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Review of Structural Integrity Concerns in High-rise Buildings in Coastal Regions

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Abstract The construction of high-rise buildings in coastal regions has become increasingly popular, posing significant challenges to structural integrity due to the unique environmental conditions. This review aimed to identify the prevalent structural integrity issues and remedial actions for safer, more durable, and sustainable coastline high-rise structures. A literature review was conducted, revealing that high-rise structures along coastlines are vulnerable to issues such as base design, material corrosion, coastal erosion, seismic forces, wind, and earthquake loads. Corrosion-resistant materials, base isolation systems, and the application of resilient design concepts were found to be viable remedial actions to lessen the impact of these issues. The findings demonstrate the crucial importance of designing, constructing, and maintaining high-rise structures while considering the unique environmental characteristics of coastal areas. The resilience and durability of these structures can be enhanced by implementing resilient design concepts, base isolation systems, and corrosion-resistant materials. The results have significant implications for the design, construction, and maintenance of high-rise buildings in coastal regions, emphasizing the need to account for potential natural hazards.

Keywords Structural Integrity, High-rise Buildings, Coastal Regions, Earthquake, Foundation Design and Coastal Erosion

1. Introduction

As technology continues to advance, we expect to behold more awe-inspiring high-rise buildings to en-grace our coastal lines, thereby changing the face of urban architecture. This does not come without its consequences. Due to the intensity of exposure to natural forces like wind, waves, and seawater, as well as the corrosive effects of salt water on building materials, high-rise buildings in coastal areas are becoming more and more prone to environmental hostility [1,2]. This has led to specific structural integrity challenges such as sustaining stability and material degradation.

High-rise structures in coastal areas are subjected to a variety of environmental conditions that could compromise their structural integrity, including hurricanes, storm surges, corrosion from seawater, and seismic activity [3]. These elements working together can create significant safety risks and worries for both the building's inhabitants and the entire neighbourhood. Therefore, it is essential to comprehend the root causes and consequences of these issues when designing, building, and maintaining such structures.

Despite the substantial amount of research done in this field [4-6], a thorough examination of the current state of knowledge about structural integrity issues with high-rise structures in coastal areas is still lacking. Therefore, the purpose of this study is to examine issues of high-rise buildings in coastline regions to identify the most prevalent structural integrity issues of concern and the remedial actions that can be performed to address them, towards the development of safer, more durable and sustainable coastline high-rise structures. The study also targets providing information on upcoming demands for research in this area as well as current mitigating tactics. The study is relevant towards promoting the eleventh target of the sustainable development goals which advocates for the development of cities and communities to be safe, resilient, inclusive and sustainable.

2. Materials and Methods

The study adopted a literature review approach. It is therefore a qualitative research. A literature search was conducted for the review using a variety of databases, including Google Scholar, Science Direct, Web of Science, Elsevier and Covenant University Repository of peer-reviewed published research. Keywords used for the search include high-rise buildings, structural integrity, coastal regions, earthquake, foundation design and coastal erosion. The search was limited to papers in English that were published between 2010 and 2023 in order to situate the study within current knowledge in the field.

A total of forty papers were found and thirty were eventually reviewed. The inclusion criteria for relevant literature selection for review were that it addressed the issues of high-rise buildings' structural integrity in coastal areas. Articles that had not undergone peer review or that were not pertinent to the study's subject were excluded. The data extraction process involved reading the chosen papers and taking note of pertinent information, including the kinds of structural integrity issues covered, the approaches taken to solve them, and the outcomes of any studies that had been done. The data were then content analysed. Similar topics were grouped together in order to discover common themes throughout the literature, and this thematic approach was used to arrange the data. To find patterns and trends in the data, the analysis was carried out using qualitative methodology. The results were presented and discussed using a descriptive approach.

3. Results and Discussion

3.1. Structural Integrity Issues in High-rise Structures in Coastal Regions

The design and construction of high-rise structures in coastal regions present a unique set of challenges that demand careful consideration and innovative solutions. These towering structures, situated in proximity to water bodies, are subjected to a complex interplay of environmental factors that can severely impact their structural integrity throughout their service life.

