%, in peak acceleration against the El Centro earthquake. In contrast, the reductions for "STMD-Fund T," "STMD N-L T1," and "STMD N-L T2" are 23.4%, 36.3%, and 37.6%, respectively. In summary, MTMDs demonstrated higher effectiveness compared to all STMD scenarios. This order of effectiveness holds true for the three other earthquake records, as illustrated in **Figures 18–20**.

6.3. Wind response

Due to the sensitivity of tall structures to strong winds, only the previous 25-story building serves as the focus of wind load analysis. The models include the base case without TMD and three additional scenarios, incorporating STMD and MTMDs. The dynamic wind load is simulated using the NatHaz online wind simulator[14,17], generating wind velocity time history. This analysis assumes that gust wind speed is 50 m/s, and the building is situated in an area categorized as exposure category C (open terrain with scattered obstructions having heights generally less than 30 feet (9.14 m); according to ASCE 7–10). Subsequently, the wind force time history at each floor level is computed by applying Bernoulli's theorem.

$$F_i(t) = 0.5\rho C_d A_i [U_i + u_i(t)]^2 \quad (7)$$

where ρ is the density of air; C_d is the drag coefficient; A_i is tributary area of the i^{th} floor; U_i and $u_i(t)$ are the mean wind speed and the fluctuating wind speed at the i^{th} floor, respectively. For this study $\rho = 1.2\ {kg}/{m^3}$ and C_d is set to 1.3 based on the rectangular shape of the building[18]. Using the Equation (7), the wind force time history of the 24^{th} story is generated as shown in **Figure 21**.

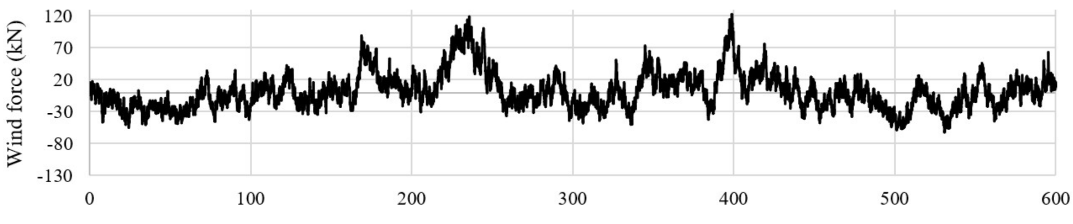


Figure 21. Wind load time history for the 24th story of 25-story building.

Considering the decided mass ratio (3%), and applying Equations (2)–(6), the stiffness and damping coefficients for each TMD are computed and presented in **Table 9**. Given that the wind load is comparatively less formidable than seismic loads, the building's stiffness is not expected to undergo a significant reduction. For example, in the context of the 25-story building under study, the base shear acting on the non-controlled structure is $3.005 \times 10^3\ kN$ due to wind load. Consequently, the third segment of the idealized trilinear is disregarded in this analysis.

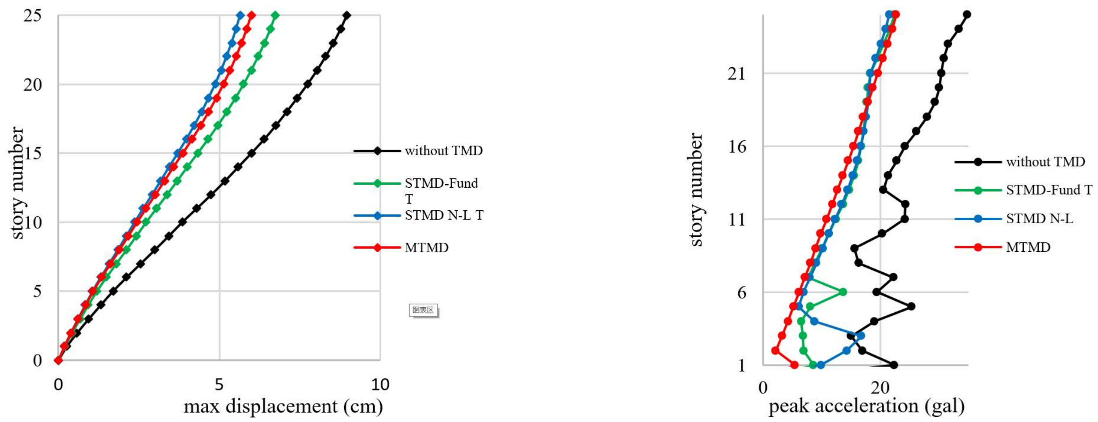
Table 9. Parameter values and information of TMDs designed for 25-story building-wind excitation.

