

Article

Integrated Analysis of the Geotechnical Factors Impeding Sustainable Building Construction—The Case of the Eastern Province of Saudi Arabia

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Abstract: Sustainable building construction in the Eastern Province of Saudi Arabia is fraught with issues, ranging from groundwater table fluctuation to inappropriate earthwork techniques, particularly in areas that were previously reclaimed. This paper analyzes the geotechnical factors that affect the safety and serviceability of infrastructure construction on reclaimed land. The data were collected mainly from expert-based surveys and semi-structured interviews with geotechnical experts across the Eastern Province of Saudi Arabia. Ten critical factors were identified, and an integrated assessment was conducted using the Interpretive Structural Modelling (ISM) technique to examine the hierarchical structure of the relations between the factors. In addition, the Cross-impact Matrix Multiplication Applied to Classification (MICMAC) technique was used to classify the factors from a driving to driven perspective. Findings of the study reveal the driving factors, which have the propensity to affect other factors and are the most crucial factors hindering the safety and serviceability of sustainable building construction. These factors are the presence of low-bearing sabkha soil, shallow and fluctuating depth of the groundwater table, and the lack of soil improvement applications. It is expected that concerned authorities may find the outcomes of this study useful in formulating effective policies, standards, and regulations that will protect infrastructure construction from safety and serviceability problems. While the evidence on which the results of this study are based is from experiences related to coastal areas of Saudi Arabia, the outcomes of this paper could be adopted in other coastal areas in the Gulf region. This paper adds to the current knowledge on safety and serviceability management of infrastructure constructed on reclaimed lands.



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Keywords: reclaimed land; coastal areas; sustainable construction; safety and serviceability

1. Introduction

With significant population growth and economic development, urbanization is increasing at a rapid pace. The prominent oil boom of the 1970s provided the much-needed boost for the economic transformation of the Gulf region [1]. Today, many countries in the region boast the fastest-growing economies in the world and are highly rated among the community of rich nations. Remarkably, the past four decades have witnessed a tripled demographic growth in the region [1], which has demanded the expansion of cities. To meet the requirements of rapid urbanization and the development of cities, coastal cities are opting for land reclamation as a workaround solution. At present, it is estimated that in United Arab Emirates, Qatar, Oman, Kuwait, and Bahrain, nearly ninety percent of the people reside in areas within one hundred kilometers of the coastline. It is also predicted that the population will continue to grow along the coastline of the Gulf [2].

Saudi Arabia, being the largest and most populous country in the Gulf region, is moving at a fast pace in infrastructure and building construction, to provide required housing for its teeming population and to diversify the economy [1,2]. To date, large construction areas have been duly reclaimed, but the safety and serviceability of the buildings being

constructed in these areas have been a major cause for concern. The shallow soil profiles of Saudi Arabia's coastline show that the area is covered mainly by dune or beach sand. The soil in shallower depths, which bears the foundations for most of the infrastructure, is in a loose state, with solvable salts, and is generally termed as sabkha [3,4]. Sabkha soil is very problematic in nature and offers a variety of geotechnical problems, including primary and secondary settlement, salt heaving, corrosion, and flooding problems due to low infiltration rates [5]. In addition to the poor and problematic natural ground conditions, inappropriate construction techniques are also adopted in this region. Coastal land is often reclaimed with poorly graded local material, and foundations are laid on the ground without state-of-the-art deep compaction methods and cutting-edge soil improvement techniques. This significantly affects the safety and serviceability of the buildings, roads, and other infrastructure facilities, especially those built on reclaimed land. This study determines and prioritizes the crucial factors that affect the safety and serviceability of infrastructure construction on reclaimed lands in the Eastern Province of Saudi Arabia.

2. Literature Review

There are several factors contributing to the poor performance of infrastructure facilities. These include high vulnerability to strength loss for saline soil, variation of the soil moisture, selection of unsuitable types of structures, inappropriate construction materials and techniques, and many others. Though not integrated together, different researchers have investigated the effect of these factors on the safety and serviceability of infrastructure. Sabkha soils have very low bearing capacity and are susceptible to excessive settlement [4]. Several studies have investigated the performance of infrastructure built on dry and saturated sabkha soils [6–9]. While studying the effect of dry sabkha soil, refs. [10,11] reported cracking failure of the pavement structures due to salt crystallization. Similarly, refs. [12,13] anticipated a complete collapse when sabkha soil comes in contact with water. A similar behavior has also been observed in other Gulf countries, e.g., despite using a significant amount of quality rocks in reclamation, extensive vibrocompaction of the sand, and a careful engineering design, Palm Jumeirah island of Dubai has been reported to be sinking down slowly [14].

The selection of appropriate materials and engineering practices on sabkha formations has always been a challenge. Ref. [11] reported severe safety and serviceability problems in the infrastructure of King Fahd Suburb due to inappropriate construction practices. Likewise, some researchers have comprehensively reported compression zone and settlement-induced damages to newly constructed roads in the Kingdom of Saudi Arabia and other desert regions [15,16]. The main reason for these failures is conventional construction practices, where no attention is paid to strengthen the subgrade.