Studies [7, 8] have highlighted that high-rise structures near coastal areas are susceptible to a range of structural integrity issues, including reinforcement bar corrosion, ground-bearing capacity concerns, and improper connections between structural components. These issues can stem from various factors, such as inadequate building design, poor construction quality, insufficient maintenance procedures, as well as external elements like wind loads, water loads, earthquakes, and unstable soil conditions. Kumar [9] emphasized the significance of robust structural design and effective maintenance practices to mitigate these issues, underlining the importance of a holistic approach that considers the entire lifecycle of the building.

The coastal environment presents unique challenges that can exacerbate these structural integrity concerns. The high concentration of chloride ions in the air and seawater can accelerate the corrosion of steel reinforcement in concrete structures, with studies [10, 11] indicating that the corrosion rate in coastal regions can be up to five times higher than in non-coastal areas. This accelerated deterioration can weaken the structural components, compromising the overall integrity of the building over time.

Moreover, the dynamic response of high-rise buildings in coastal areas is influenced by complex interactions between wind, waves, and the building structure itself [12]. These interactions can result in increased lateral loads, vibrations, and stresses on structural elements, posing a significant risk to the building's structural performance and serviceability. The design of these structures must account for these dynamic effects to ensure adequate stiffness, strength, and serviceability under various loading conditions.

Seismic hazards also pose a significant threat to high-rise structures in coastal regions, particularly those located near active fault lines. The proximity to the sea introduces additional complexities, such as the potential for soil liquefaction, tsunami impacts, and site-specific amplification or deamplification of seismic waves [13-18]. These factors must be carefully considered in the seismic design of tall buildings to ensure their resilience and safety during earthquakes, as well as to mitigate the risk of catastrophic failure.

Furthermore, coastal erosion and sea-level rise associated with climate change can undermine the foundations of high-rise structures, leading to differential settlements, loss of soil support, and potential foundation failure [19-21]. This issue is particularly concerning for tall buildings due to their significant weight and the increased consequences of foundation failure or excessive deformation, which can result in substantial damage or even collapse.

To address these multifaceted challenges, a comprehensive understanding of the structural integrity issues faced by high-rise structures in coastal regions is essential. The following sections delve into the key concerns, including corrosion, wind and wave loading, water issues, seismic design considerations, foundation design, and coastal erosion. Each section explores the unique challenges posed by the coastal environment, the potential impact on structural integrity, and potential solutions and mitigation strategies tailored to these iconic structures. Through this in-depth analysis, architects, engineers, and construction professionals can gain valuable insights and develop effective strategies to ensure the long-term safety, serviceability, and resilience of high-rise structures in these demanding coastal environments.

3.1.1. Corrosion, Wind and Wave Loading Issues

Archer [22] discovered that high-rise structures in coastal areas are vulnerable to progressive collapse, a phenomenon that can happen as a result of the loss of load-bearing capability of crucial structural components. Corrosion, wind, and waves were also recognized in the study as important factors in progressive collapse. The effects of corrosion on structural components can be more severe in tall buildings due to their increased surface area and exposure to corrosive environments at greater heights. As a building's height increases, so does its exposed surface area, making it more susceptible to the effects of salt air, moisture, and wind-driven rain, which can accelerate the corrosion process. This heightened corrosion can weaken the structural elements, such as reinforcing steel or steel frames, compromising the overall integrity of the building over time.

Due to the high concentration of chloride ions in the atmosphere and ocean, corrosion, in particular, is a problem that frequently affects high-rise buildings in coastal areas [10]. High-rise structures near the seaside are more vulnerable to corrosion, which could compromise the structure of the building [23]. Several researchers have examined the corrosion behavior of steel structures exposed to marine environments to address this issue. For instance, Rajput [24] examined the behavior of steel corrosion in seawater and concluded that the corrosion rate increases with water salinity. Similarly, Qian [25] determined that the corrosion rate increases with the concentration of chloride ions after studying the corrosion behavior of steel bars in concrete subjected to simulated coastal settings. Figure 1 shows the advanced stages of corrosion on structural steel components, such as reinforcing bars or steel frames, from a high-rise building in coastal regions. The image clearly depicts the extent of material loss and deterioration due to the corrosive marine environment.