TMD Scenarios		$K_{di}(kN/mm)$	$C_{di}(kN.s/mm)$	$W_i(kN)$	μ_i
STMD	STMD Fund-T	2.616	0.207	3402	0.03
	STMD N-L T	0.835	0.117	3402	0.03
MTMD	TMD Fund-T	1.364	0.076	1701	0.015
	TMD N-L T	0.852	0.060	1701	0.015

The wind load time history generated is applied along the height of the building using a distribution pattern that takes into account the ratio of wind force at each floor for the analysis. The results of the analysis, considering the maximum floor displacement and peak acceleration as performance objectives, are illustrated in **Figure 22**.

As illustrated in **Figure 22a**, both "STMD N-L T" and MTMD demonstrate closely aligned outcomes in minimizing maximum floor displacement, with a slight performance advantage observed for "STMD N-L T" over MTMD. In contrast, the STMD tuned to the fundamental period of the building demonstrates less effectiveness compared to the other two scenarios. The reduction in the maximum displacement of the top floor is 24.8%, 37.0%, and 33.1% for "STMD-Fund T," "STMD N-L T," and MTMD, respectively.

The peak floor acceleration is also considered as another performance objective and the result of the analysis presented in **Figure 22b**. Both scenarios of STMD exhibit comparable performance, with minor variations observed on specific floors. Notably, in the initial four floors, "STMD-Fund T" demonstrates superior performance, while on the 5th and 6th floors, "STMD N-L" outperforms. Upon conducting a comprehensive comparison, it is evident that MTMD outperforms STMD from the ground floor up to the 19th floor. However, it is worth mentioning that STMD scenarios marginally outperform MTMD on the top six floors.



(a) Displacement **(b)** Acceleration

Figure 22. Response of the 25-story building against wind excitation.

To visualize the temporal evolution of acceleration, **Figure 23** portrays the time history of acceleration experienced by the top floor against wind excitation.