The above-mentioned studies evaluate individual factors for their effects on the safety and serviceability of infrastructure facilities. To promote sustainable building construction and enhance the safety and serviceability of constructed facilities, it is necessary to identify and analyze, in an integrated way, all the factors challenging sustainable building construction in such areas. Due to the paucity of literature focusing on geotechnical factors impeding sustainable building construction in the Eastern Province of Saudi Arabia or any closely related area, it was apparent and necessary to source the study data by considering opinions of experts related to the area of the study. Thus, this paper describes the factors affecting the safety and serviceability of the infrastructure built on reclaimed land. While the evidence on which the results of this study are based is from experiences related to coastal areas in the eastern region of Saudi Arabia, the outcomes of this paper could be adopted in other coastal areas located in the Gulf region. This paper updates current knowledge on the safety and serviceability management of infrastructure constructed on reclaimed lands and offers valuable help to regulatory decision makers and practitioners.

This paper presents a consolidated assessment method to evaluate the relationship between the geotechnical factors that affect the safety and serviceability of infrastructure construction on reclaimed land. Several published research works have adopted the

consolidated approach in various fields of construction engineering and management. The approach adopted in this paper represents a different leading edge in construction research. This is evident in the work of [17], where the authors used an inventive and unified method for repairing residential buildings using green construction materials. Similarly, a consolidated technique was earlier implemented by [18] to investigate the seismic performance of an existing multi-span masonry arch bridge. Thus, the above-mentioned studies have clearly substantiated the use of new and integrated strategies for different areas of construction and help to provide new perspectives with respect to research in the construction area.

The inadequate and fragmented literature on the geotechnical factors that affect the safety and serviceability of infrastructure construction on reclaimed land makes it necessary to have a comprehensive understanding of these factors or impediments.

It should be noted that while some of the factors described in the literature are clearly inadequate and fragmented for a study of this nature, the intricate interrelations between the factors have also not been examined. Comprehensive knowledge of the interrelations between the factors will help to overcome the safety and serviceability challenges of infrastructure construction on reclaimed lands. Thus, this paper is aimed at performing a comprehensive assessment of the factors and examining the interrelations among them. The outcomes of this evaluation are expected to serve as a helpful platform for construction policy makers to understand how best to overcome the safety and serviceability challenges of infrastructure construction on reclaimed lands.

3. Study Area

The study area is the whole Eastern Province of Saudi Arabia, which encompasses a total land area of 672,522 square kilometers and a population of about 5.1 million [19]. To meet vision 2030 (<https://www.vision2030.gov.sa/>, accessed on 25 January 2021) and ensure diversity of the economy of Saudi Arabia, the eastern region is witnessing enormous development, ranging from individually owned houses to megaprojects. According to statistics, there has been a considerable increase in building permits issued by the municipalities of the region. Being the hub of oil industries in the country, the Eastern Province is continuously demanding expansion of infrastructure facilities. For residential as well as industrial development, coastal areas are considered as the first choice, justified by the fact that nearly ninety percent of the Gulf's people reside in areas within one hundred kilometers of the coastline. Land is continuously reclaimed to meet these growing needs.

The whole study area has complex and problematic subsoil conditions. The explorable strata of the region is mainly composed of loose sand with numerous salts, commonly termed as sabkha [3,4]. These salts occur as crusts on the surface or in the dissolved form in soil moisture [20]. Previous studies [21–24] revealed that magnesium, calcium, sulphates, sodium, chlorides, and carbonates of calcium dominate the salt precipitation in the Middle Eastern desert region. The bond between the soil grains is weakened by the presence of crystalized salt. The variation in the strength, consistency, and expansive characteristics of salt-bearing sabkha soil is further extrapolated by the changes in moisture content and extreme environmental conditions of the region [6,7,25]. Relatively shallow layers of soft and loose deposits overlying medium-dense to dense sands are observed in the low-lying coastal areas. Sabkha soils are usually associated with a shallow groundwater table, and in the study area it is generally located at a depth of less than 1.5 m below the ground surface.

The coastal land of the study area is reclaimed using locally available material, which is very poor in quality and gradation. With the exception of large and important structures, which make up a very small percentage of building construction in the region, the buildings are individually owned and limited to less than five stories. Generally, these buildings are made of reinforced concrete and have isolated shallow foundations, which are laid on the ground without adopting deep compaction methods and soil improvement techniques. A similar practice is observed in the construction of roads. The base and subbase courses are laid without treating the problematic subgrade.

The variation in strength, consistency, and expansive characteristics of sabkha soils as well as the inappropriate construction techniques confer a variety of problems to the infrastructure. Settlement-induced damage to the buildings and roads is commonly reported in the whole study area [8–14].