According to a study by Li [10], steel in concrete structures corrodes far more quickly in coastal areas, shortening the structures' useful lives. The requirement for proper corrosion-resistant measures to maintain the structural integrity of high-rise structures in coastal areas was also underlined in a study by Kumar [9], Archer [22], and Abbas [14].

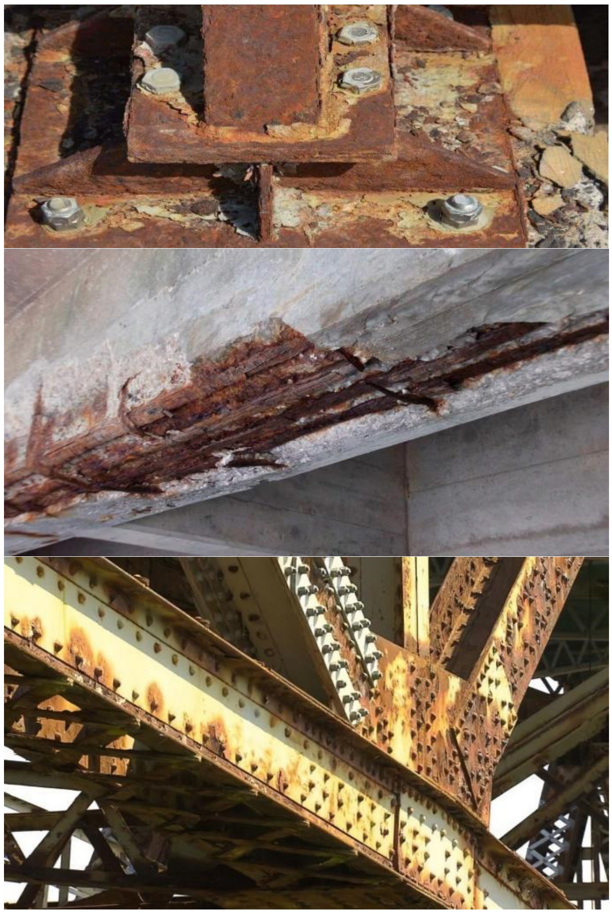

Figure 1. Advanced stages of corrosion on structural steel components

Additionally, wind and wave loads have a more significant impact on tall buildings because of their increased height and slenderness. The higher the building, the greater the wind forces acting on it, causing increased lateral deflections, vibrations, and stresses on the structural elements. These excessive lateral loads can lead to cracking, deformations, or even failure of structural components if not properly designed and reinforced. Furthermore, wave-induced loads can result in severe structural damage and pose a significant risk to the safety of tall buildings in coastal areas, as they are more exposed to the impacts of storm surges and wave action due to their proximity to the shoreline. Figure 2 depicts the effects of wind and wave loads on high-rise buildings in coastal regions. The image shows the building's lateral deflection, highlighting the increased stresses and potential for cracking or deformation in structural elements due to these lateral loads.

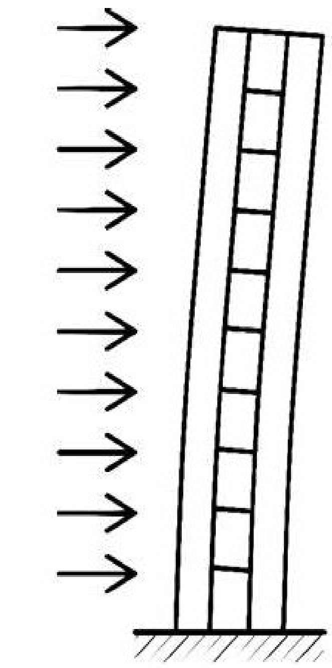

Figure 2. Illustration depicting the effects of wind and wave loads on a high-rise building in coastal regions