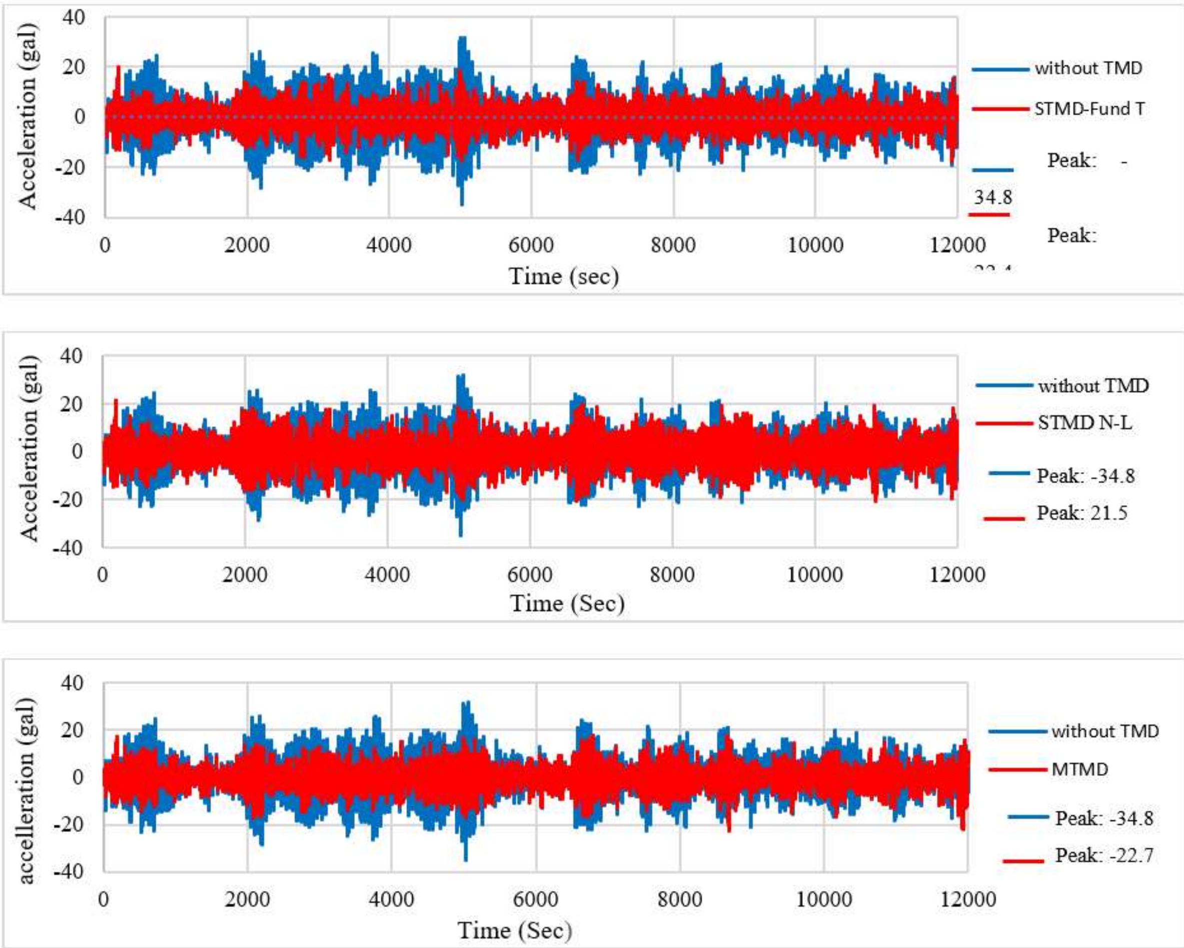


Figure 23. Top floor acceleration time history of the 25-story building subjected to wind load.

Examining **Figure 23**, within the STMD category, the effectiveness of scenarios demonstrates a noticeable trend from less effective to more effective, with "STMD-Fund T" and "STMD N-L T" arranged in ascending order of effectiveness. The recorded reduction in peak acceleration values for these two STMD scenarios are 35.6% and 38.2%, respectively, while the corresponding value for the MTMD scenario is 34.8%.

In summary, the study emphasizes the importance of considering stiffness degradation due to nonlinear behavior when designing TMD for addressing building nonlinearity. Results altogether highlight the robustness of STMDs tuned to time periods corresponding to nonlinearity segments compared to conventional STMDs under dynamic loads, especially in tall buildings. Notably, MTMD, each tuned to three distinct time periods aligned with trilinear segments, demonstrates even greater robustness than any STMD scenario. These findings provide valuable insights for seismic retrofitting and structural dynamics, positioning MTMDs as a compelling solution to minimize maximum floor displacement and acceleration, enhancing overall building dynamic performance.

7. Conclusions

In conclusion, this study introduces a novel control strategy for addressing non-linear building behavior by precisely tuning TMDs to specific time periods following non-linearity onset. The proposed methodology incorporates pushover analysis to establish the pushover capacity curve. Subsequently, this curve is represented by an idealized trilinear form, characterized by key points at the origin, nonlinearity onset, and positions corresponding to target drifts (1/400 and 1/150). This representation facilitates the calculation of time periods for each segment of the trilinear, enabling the precise tuning of TMDs to match these specific time periods. The proposed approach represents a significant advancement in enhancing building performance under non-linear conditions.

The research underscores the critical importance of tuning TMDs to specific time periods corresponding to the non-linear behavior zone. STMDs tuned to these periods exhibit remarkable robustness, surpassing the performance of conventional STMDs tuned to the fundamental period. Moreover, MTMDs tuned to three distinct time periods demonstrate superior robustness compared to all STMD scenarios, particularly in minimizing maximum floor displacement and acceleration of tall buildings under seismic loads.

Furthermore, wind load analysis reveals the effectiveness of TMD scenarios, with both MTMDs and STMDs tuned to time periods corresponding to non-linearity regions outperforming conventional STMDs tuned to the fundamental period. This study not only establishes the effectiveness of the proposed strategy but also positions MTMDs as a compelling solution, showcasing their robustness in minimizing both maximum floor displacement and acceleration.

In summary, the strategy of tuning TMDs to specific time periods following non-linearity onset proves effective in enhancing building performance under non-linear conditions. The findings from this study suggest a valuable framework for improving the seismic and wind resilience of tall buildings.