4. Methods

An integrated analysis was employed to attain the objectives of this study. The analysis entails determining the hierarchical structure of governing factors from driving power to driven power perspective or position. The established hierarchical structure is considered valuable in interpreting the complex relationship between the impediments. The structure was formed using the interpretive structural modeling technique to describe and simplify the intricate correlation between variables. The study utilized a hybrid interpretive structural modeling (ISM) and cross-impact matrix multiplication applied to classification (MICMAC) approach to evaluate the extent to which each factor could promote the safety and serviceability of infrastructure constructed on reclaimed lands. This hybrid approach helped to set up a structure within the set of the determined factors. A structural model was created for the factors according to the direct and indirect relationships among them. These relationships among the factors describe the complexities of the safety and serviceability of infrastructure construction on the reclaimed land more accurately than the individual factors considered separately. Therefore, the adoption of the hybrid approach provided insights into collective understandings of these interrelationships among the factors. The techniques adopted for achieving the aim of this paper are presented in the sections that follow.

4.1. Determining the Barriers

From the start, the governing geotechnical factors affecting the safety and serviceability of infrastructure constructed on reclaimed lands were identified using content analysis. Content analysis is considered a valuable technique for gathering, investigating, and assessing research data to establish research problems from the literature. Nevertheless, owing to the dearth of literature related to the research problem and study area, a sufficient number of governing factors could not be obtained through content analysis. Therefore, opinions of experts, experienced in the research problem and study area, were also collected to strengthen the collected data.

Ninety-six geotechnical experts from across the Eastern Province of Saudi Arabia were involved in this survey. This number can be considered as sufficient for an expert-based survey, particularly when judgmental sampling is implemented [26,27]. The judgmental sampling was adopted to augment the validity and reliability of the outcomes. The participants not meeting the survey requirements were excluded [28].

Survey Requirements

To start with, the participants were provided with a list of factors. This list was prepared by combing the content analysis data using the authors' knowledge of geotechnical problems and construction techniques in the study area. The participants were urged to assess the listed factors, exclude irrelevant factors, and add other factors. Thus, a list of 19 geotechnical factors affecting the safety and serviceability of infrastructure constructed on reclaimed lands was prepared. This list was finalized after a detailed discussion with experts from the construction industry and academics/researchers from reputable universities around the province. The demographic profile of the geotechnical experts who participated in this survey is presented in Figure 1.

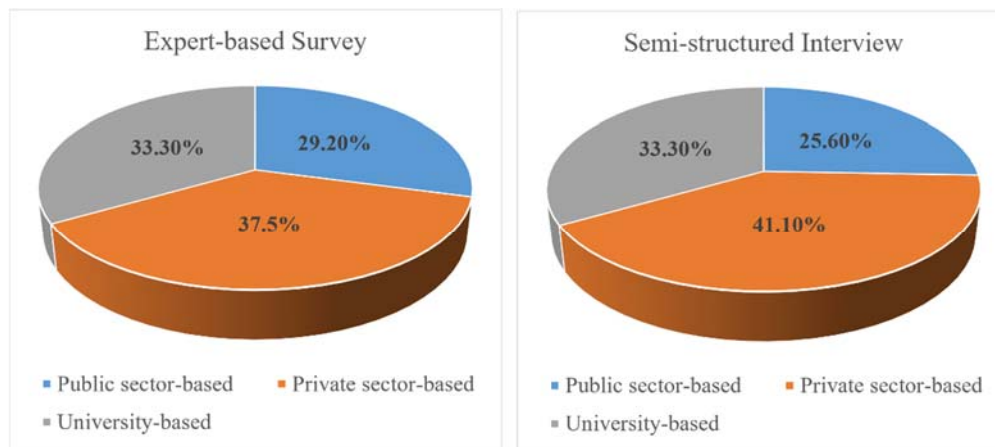


Figure 1. Grouping of the specialists that participated in the study.

In the next phase, the participants with higher levels of experience and expertise were interviewed to collect their detailed observations about the factors affecting the safety and serviceability of infrastructure constructed on reclaimed lands. For the online interviews, the experts were given three different time slots and were requested to choose the one convenient for them. Forty-five experts responded and agreed to be interviewed. Ultimately, thirty-nine experts participated in the online interview meetings. The participants were asked to evaluate the extent to which each factor could promote the safety and serviceability of infrastructure constructed on reclaimed lands. They were provided with the following items in the meeting agenda to effectively evaluate the governing factors:

- Ensure the relevance of the listed factors.
- Add other important factors that were not included in the list; give the reason for the addition of these factors.
- Determine whether the factors are suitably stated. If not, suggest improvements.
- Identify similar factors and suggest their merging.
- Determine whether the factors could significantly promote the safety and serviceability of infrastructure constructed on reclaimed lands. If yes, justification is requested.