High-rise structures in coastal areas have been found to operate differently due to wind and wave loading. A study by Kwon [1] found that wind loads on tall buildings in coastal areas are complex and differ greatly from those in inland areas. Similarly, Xiong [26] found that wave-induced loads can result in severe structural damage and pose a risk to safety. Wind-induced vibrations are one of the biggest issues for high-rise structures in coastal areas. Both the inhabitants' discomfort and the structure's damage could result from these vibrations [7,27]. To this end, some academics have looked into the impacts of wind-induced vibrations on high-rise buildings to address this concern. Amini and Memari [28], for instance, examined the dynamic properties of a high-rise building subjected to wind loads and concluded that the wind-induced vibrations could cause fatigue damage to the structure. Similarly, Wang [29] used a numerical simulation procedure to examine the dynamic response of a high-rise structure to wind loads and found that the vibration amplitude rises with wind speed and building height.

3.1.2. Water Issues

High-rise structures near the shore are also vulnerable to water damage, which can jeopardize the building's structural stability. Water damage, such as the effects of wetting-drying cycles or salt-water immersion, can have a more severe impact on tall buildings due to their increased exposure to these environmental conditions at greater heights. The cyclic wetting and drying can lead to a drastic reduction in the compressive strength of concrete, which is a critical structural element in tall buildings. Similarly, salt-water immersion can significantly diminish the strength and durability of concrete, posing a greater threat to the structural integrity of tall buildings that rely heavily on the performance of concrete elements to resist lateral loads and maintain overall stability.

Some studies were found to have investigated how water damage affects the qualities of building materials towards finding a solution to this issue. For instance, Dehestani [30] examined the impact of wetting-drying cycles on the characteristics of concrete and came to the conclusion that the cycles could drastically lower the concrete's compressive strength. Likewise, Su and Zhang [31] investigated how salt-water immersion affected the characteristics of concrete and came to the conclusion that it might considerably diminish the concrete's strength and durability.

The impact of water damage on the structural integrity of tall buildings can be severe due to their reliance on concrete elements as the primary load-bearing components. A reduction in the compressive strength and durability of concrete can compromise the ability of these structural elements to withstand the significant lateral and vertical loads experienced by tall buildings, particularly in coastal regions where wind and seismic forces are amplified. Furthermore, the increased exposure to wetting-drying cycles and salt-water immersion at greater heights can exacerbate the deterioration of concrete, potentially leading to accelerated degradation and a higher risk of structural failure over time.

3.1.3. Seismic Design Issues

Due to the presence of active fault lines nearby, high-rise buildings situated in coastal areas are particularly vulnerable to earthquakes. However, the proximity to the sea introduces additional complexities and considerations for seismic design in these regions. Coastal areas often have different soil conditions compared to inland areas, such as softer or saturated soils, which can amplify seismic waves and increase the risk of soil liquefaction during earthquakes [13,16-18]. Soil liquefaction can cause severe damage to building foundations, jeopardizing the entire structure's integrity, making it a critical concern for high-rise buildings with deep foundations.

Furthermore, coastal regions are susceptible to tsunamis, which are large sea waves typically caused by earthquakes. High-rise buildings in these areas must be designed to withstand the potential impact and inundation from tsunamis, as well as the associated hydrostatic and hydrodynamic forces [14,15]. The proximity to the sea can also affect the site response during an earthquake, modifying seismic waves due to local geological conditions, which can lead to amplification or deamplification of ground motions [14].

In addition to seismic pressures, high-rise buildings in coastal areas must be designed to withstand environmental elements such as wind loads and storm surges [13]. The presence of salt in the air and water can accelerate corrosion of reinforcing steel and other structural components, weakening the structural integrity over time and potentially compromising their performance during seismic events [14].

To address these challenges, coastal-specific seismic design regulations may be required to ensure the longevity and safety of high-rise structures [14,15]. These regulations offer recommendations for designing for coastal-specific earthquake loads, such as soil liquefaction and tsunami effects. Base isolation systems, which involve adding shock absorbers between the building's base and the structure, can be an effective solution to reduce the effects of earthquakes on high-rise structures in coastal environments [32].