Author contributions

Conceptualization, TS and HA; methodology, TS and HA; software, TS; validation, TS; formal analysis, HA; investigation, HA; resources, TS and HA; data curation, HA; writing—original draft preparation, HA; writing—review and editing, HA; visualization, HA; supervision, TS; project administration, TS. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

The authors declare no conflict of interest.

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Original Research Article

Evaluating the efficiency of dam construction management and ways to improve it

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ABSTRACT: The main purpose of this study is to investigate the effect of environmental transformational leadership. Due to the dry climate, Iran always needs to plan for water facilities. Among the water facilities, the dam is the most important because of the supply of drinking water, agriculture, hydroelectric energy, etc. The construction of a dam has always been important due to the huge cost involved, and on the other hand, due to the complexities involved in its construction, it is accompanied by risks. In this research, the ways of increasing productivity in construction management and dam construction have been discussed by considering the issue of project control in order to save costs and time and increase the quality of construction.

KEYWORDS: construction management; dam construction; productivity

1. Introduction

From a long time ago, in the ancient history of this border and landscape, water and its extraction have always played a key role, and the ancestors of this land needed to obtain water and increase it with continuous and forward-looking efforts and with the amazing construction of water engineering infrastructure according to the conditions of their era. They have paid attention to the extraction of this precious substance. The vast land of Iran, with an area of 1,648,195 square kilometers, is one of the vast plateaus of Asia, in which about 13% of its area has a cold and mountainous climate, 14% has a temperate climate, and about 73% of the country has a dry and semi-arid climate. The main source of the country's water resources is the annual precipitation, and only a small part of the water resources is imported from neighboring countries. The average annual rainfall of the country is about 250 mm, which is less than the average rainfall of Asia (732 mm) and less than about a third of the global average (831 mm), although the range of rainfall due to climatic diversity and topographical and geographical conditions is from a maximum of 2000 mm in the northern coasts to 50 mm in the central desert, and 52% of annual rain and snow occurs in only 25% of the country's surface. In addition to improper spatial distribution, there is also improper temporal distribution of rainfall, so that about 90% of rainfall occurs in cold and wet seasons and the remaining 10% in hot and dry seasons. Thirty percent of the precipitation in the country falls in the form of snow and the rest in the form of rain, and considering the size of the country, the annual volume of atmospheric precipitation is 427 billion cubic meters, and the total amount of renewable water annually is about 130 billion cubic meters, which is equivalent to 30.5% of atmospheric precipitation. The increasing development of water facilities in order to extract as many water resources as possible, produce energy, control floods, deal with drought, protect water resources, etc. has been one of the most important goals of the government in realizing the development plan. Considering the very important role of such facilities in the development of the country, the need to maintain their performance, achieve predetermined goals, the possibility of sustainable exploitation of water facilities, and the need to return large investments made in this industry, scientific management and methodicalization of the issue of exploitation. The maintenance and safety control of water facilities is of particular importance. Today, the water of this life-giving resource is considered one of the three factors of the formation and survival of the environment (soil, air, and water) more than ever before. Undoubtedly, nowadays, the preservation and protection of water resources and the optimal, economical, and fair use of water is a global issue, and for this reason, water is referred to as an all-encompassing human challenge. The emphasis of the world community is that governments and nations look at water as the key to development.

Completion on time and with the expected cost of any project is one of the main criteria of its success. Failure to complete the plan or project on time and with the expected cost will cause the employer's demands and project goals to not be met. This issue is more important in national and large projects such as dam construction, whose implementation period is usually long and their implementation takes more than six years on average. Dam construction projects, due to their importance in terms of exploitation and the huge amount of investment in them, as well as in terms of the nature of their complexity and the existence of many uncertainties in them, including underground conditions, facing disasters natural, and their high construction cost, are of particular importance in finishing on time and with the prescribed cost. Therefore, investigating, identifying, and evaluating the reasons for the increase in time and cost and providing solutions to solve them will bring significant benefits for the country's economy.