4.2. The Approach for the Integrated Analysis of the Factors

The integrated analysis approach was adopted to determine the interrelationships among the governing factors by introducing the hierarchy structure between the identified factors. The factors were categorized from a driving to driven perspective. The interpretive structural modeling technique [29] was used to determine the hierarchy structure and complicated relations between the variables. As corroborated by [30], the interpretive structural modeling technique has been extensively used to examine interrelations among numerous variables in a complex system. Typically, researchers [31–35] have also used mean value and weighted score techniques to establish interrelationships of this nature, though without due consideration to the detailed examination of the complications associated with the interrelatedness of the variables. Considering the targeted number of geotechnical experts for the study, interpretive structural modeling was adopted as a reliable technique. The adaptation of this technique can also be justified by the fact that the quality of responses from the expert-based survey was prioritized over quantity in this study. Refs. [29,36] affirmed that two proficient specialists can provide the much-needed validity and reliability required of the interpretive structural modeling technique in establishing the hierarchical formation for the factors under study. In view of this, the number of experts that participated in this study—39—is considered highly satisfactory and adds validity to the findings of the study.

In contrast, the Cross-impact Matrix Multiplication Applied to Classification (MICMAC) technique was employed to categorize the governing factors from the driving to

driven context. Similarly, the factors were subsequently grouped based on their dependence and driving strengths to provide better understanding of the intricate relationships among the factors [29,30]. Figure 2 comprehensively describes the methodology of the integrated analysis using the interpretive structural modeling and Cross-impact Matrix Multiplication Applied to Classification techniques.

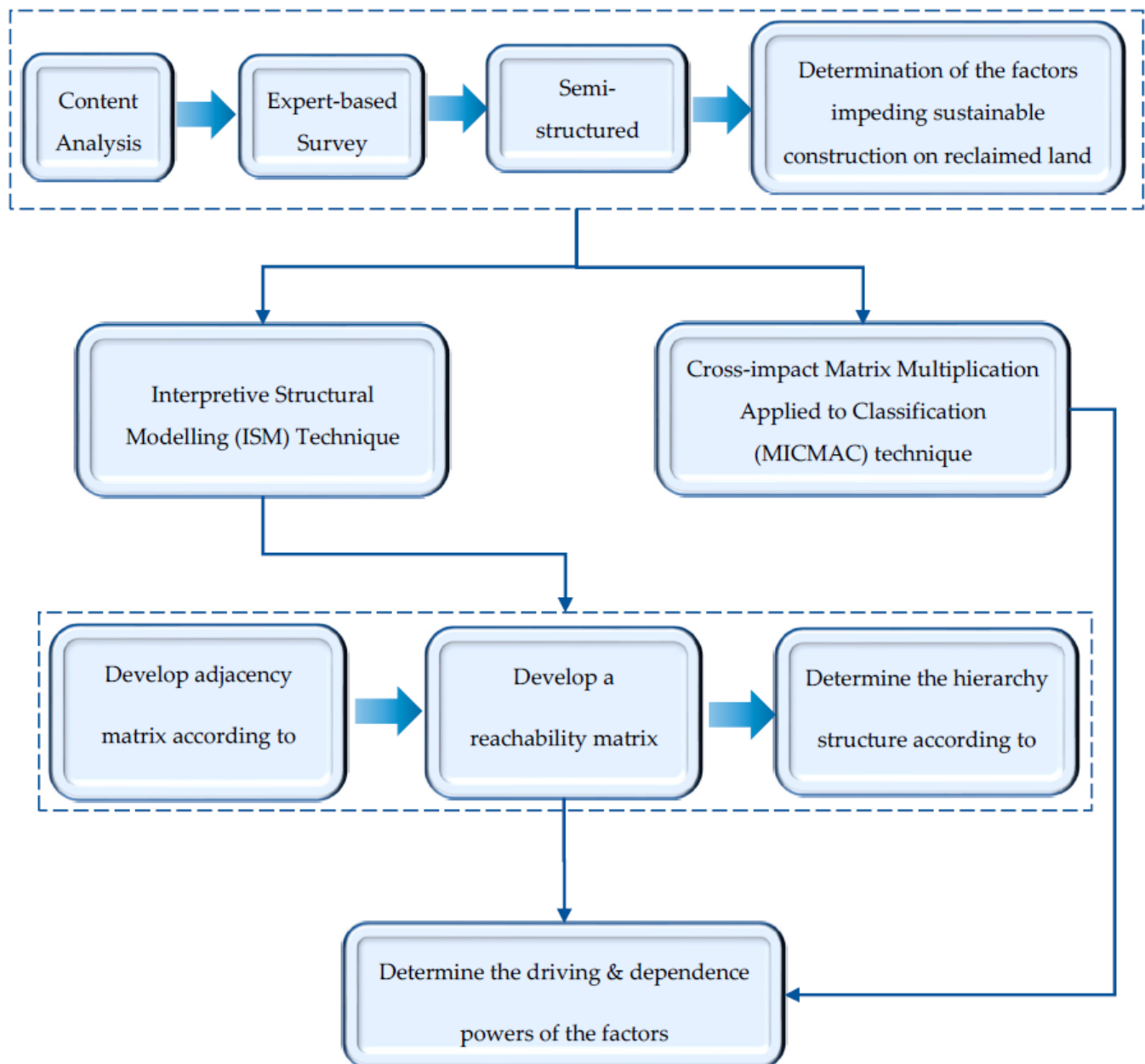


Figure 2. Procedure for the integrated evaluation approach using ISM and MICMAC techniques.