Resilient design concepts can also be employed to increase the capacity of high-rise structures in coastal areas to resist earthquakes and recover quickly [22,33]. Buildings designed with resilience can withstand natural disasters and bounce back rapidly, which is particularly beneficial in coastal regions where there is a significant risk of earthquakes and other natural hazards [34]. Figure 3 depicts the process of soil liquefaction during an earthquake, with a focus on its effects on the foundations of a high-rise building in coastal areas. The image clearly depicts the loss of soil strength and the potential for foundation failure or excessive settlement.

The proximity to the sea introduces unique seismic design considerations for high-rise buildings in coastal regions, including soil conditions, tsunami risk, site response, corrosion effects, and wind loads. Addressing these factors through coastal-specific design regulations, base isolation systems, and resilient design principles is crucial to ensure the structural integrity and safety of these structures.

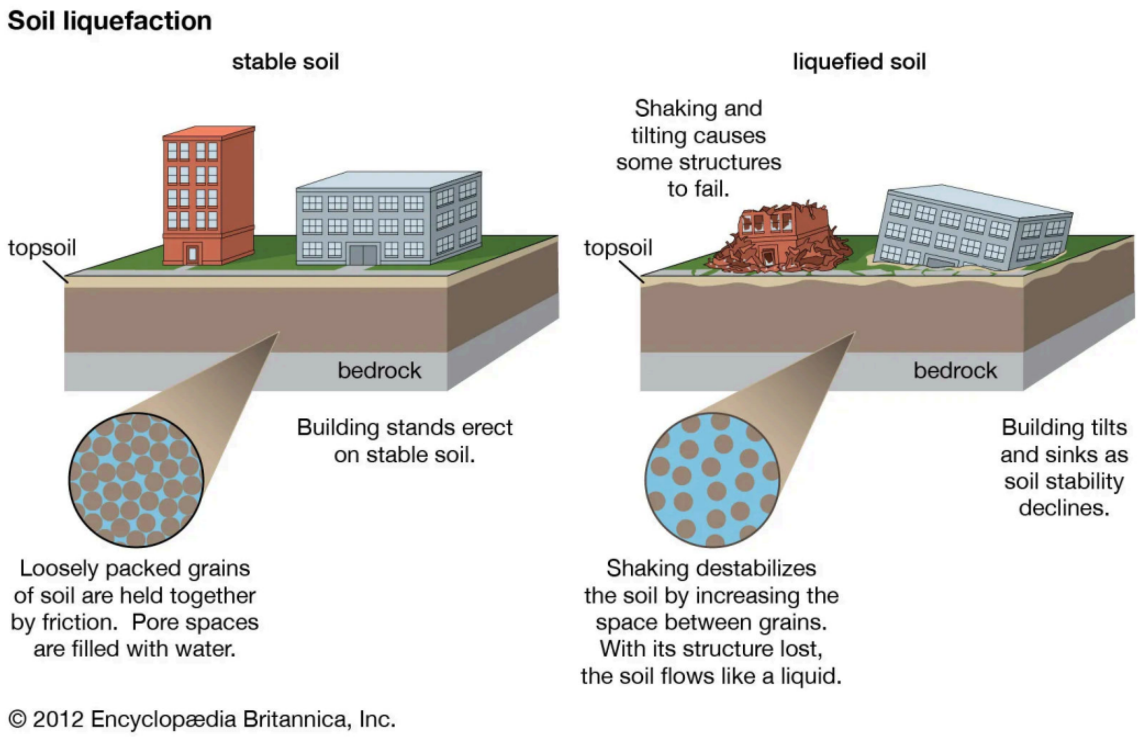

Figure 3. Diagram showing the process of soil liquefaction during an earthquake [35]

3.1.4. Foundation Design Issues

When it comes to high-rise structures in coastal areas, foundation design is an important factor to take into account [36]. The foundation design issues discussed in this subsection, such as soil liquefaction, differential settlements, and lateral loads, can have a more significant impact on tall buildings due to their higher weight and more extensive foundation systems. The consequences of foundation failure or excessive deformation can be catastrophic for tall buildings, leading to potential collapse or severe damage.