2. The necessity of doing research

Iran has a dry climate, where the main source of water is atmospheric precipitation, which is less than 1.3 of the world average. After clarifying the importance of the need for water, the search for the best way to supply or transfer it is considered. Dam construction has been identified as one of the possible solutions, and dam construction projects are one of the most important and largest projects in the country. Most large projects are implemented in dynamic and complex environments in such a way that uncertainty and risk are among their inherent characteristics. This uncertainty has made most of the country's projects not achieve significant success in reaching the predetermined goals. This issue leads to problems such as the lack of economic justification for the exploitation of projects, the reduction of efficiency, and the emergence of dissatisfaction among the key stakeholders of the project. Therefore, due to the lack of a clear strategy and systematic rules for greater management efficiency in the construction of water facilities, in this research, while recognizing the deficiencies and systematic problems, we tried to eliminate the existing gaps and reach certain principles for efficiency in system management, and hopefully we will be more efficient in this field.

3. Research background

Taghipour et al.[1] studied "Risk analysis in the management of urban construction projects from the perspective of the employer and the contractor".

Mahboobi et al.[2] discussed "Assessing ergonomic risk factors using combined data envelopment analysis and conventional methods for an auto parts manufacturer", occupational injuries are currently a major contributor to job loss around the world.

Taghipour et al.[3] studied "The impact of ICT on knowledge sharing obstacles in knowledge management process (including case-study)".

Khalilpour et al.[4] studied "The impact of accountant's ethical approaches on the disclosure quality of corporate social responsibility information an Islamic perspective in Iran".

Mirzaie et al.[5] studied "The relationship between social bearing capacities with conflict as a result, in the perception of the visiting historical sites".

Alamdar Khoolaki et al.[6] studied "Effect of integrated marketing communication on brand value with the role of agency's reputation (including case study)".

Taghipouret et al.[7] studied "A survey of BPL technology and feasibility of its application in Iran (Gilan Province)".

Seddigh Marvasti et al.[8] studied "Assessing the effect of the FRP system on compressive and shear bending strength of concrete elements".

Jalili et al.[9] studied "Comparative study of Khaje Rashid al-Din views on Rab-e Rashidi Islamic Utopia and Kevin Lynch ideas".

Taghipour et al.[10] studied "Insurance performance evaluation using BSC-AHP combined technique".

Rezvani et al.[11] discussed "The design of high-rise building with ecological approach in Iran (Alborz Province)".

Taghipour et al.[12] studied "The identification and prioritization of effective indices on optimal implementation of customer relationship management using TOPSIS, AHP methods".

Taghipour and Yazdi[13] studied "Seismic analysis (non-linear static analysis (pushover) and nonlinear dynamic) on Cable-Stayed Bridge".

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4. Research objectives

Due to the dry climate, Iran requires the use of water and drainage facilities, and on the other hand, some dams and irrigation and drainage networks are unprofitable due to a lack of proper construction or non-compliance with operating rules. According to these propositions, there has not been a systematic and comprehensive study about the productivity in the dam construction management system, and in this research, it has been tried to provide suggestions to improve this situation by stating the necessary generalities and rules. Therefore, improving the system management in water facilities, stating the rules and regulations necessary for greater productivity, and collecting appropriate information for local use in Iran are among the goals of this project. The present research is in order to evaluate the efficiency of dam construction management and ways to improve it. This research was done to answer this question:

How to increase the efficiency of the construction of water facilities?

Ways to increase the efficiency of dam construction

Project planning and control process:

The first way to control time and cost and thus increase productivity is to resort to project planning and control.

To do any activity, you have to plan so that the waste of time and effort reaches its minimum. This point is true for any activity. The schedule is the schedule of the work stage in terms of time. The schedule is a guide for carrying out operations to control the progress of the activities and the possibility of completing them in the desired or necessary time. Setting the schedule in many different stages of construction. It is used from planning to construction and operation and maintenance. Construction phase schedules are used for various purposes before the start of the project and after its completion, as well as during the construction phase.

5. Planning and control steps

First step: defining the project and setting goals

In this step, we define the project and determine the goals to be achieved.

Second step: specify the necessary activities

In this step, we specify the activities that we have to do to achieve the goals of the project. We prepare the project.

Work Breakdown Structure (WBS)

Since specifying all the activities of a project at once is exhausting, we first break the whole work into major activities. Then we can break these major activities into the big activities that make up it in the next step. And again, in the next step, divide the big activities into smaller activities. And this work breakdown can continue for many stages. In fact, the structure of the work breakdown is a pyramid showing the activities of the project (**Figure 1**).