5. The Factors Impeding Sustainable Building Construction on Reclaimed Land

Despite putting significant efforts into the reclamation work and using sophisticated engineering designs, the problems plaguing the safety and serviceability of infrastructure construction on reclaimed lands in the Eastern Province of Saudi Arabia continue to escalate. Thus, this section describes in detail the major factors that challenge the effective improvement in the safety and serviceability of infrastructure constructed on reclaimed lands. By analyzing the responses of the participants, a final list of ten governing factors

affecting the safety and serviceability of infrastructure constructed on reclaimed lands was produced (Table 1).

Table 1. Factors affecting the safety and serviceability of infrastructure constructed on reclaimed lands.

Factor Number	Description of the Impediments
F1	Improper soil investigation before construction
F2	Inappropriate foundation system
F3	Insufficient time for the soil to settle before construction
F4	Lack of quality fill material
F5	Low bearing capacity of the soil
F6	Lack of soil improvement applications
F7	Poor compaction work
F8	Poor gradation of the soil
F9	Salt-bearing sabkha soil
F10	Shallow and fluctuating depth of groundwater table

5.1. Improper Soil Investigation before Construction (F1)

The improper soil investigation before construction remains one of the crucial barriers to the improvement of the safety and serviceability of infrastructure constructed on reclaimed lands. With the exception of very important governmental projects, soil is not thoroughly investigated before the construction of infrastructure facilities. In the study area, only bearing capacity is determined for most of the projects, and even this determination is inadequate. The problematic sabkha soil needs to be properly examined for its strength and deformation behavior for different proportions, types, and forms of salts. There are frequent chances for the soil to be saturated by infiltration of the rainwater, leaking of water from drainage pipes and gutters, and fluctuation of the groundwater table. Therefore, the behavior of soil should be studied both in its dry and wet conditions. Laying foundations on a soil without knowing its actual behavior will have serious consequences.

5.2. Inappropriate Foundation System (F2)

For two- to three-story buildings, particularly those individually owned, an isolated foundation system is adopted in the study area. Considering the complex behavior of sabkha soil, an isolated foundation leads to differential settlement and consequently cracking of the building (Figure 3). It is therefore necessary to adopt either effective ground improvement or heavy foundations to ensure the safety and serviceability of the buildings built on problematic coastal land.

5.3. Insufficient Time for the Soil to Settle before Construction (F3)

The study area is also known for the short construction time of small-size projects. Some small roads and other structures are constructed so quickly that the soil is not given enough time for settlement. Therefore, such structures experience settlement soon after being opened, particularly if a clay layer is encountered in the loaded zone.

5.4. Lack of Quality Fill Material (F4)

The surface strata of the eastern region of Saudi Arabia are mainly composed of sand. Therefore, this region lacks good quality fill material. Good quality gravels are available in the western part of the country, but it is too far to transport the required material to the Eastern Province.



Figure 3. Excessive foundation settlement and cracking of the walls of a two-story house built on sabkha soil in the Eastern Province of Saudi Arabia.

5.5. Low Bearing Capacity of the Soil (F5)

Due to its poor gradation and expansive behavior, the soil in the studied region has very low bearing capacity, having an average value of less than 100 kN/m^2 . At some locations it is even below 80 kN/m^2 . Such a low bearing capacity results in shear failure or excessive settlement of the infrastructure.

5.6. Lack of Soil Improvement Applications (F6)

Despite the problematic soil with low bearing capacity, application of ground improvement is very limited in the study area. This could be attributed to lower awareness and increased initial cost of the project. Laying the foundation on untreated soil leads to the cracking and failure of infrastructure well before expected.

5.7. Poor Compaction Work (F7)

A typical approach for the construction of flexible pavements in the study area is to lay sub-base and base courses without thoroughly compacting and treating the subgrade stratum. The authors had an opportunity to examine the construction of drainage work for a road and parking, whose base and sub-base courses were previously laid (Figure 4). It is very clear from the picture that the subgrade stratum is very poorly graded, and no attempt was made to treat or compact it. It will definitely undergo settlement and bearing problems under applied loading. The use of compaction equipment, the thickness of soil layers, and the optimum moisture content are also compromised in many small- to medium-size projects (Figure 5).

5.8. Poor Gradation of the Soil (F8)

Most of the shallower strata in the study area, which carry the foundation loads, consist of poorly graded loose sand. Refs. [37,38] investigated the geotechnical properties of soil collected from the foundation zones of different infrastructures located in the Eastern Province of Saudi Arabia. The samples collected from all the sites were classified as poorly graded sand, with a negligible percentage of gravel and fines. Owing to the fact that it has more void spaces between the particles, poorly graded soil is more vulnerable to settlement under applied loads. Though the study area lies in a low seismic zone, poorly graded loose sand is highly susceptible to the liquefaction phenomenon under dynamic loading. Liquefaction results in a complete loss of shear strength and, consequently, settlements, tilting of structures, and lateral displacements.



Figure 4. Very loose, poorly graded, and untreated subgrade stratum underlying relatively well graded, higher quality, and compacted sub-base and base courses. The resources and time utilized on the sub-base and base courses will be in vain once the poor subgrade strata settle under applied loads and varying degrees of saturation.