Due to its traits, such as liquefaction potential, susceptibility to erosion, and limited bearing capacity, the soil in these places can be difficult to work with. As a result, to design stable and secure foundations for high-rise buildings in these areas, it requires specific considerations such as soil-bearing capacity, soil type, ground-water conditions and seismic activities [36,19]. Building on coastal soils can be difficult since they are frequently brittle and compressible [37]. High settlement rates brought on by soft soils may result in differential settling and structural damage to the building. Engineers must ensure that the foundation design can evenly distribute the building's weight and minimize soil settlement to reduce this risk. This is frequently accomplished with deep foundation systems like piles or caissons that can reach more stable soil strata by penetrating soft soil layers [38,39].

The possibility of soil liquefaction should be taken into account when planning high-rise building foundations in coastal settings. When pore water pressure builds up during an earthquake, the strength and rigidity of the soil are lost, leading to soil liquefaction. When this occurs, the earth behaves like a liquid and is less able to support the weight of the building [18]. For tall buildings, the consequences of soil liquefaction can be catastrophic due to their higher weight and the increased risk of foundation failure or excessive deformation. Foundation designers can utilize ground improvement techniques to boost the soil's resistance to liquefaction, such as densification, grouting, or vibro-compaction, to lower the danger of soil liquefaction [40,41].

Coastal environments may be exposed to additional environmental elements, such as wind loads and storm surges that may affect foundation design in addition to soil-related difficulties. To maintain the stability and safety of the building, these forces must be taken into consideration while designing the foundation [22,36]. Generally, these forces can result in large lateral loads on the building foundation, which can be particularly challenging for tall buildings due to their increased height and slenderness, potentially leading to increased stresses and deformations if not properly accounted for.

3.1.5. Coastal Erosion Issues

Due to the potential for foundations to deteriorate and for the structural integrity of the entire building to be jeopardized, coastal erosion is a major worry for high-rise structures in coastal settings. Coastal erosion poses a greater threat to the structural integrity of tall buildings compared to low-rise structures due to the potential exposure and undermining of their foundations. As the shoreline retreats due to erosion, the foundations of tall buildings can become exposed, leaving them vulnerable to the effects of wave action, currents, and other erosive forces. This can lead to the gradual loss of soil support, potentially causing differential settlements or even complete foundation failure.

The consequences of such failures can be more severe for tall buildings due to their height and weight. Even relatively minor differential settlements can induce significant stresses and deformations in the structural elements of a tall building, potentially leading to cracking, damage, or even collapse in extreme cases. Additionally, the sheer weight of a tall building can amplify the effects of foundation failure, increasing the risk of catastrophic consequences.

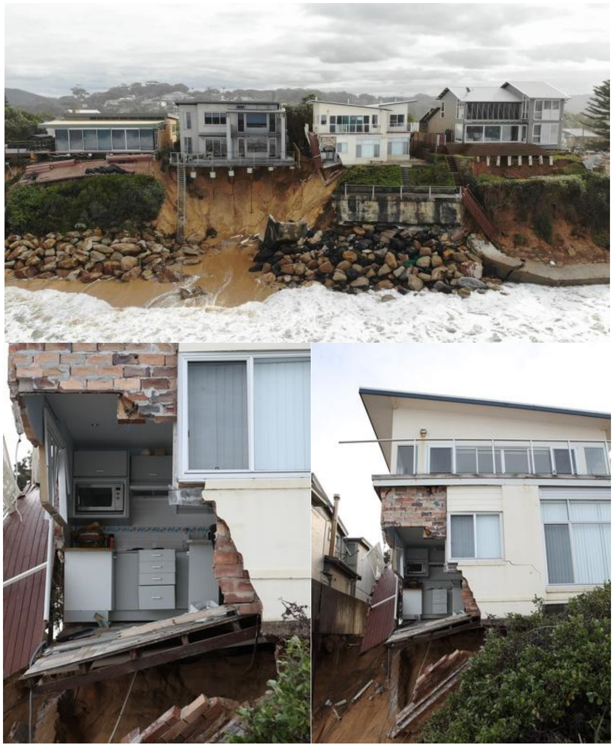

Figure 4. Images demonstrating the effects of coastal erosion on buildings in coastal regions [42]