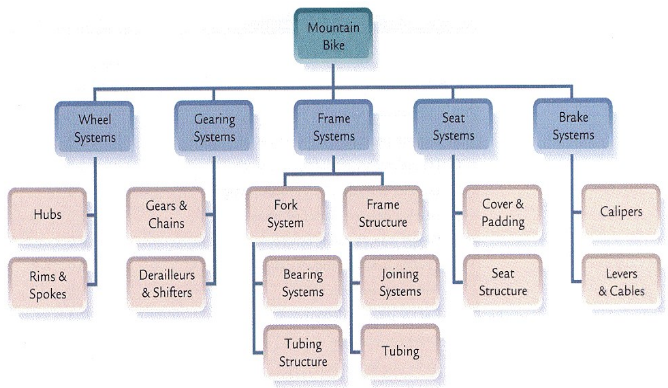

Figure 1. Work-break structure.

The third step: specifying prerequisite relationships and dependencies

In this step, we specify the order of activities and the dependence of each of them on other activities.

Fourth and fifth step: specifying the implementation methods and required people

In this step, we define the implementation methods of each of the activities and the people needed to do them.

Sixth step: Allocation of time and resources

In this step, based on the implementation methods of each of the activities and the people needed to do them, first we allocate time and then, according to the case of other resources such as manpower, machinery, and budget, to each of the activities. Time and resources are often possible using a combination of calculation and experience. In order to calculate time and resources, you can use the analysis of the prices of the items in the price list, and by experimentally adjusting the obtained results, you can reach the appropriate amount.

Seventh step: Considering resource limitations

In this step, according to the limitations we have in the use of resources, we modify the program so that the available resources are used in the best way. In this step, techniques such as resource leveling techniques and time and cost balancing techniques are used.

Eighth step: collecting feedback during the execution and adjustment of the program

In this step, which is done during execution, the program is adjusted and updated using real data collected and execution experiences.

6. Analyze

Due to their importance in terms of exploitation as well as the huge amount of investment in them, dam construction projects are of special importance in completing them on time and with the prescribed cost. Unlike many government projects that are carried out for public benefit purposes (such as the construction of hospitals, schools, and roads), failure to use dams on time will cause a lot of unprofitable damage to the government. At the same time, they can cause heavy physical and financial losses. For this reason, investigating the reasons for the increase in time and cost of dam construction projects is of particular importance.

6.1. Research method

Dam projects are one of the biggest construction projects in the country, which annually allocate significant amounts of the country's construction budget. The design and construction of these projects usually take at least 6 years on average. Therefore, despite the great job creation of these projects, due to the long duration of their implementation, several factors have threatened their successful implementation and have led to the non-achievement of the planned goals in these projects, i.e., completion on time and with the expected cost and quality. Investigating, identifying, and presenting solutions to solve the mentioned causes will result in significant gains for the country's economy. Failure to complete the plan or project on time and with the expected cost will not meet the employer's demands and the goals of the plan or project. An increase in the time and cost of completing the project causes a loss of profits to the user. In many cases, even the excessive delays in the project or plan cause the economic and technical failure of the project. As the duration of the project increases, overhead costs increase. Inflation created in the market increases the costs of performing activities that have not been performed. The possibility of doing similar projects by competitors and losing the market and the justification of the project in the new market increases. New technologies have entered the market, and the possibility of not finding the materials and equipment needed for the project or not justifying their use is increasing. In other words, the losses caused by not completing the project on time impose huge costs on the project or plan. Sometimes these costs are so high that the plan or project is no longer justified. Several factors, such as changes in the amount of work, weakness of the contractor, failure to pay the contractor's demands on time, and many other factors, increase the time and cost of the project. In order to complete the project on time and with the expected cost and to avoid the final losses and losses caused by delays and increased costs, there is no other way than to investigate and recognize these factors and deal with them appropriately and finally manage them. In this research, the way of time and cost management and, as a result, increasing the efficiency of dam construction have been investigated.

6.2. Method

Today, the uncertainty in estimating the estimated time and cost of industrial projects is considered a major challenge in the science of project management. In this regard, one of the most important and effective ways to solve this problem is risk analysis. In fact, risk management is the systematic application of management policies, procedures, and processes related to risk analysis, evaluation, and control activities. Therefore, before starting the project, project risks must be identified, quantified, and finally, to prevent their occurrence, a suitable strategy to reduce the effects of risk is adopted.