Figure 5. Compaction of the base layer of a road and parking in the Eastern Province of Saudi Arabia. An amount of water far above the optimum moisture content was added randomly, which will result in reduced dry density. Consequently, this may result settlement of the pavement, requiring repeated repair work.

5.9. Salt-Bearing Sabkha Soil (F9)

Shallow soil profiles of Saudi Arabia's coastline show that the area is covered up mainly by dune or beach sand with soluble salts. This soil is generally named as sabkha soil. Sabkha soils are usually formed in hot, semi-arid to arid climates and are associated with shallow groundwater table [4]. When wet, sabkha soil becomes very weak, and even a medium-weight vehicle will easily sink into it. The presence of high salt content, fluctuation of the groundwater table, and extreme environmental conditions result in large changes in strength, consistency, density, and shrinkage and swelling characteristics of the soil [6,7,25]. The salt crystallization and highly expansive behavior of the soil leads to differential settlement and cracking of the pavement structures [10]. Some researchers have comprehensively reported compression zone and settlement-induced damages to newly constructed roads in Saudi Arabia and other desert regions [15,16]. Excessive settlement

and cracking of the infrastructure built on sabkha soil has also been reported [11]. Therefore, it is very important to properly study and treat this soil before construction of any structure.

5.10. Shallow and Fluctuating Depth of Groundwater Table (F10)

Sabkha soil is usually accompanied by a shallow groundwater table. In the coastal region, the level of the groundwater table fluctuates due to the change in seawater levels as well as due to rainwater infiltration. The fluctuation in the level of the groundwater dissolves the crystalized salts present in the soil, leaving void spaces and consequently causing the failure and excessive settlement of foundations. The combination of sabkha soil and a shallow fluctuating groundwater table poses very serious threats to the safety and serviceability of infrastructures.

6. Integrated Analysis of the Factors

The integrated analysis of the governing geotechnical factors affecting the safety and serviceability of infrastructure constructed on reclaimed lands is presented in this section. The evaluation method incorporated analysis of the hierarchical structure of the governing factors by employing the interpretive structural modeling technique. Furthermore, the classification technique was used to group factors based on their driving and dependent powers.

6.1. Developing the Hierarchy Formation of the Governing Factors

The interpretive structural modeling technique was adopted to create the hierarchical formation of the factors that hinder the enhancement of the safety and serviceability of infrastructure constructed on reclaimed lands in the Eastern Province of Saudi Arabia. The complex relationship between the governing factors can be interpreted with the help of this hierarchical structure.

6.1.1. Adjacency Matrix Formation

Usually, the contextual interrelationships among governing factors are illustrated by the adjacency matrix [29]. The expert judgements are considered vital to develop contextual interrelationships among the factors. A “direct impact” contextual interrelationship is used to understand the interactive relationship among different factors. For example, Factor A affects Factor B, and Factor B affects Factor C. Accordingly, there is direct impact relationship between Factors A and B, while the relationship between A and C involves an indirect impact. However, the “direct impact” concept needs to be examined carefully. The two-way direct impact relationship between any two factors is not always guaranteed. For example, Factor A may have a direct influence on Factor B, but Factor B may not have a direct influence on Factor A.

The interrelationship between any two factors could be mathematically presented in the form of zero or one values in an adjacency matrix. The interrelationships provided in the adjacency matrix are interpreted below.

- If Factor A has a direct impact on Factor B, 1 will be assigned to the (A, B) entry of the matrix. Otherwise, 0 will be the assigned score.
- If Factor B has a direct impact on Factor A, 1 will be assigned to the (B, A) entry of the matrix. Otherwise, 0 will be the assigned score.
- If Factor A has a direct impact on Factor B, and Factor B also has a direct impact on Factor A, a score of 1 will be assigned to both (A, B) and (B, A) entries of the matrix.

To weigh the contextual interrelationship among all the predetermined factors, pairwise assessments were conducted by the experts to ascertain if there was any direct influence between any two given factors under comparison. As noted by [29], each participant evaluates the interrelationship in a distinct way. Therefore, “the minority gives way to the majority” concept was applied to the final evaluation results. The outcome of the assessments, in the shape of an adjacency matrix, is presented in Table 2.

Table 2. Factors' adjacency matrix.

Factors	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10
F1	1	1	0	0	1	0	0	0	0	0
F2	0	1	1	0	0	1	0	0	0	0
F3	0	0	1	0	0	0	0	0	0	0
F4	0	0	0	1	0	1	0	0	0	0
F5	0	1	0	0	1	1	1	0	0	0
F6	0	1	0	0	1	1	0	0	0	1
F7	0	0	0	0	0	0	1	1	0	0
F8	0	0	0	0	0	1	1	1	0	0
F9	0	1	0	0	1	1	1	1	1	1
F10	0	1	0	0	1	1	1	1	1	1

6.1.2. Reachability Matrix Formation

As presented in Table 2, the adjacency matrix highlights only direct relationships between the factors, giving no consideration to the indirect interactions. Therefore, the development of a reachability matrix was vital to establish both direct as well as indirect interrelationships between the factors in the matrix. Power iteration analysis was employed to develop a reachability matrix from the adjacency matrix. Table 3 presents the reachability matrix. A score of one in the reachability matrix shows either a direct or indirect interrelationship between any two factors in a pairwise comparison.