When sand and other materials are lost to the shoreline due to natural processes such as waves, wind, and currents, the shoreline retreats inland [19]. Sea level rise, a result of climate change, is one of the main factors causing coastal erosion. Rising sea levels make storm surges and coastal flooding more frequent and severe, which can hasten erosion rates and endanger high-rise structures [20]. High-rise buildings can be protected from the effects of coastal erosion in a number of ways. Building structures far enough from the shoreline to reduce erosion's effects is one of the most efficient strategies [20]. Additionally, to safeguard the shoreline and stop erosion, engineering solutions like seawalls, revetments, and breakwaters can be deployed [21]. Figure 4 demonstrates the effects of coastal erosion on buildings in coastal regions. The image shows the gradual exposure and undermining of building foundations due to shoreline retreat, as well as any visible structural damage or deformation resulting from this erosion.

Coastal high-rise building design and construction must also take into account the potential effects of coastal erosion. Site-specific geological and geotechnical investigations should be carried out to identify the hazards associated with coastal erosion, and building foundations should be built to withstand probable erosional effects [21,22,41]. For tall buildings, the consequences of foundation exposure and erosion can be catastrophic, making it essential to address this issue through proper site evaluation, design considerations, and protective measures.

3.2. Most Prevalent Structural Integrity Issues and Remedial Measures in Coastal Regions

A variety of structural integrity issues affecting high-rise buildings in coastal areas were found in the literatures reviewed. Seismic stresses from earthquakes, problems with foundation design, coastal erosion, wind loads, soil liquefaction, and storm surges are some of these worries. The review also discovered that developing high-rise structures in coastal areas presents special difficulties, but that certain seismic design rules and resilient design concepts can help allay these worries.

Seismic forces, foundation construction, and coastal erosion were the three most prevalent structural integrity issues uncovered in literature. High-rise structures along coastlines are particularly vulnerable to damage from earthquakes, especially if they are near active fault lines [22,33]. Because the soil in coastal places is frequently unsuitable for supporting tall buildings, foundation design is another important consideration. Another issue is coastal erosion, which can make high-rise structures' foundations unstable and jeopardize their structural integrity. Due to the closeness of active fault lines, earthquakes frequently occur in coastal areas and generate seismic forces. High-rise structures can experience considerable structural damage, floor collapse, and even total collapse as a result of seismic pressures [32]. The inadequate soil present in many coastal places results in foundation design problems, which can cause settling and instability in high-rise buildings [37]. Natural phenomena like waves and tides can produce coastal erosion, which can progressively erode the shoreline and undermine the foundation of tall buildings.

In general, the literature review analysis revealed that high-rise structures in coastal areas are vulnerable to a variety of structural integrity difficulties, such as seismic forces, poor foundation design, and coastal erosion. These issues can have a big impact on the safety and longevity of high-rise buildings and are brought on by natural phenomena including earthquakes, unsuitable soil, and coastal erosion. High-rise structures in coastal areas can be kept safe by following specific seismic design rules [43-45], resilient design concepts [46-49], and base isolation systems.

4. Discussion

The findings of this comprehensive study highlight the multifaceted structural integrity issues that high-rise structures in coastal regions are vulnerable, including foundation design challenges, material corrosion, coastal erosion, seismic forces, and wind and wave loading [13,19,23,36,40]. The results underscore the necessity for careful consideration of these factors throughout the design, construction, and maintenance phases of high-rise buildings in such environments [50]. Building in coastal regions is a complex endeavor due to the extreme environmental conditions present.

According to the findings by Fang [36] and Poulos [51], the foundation designs for high-rise buildings in coastal areas must be meticulously considered to ensure that the structure can withstand the loads imposed by its weight and external influences, such as soil erosion and liquefaction. The consequences of foundation failure or excessive deformation can be catastrophic for tall buildings, leading to potential collapse or severe damage, as highlighted in Figure 3.

The analysis also revealed that corrosion of building components is a significant issue in coastal areas due to the high salt content in the air and water [10,52,53]. Corrosion can result in a loss of structural integrity, potentially compromising the building's safety. This problem can be mitigated through the use of corrosion-resistant materials and routine maintenance. Figure 1 illustrates the severity of corrosion on structural elements in a coastal high-rise building, underscoring the importance of addressing this issue.