The Project Management Body of Knowledge (PMBOK) is one of the most reliable references in the field of project management. This standard is the result of research by the American Project Management Association (PMI), which has made continuous efforts to develop project management knowledge since 1969. In the field of project risk analysis, the PMBOK standard has been able to provide a process that is very efficient and has made this analysis easier for project managers. Risk analysis in this standard includes qualitative and quantitative risk analysis. Qualitative risk analysis is used to rank the risks and determine the risks whose effects are significant on the project goals. The important point is that the technique (FMEA) can replace the process defined in the standard (PMBOK) in this analysis. Although this technique is used to identify potential error states in a process or product, it can be developed and used to identify and rank possible risks in a project. The advantage of this technique over the standard process is that it performs qualitative analysis in much less time and is more accurate in identifying critical risks. Dam construction projects are among the most important projects of the country, which annually allocate significant amounts of the country's budget, and due to the long duration of their implementation, they always deal with many risks and uncertainties, which lead to non-achievement. On time, the planned goals, the deviation of the cost and time of the project with their estimated value, and also the timely completion of the projects are threatened; therefore, a tool is needed that can effectively analyze the risks with less time and cost. In this research, the researcher aims to analyze the risks of the country's dam construction projects by using a widely used qualitative-quantitative methodology (FMEA), determine their level of effect, and finally, after ranking the risks, identify critical factors.

6.3. Questionnaire design process

In this research, the causes of cost and time increase in the country's dam construction projects and the amount of effect of each factor have been identified from the experts' point of view in two stages as follows.

The first stage is conducting preliminary studies and designing the questionnaire.

At this stage, in order to design a suitable questionnaire, in addition to the above-mentioned projects, a number of ongoing or completed projects that were facing an increase in cost and time were selected and studied completely. In these plans, the items that faced an increase in cost were identified. The reports related to the increase in the time of these projects were studied, and the apparent reasons for the increase in the time in these projects were identified. By referring to the managers and experts involved in these projects, an initial and comprehensive list (about 100 items) of the reasons for the increase in time and cost in these projects was identified and collected. After further investigation, it was determined that some reasons are common and can be eliminated, and also some of them can be integrated into each other. Therefore, with the final summation of 39 cases as reasons for increasing the cost and time of dam construction projects, they were selected to start the consultation process, and a form was designed for consultation.

Collecting the opinions of the project agents, the second stage

At this stage, managers and a number of knowledgeable and opinionated experts involved in these projects in different factors (employer, consultant, and contractor) were selected, and a survey form was sent to them. Even a large number of them were interviewed in person with explanation and discussion in If the item is selected, the form has been submitted. The number of statistical population selected in this stage according to the table. Ninety questionnaires were distributed among the selected statistical population. After the follow-ups, approximately 50% of the questionnaires were collected and analyzed according to **Table 1**.

Table 1. Question factors.

Total	Contractor	Consultant	The employer	Number of questionnaires
90	30	30	30	Distributed
33	13	15	15	Collected
39	36	50	50	The percentage of collected questionnaires

Studies conducted on the causes of delays

The Union of Large Projects In the investigation of the body of large projects, the reasons for the increase in time and cost in large projects are divided into two categories of reasons related to strategic decisions that are usually made by the senior managers of the organization before signing a contract (including the selection of the type of system). It divides the project (how to choose the factors involved in the project, etc.) and the operational reasons that arise during the implementation of the project (such as lack of materials, weakness of the contractor).

The World Organization of Dams (WCD), during research that it has done in a very general way on 99 projects, states that only half of them have been completed on time, and about 30% of them are from one to two years, and 4 projects are more than it has been delayed for 10 years. The main reasons for the delay in these projects are financial problems, inefficiency of the contractor and construction management, unrealistic schedule, dissatisfaction of manpower, and legal and legal challenges.