Table 3. Factors' reachability matrix.

Factors	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	Driving Power
F1	1	1	0	0	1	0	0	0	0	0	3
F2	1	1	1	0	0	0	0	0	0	0	3
F3	0	0	1	0	0	0	0	0	0	0	1
F4	0	0	0	1	0	0	1	1	0	0	3
F5	1	1	0	1	1	1	1	0	1	0	7
F6	1	1	1	0	1	1	1	0	0	0	6
F7	0	0	0	0	0	0	1	1	0	0	2
F8	0	0	1	0	0	0	0	1	0	0	2
F9	1	1	1	1	1	1	1	1	1	1	10
F10	1	1	0	1	1	1	1	0	1	1	8
Dependence Power	6	6	5	4	5	4	6	4	3	2	45/45

6.1.3. Development of the Hierarchical Structure

The identification of level segmentation for all the factors under consideration is essential to develop the hierarchical structure of the factors. Table 4 presents the level segmentation of all the studied factors. This includes the reachability, antecedent, and intersection groups as well as the segmentation level for each specific factors under examination. The reachability group for each factor consists of the factor itself along with the other factors that it was able to reach (row-wise) in the reachability matrix. The reached factors are generally termed as reachable factors. The reachable factors of a certain factor are assigned a value of one in the horizontal row associated with that particular factor in the reachability matrix (Table 3). For example, the reachable factors for F1 (improper soil investigation before construction) are F1, F2, and F5. Correspondingly, the reachable factors for F2 (inappropriate foundation system) are F1, F2, and F3.

Table 4. Reachability matrix level partitioning.

Factor	Reachability Set	Antecedent Set	Intersection Set	Level
3	3	2, 3, 8, 9	3	L1
8	8	4, 7, 8, 9	8	L2
7	7	4, 5, 6, 7, 9, 10	7	L3
4	4	4, 5, 9, 10	4	L4
2	1, 2	1, 2, 5, 6, 9, 10	1, 2	L5
6	5, 6	4, 5, 6, 9, 10	5, 6	L6
9	9, 10	9, 10	9, 10	L7
10	9, 10	9, 10	9, 10	L7

Similarly, the antecedent group for each factor consists of the factor itself along with the other factors that it was able to reach in the reachability matrix. The reachable factors of a certain factor are assigned a value of one in the vertical column associated with that particular factor in the reachability matrix (Table 3). For example, the reachable factors for F3 (insufficient time for the soil to settle before construction) column-wise are F2 and F3. Table 4 also presents the intersection group for each factor. The intersection group for a factor consists of the factors that are found in both the reachability and antecedent groups. For instance, F1, F2, and F5 are members of the intersection group for F1 (improper soil investigation before construction).

The level segmentation was performed by identifying the factors that had same set of factors in their reachability and intersection groups. As shown in Table 5, for example, the factor F3 (insufficient time for the soil to settle before construction) has the same set of factors in its reachability and intersection groups. Thus, this factor (F3) is partitioned as a Level-1 barrier. Following the Interpretive Structural Modeling (ISM) concept, the Level-1 factor needs to be removed from the table for subsequent analysis. This applies to the remaining constraints from Level 2 to Level 7. Table 5 summarizes the level segmentations of all the studied factors. Thus, the hierarchical formation of all the factors (Figure 6) was established based on the interpretive structural modeling as well as the results of the level segmentation among the factors provided in Table 5.

Table 5. Outcome of the factors' level partitioning.

Partitioning Level	Factor Number	Description of Barriers
L1	F3	Insufficient time for the soil to settle before construction
L2	F8	Poor gradation of the soil
L3	F7	Poor compaction work
L4	F4	Lack of quality fill material
L5	F1	Improper soil investigation before construction
	F2	Inappropriate foundation system
L6	F5	Low bearing capacity of the soil
	F6	Lack of soil improvement applications
L7	F9	Salt-bearing sabkha soil
	F10	Shallow and fluctuating depth of groundwater table