Seismic pressures and coastal erosion were also identified as critical concerns [16,32]. Building foundations may be undermined by coastal erosion, as shown in Figure 3, potentially leading to differential settlements or even complete foundation failure. Additionally, the building itself may sustain damage from earthquakes. Base isolation techniques can be employed to mitigate the effects of seismic forces, and resilient design concepts can ensure that a building maintains its functionality even after being subjected to coastal erosion or seismic events.

These findings have significant implications for the design, construction, and maintenance of coastal high-rise buildings. Engineers and architects must consider the specific environmental conditions found in coastal areas and ensure that the structure is robust enough to withstand them. The incorporation of modern materials and technologies, such as sensors that can monitor a building's structural health and identify issues before they become critical, should be considered.

In terms of construction, ensuring that the foundation design is appropriate for the soil conditions in the coastal region is crucial [41]. Conducting a geo-technical investigation may be necessary to determine the optimal foundation type and identify the soil properties.

Proper maintenance is vital for ensuring the durability and safety of high-rise buildings in coastal areas. Regular inspections, repairs, and corrosion control procedures can mitigate corrosion issues over time.

Furthermore, the implications of this review extend beyond high-rise structure design, construction, and maintenance. Building codes and regulations may need to be updated or modified to reflect the distinct environmental factors present in coastal regions. This could involve more stringent specifications for wind-resistant design, corrosion prevention techniques, and foundation design.

Ultimately, the findings of this review demonstrate that the design, construction, and maintenance of high-rise buildings in coastal areas require a comprehensive strategy. By considering the potential for natural disasters and other environmental conditions, and implementing appropriate mitigation measures, engineers and architects can contribute to ensuring the safety and robustness of high-rise buildings in these locations.

This review emphasizes the importance of accounting for the specific environmental aspects of coastal areas when designing, constructing, and maintaining high-rise structures. Resilient design concepts, base isolation systems, and corrosion-resistant materials can enhance the durability and longevity of these structure types while mitigating the effects of natural disasters and other risks. Nevertheless, further research is still required to better understand the intricate relationships between environmental factors and high-rise building structures in coastal areas, and to develop new technologies and models that can improve building design, construction, and maintenance practices.

5. Conclusions

This review was conducted to identify the most prevalent structural integrity issues of high-rise structures in coastal regions and the remedial actions that can be employed to address them, towards the development of safer, more durable and sustainable coastline high-rise structures. The review revealed that high-rise structures in coastal areas are especially vulnerable to foundation design, material corrosion, coastal erosion, seismic pressures, and wind loads. These issues may jeopardize the high-rise structures' structural stability and endanger occupants' safety.

This review has important practice-related implications. When designing, building, and maintaining high-rise structures, architects, engineers, and building owners must take into account the special environmental characteristics inherent in coastal areas. High-rise structures in coastal areas can be made more secure and last longer by incorporating robust design principles, base isolation systems, and corrosion-resistant materials. The analysis also makes the case that modern tools like sensors and data analytics can be used to enhance high-rise building monitoring and maintenance in real time.

This study recognizes that the methodology employed for the research constitutes a limitation for the study, but does not in anyway diminish its contributions. There is therefore the need for additional study to fully comprehend the long-term resilience of high-rise structures in coastal areas. Future studies should concentrate on creating more precise and trustworthy models for forecasting how environmental elements would affect high-rise building constructions in coastal areas. These models could be used to design and create more durable buildings that can survive dangers and natural disasters. More case studies on the effective application of resilient design principles, the use of base isolation systems, and the use of corrosion-resistant materials in high-rise buildings in coastal areas are also required. These studies will offer insights into best practices for planning and managing high-rise structures in coastal areas and can be used as models for upcoming construction projects.

In conclusion, this study emphasizes the significance of resolving high-rise building structural integrity issues in coastal areas to ensure the security and resilience of the built environment. The conclusions and ramifications of the findings can guide future study and provide guidelines for the development, construction, and upkeep of tall structures in coastal areas.

Conflict of Interest

The authors declare no conflict of interest

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