As a result

After a comprehensive review of the effect of the causes from the point of view of the main factors of dam construction projects based on the Pareto law, the factors that have 80% of the effect on increasing the time and cost of dam construction projects, according to the effect of each cause, in rows 1 to 26 of the table arranged According to Pareto's law, in most problems, 20% of the causes have 80% of the effects. Although, according to the Pareto law table, the Pareto law is not completely governing in this issue, however, nearly 70% of the causes of time and cost increase in dam construction projects are related to 20 causes, and more than 50% of the effect is related to only 12 causes. Therefore, this table can be used in order to study and provide solutions to eliminate or reduce the causes of time and cost increases in the country's dam construction projects.

6.4. FMEA technique

The failure mode and effect analysis (FMEA) technique was first used in the 1960s in the aviation industry, and then it was widely used in other industries such as automobile manufacturing. The purpose of this technique is to identify and rank defects and potential defects that occur in a product or process. These defects can occur in the fields of design, testing, quality, production line, marketing, and customer, and their effects can be reduced or eliminated with a planned corrective action. It is possible to use this technique in the form of risk management, and it can be considered as risk failure mode and effect analysis (RFMEA). In fact, FMEA is one of the most widely used techniques for analyzing risk and predicting its effects on risk objectives.

In the technique (RFMEA), in order to rank risks, in addition to the two scales of probability and risk impact, a third criterion called "discovery coefficient" is used, which can make the qualitative risk analysis more accurate. In this technique, the product of two values of probability and impact determines a coefficient called "risk score" of 3. After calculating the risk score, the coefficient or discovery value of 1 should also be determined. This coefficient is "the ability to discover and track a risk along with enough time for a contingency plan in order to respond to the risk". Finally, by multiplying the value of the detection coefficient by the risk score, a new value called the coefficient (RPN) is obtained, and any risk whose (RPN) is higher is given a higher priority.

7. Conclusion

Due to their importance in terms of exploitation and the huge amount of investment in them, dam construction projects are of special importance in completing them on time and with the prescribed cost. Also, dam construction projects are among the most important projects in the country. which annually allocate significant amounts of the country's budget, and due to the long duration of their implementation, they always deal with many risks and uncertainties that lead to not achieving the planned goals on time, cost, and time deviation. The project is threatened with the estimated amount and also the timely completion of the projects, so a tool is needed that can effectively analyze the risks with little time and cost. is to analyze the risks of the country's dam construction projects by using a widely used qualitative-quantitative methodology, FMEA, to determine the level of their effect, and finally, after ranking the risks, to identify the critical factors. Based on the obtained results, out of 14 critical risks, unknown underground factors that could not be predicted during the study period were identified as the most important risks, and finally solutions were provided to resolve these factors to lead to the elimination or reduction of delays and increase interest. and the projects of the country.

General risk factors in dam construction:

One of the studies that can be cited about construction projects in Iran is the report on the evaluation of executive bodies, which is carried out every year by the Vice-Chancellor of Technical and Civil Affairs of the Management and Planning Organization (**Table 2**).

Table 2. General risk factors.

Year 2014	Year 2013	Agents
8/4	9/9	The earth
4/5	5/3	Study and design
7/7	10/8	Executive body
4	7/6	Designer consultant
0/3	0/9	Supervising consultant
5	8/6	Contractor
5/5	6/9	Supplies and machinery
64/7	50	Validity and other reasons

General sources of risk in the project:

Risks are threatening provided that the solutions to face them are not embedded. Also, accepting some risks is considered an opportunity and causes the project elements to work (**Table 3**).

Table 3. General sources of risk.

External sources of risk in the project (uncontrollable)				
Normal	**Social**	**Economic**	**Political**	**Legal**
Atmospheric conditions, fires, floods, earthquakes	Education and culture, seasonal work, strikes, demographic fluctuations	Economic policies, prices, taxes, financing conditions, exchange rate parity	Change in policies, elections, war of threats	Local regulations, permits and approvals change in standards rules
Internal sources in the project (controllable)				
Contracts	**Supply and logistics**	**Human factors**	**Technical documents**	**Management**
Type of contract, short time frame, unrealistic rates of parties' relations	Lack of resources, lack of access to resources, lack of reliance on equipment, insufficient labor force	Productivity, disease, motivation, errors	Superficiality, inaccuracy, lack of complete documents, lack of up-to-date documents	Unrealistic goal of weak control of organizing technology

Author contributions

All authors contributed to this research.

Conflict of interest

The authors declare no conflict of interest.

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