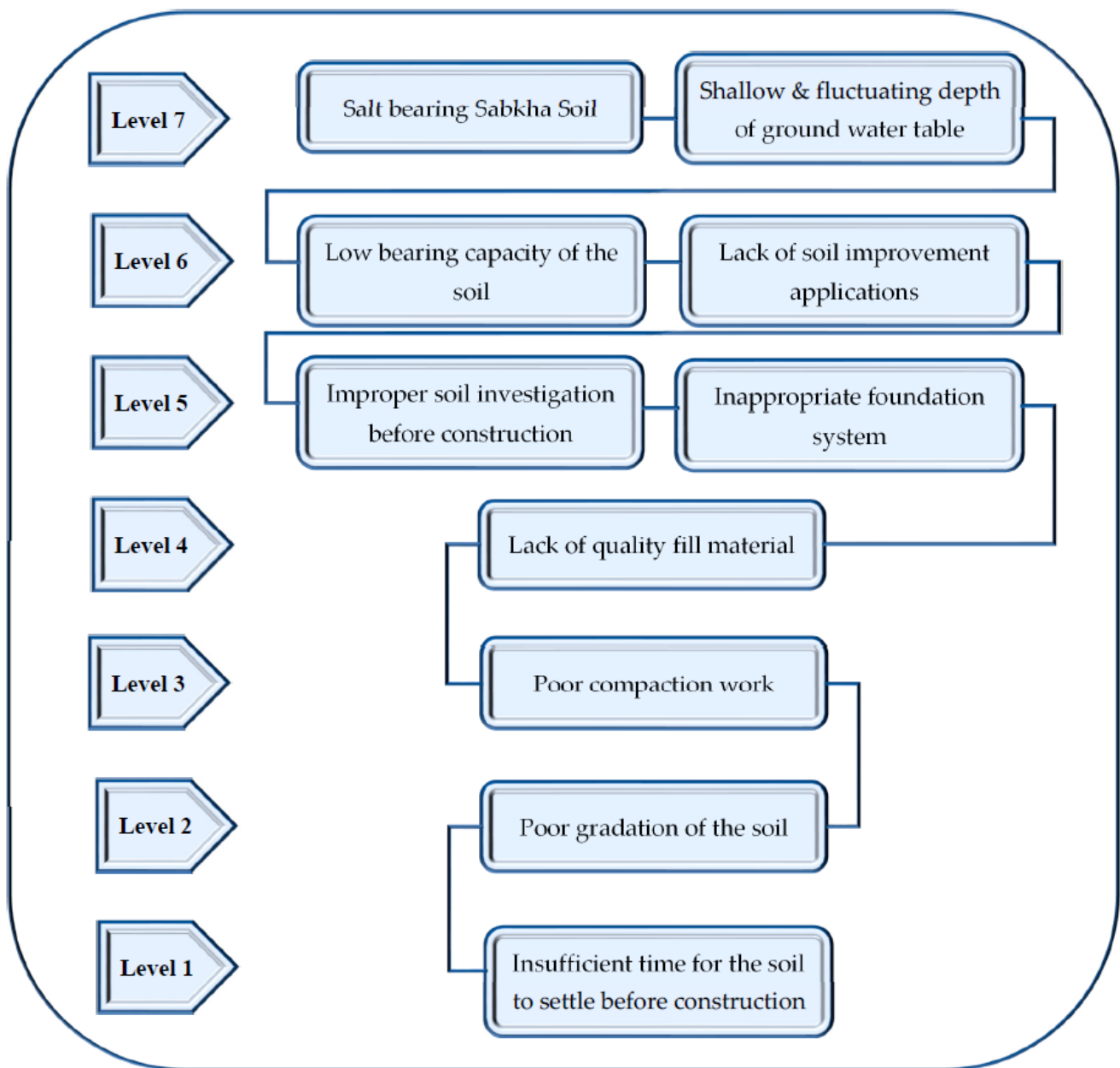


Figure 6. The hierarchical structure of all the factors.

Remarkably, the top level is L7, and the top-rated factor based on drive power is F9, which is closely followed by F10 (Figure 6 and Table 5). Thus, these two factors are the most crucial impediments to the enhancement of the safety and serviceability of infrastructure constructed on reclaimed land in the Eastern Province of Saudi Arabia. This highlights that an efficient management of these factors will significantly promote the safety and serviceability of infrastructure constructed on reclaimed land in the region. In contrast, F3 (insufficient time for the soil to settle before construction) was positioned at the lowest level (L1) and was rated the least influencing barrier, based on its dependence power, as presented in Table 3. This strongly implies that “insufficient time for the soil to settle before construction” is a superficial barrier that is influenced by all other barriers.

6.2. Classification of the Factors

The MICMAC method was utilized to group the constraints based on the information presented in the reachability matrix (Table 3) to evaluate the driving and dependence

strengths of the factors. It should be noted that the driving strength of a certain factor simply means all the factors influenced by it. This is determined by estimating the assigned scores of the horizontal cells (rows) associated with the specific factor in the reachability matrix (Table 3). For example, the driving powers of F4 and F2 are 3 and 7, respectively. In contrast, the dependence strength involves the factors affecting this specific factor and is determined by estimating the assigned scores of the vertical cells (columns) associated with the specific factor in the reachability matrix (Table 3). For example, the driven powers of F4 and F5 are 4 and 5, respectively. Accordingly, the driving and dependence powers for all the factors can be easily obtained (see Table 6).

Table 6. Factors' driving and dependence powers.

Factors	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10
Driving Power	3	3	1	3	7	6	2	2	10	8
Dependence Power	6	6	5	4	5	4	6	4	3	2

Figure 7 presents the driving and dependence powers of all the factors. As shown in the Figure, the factors were grouped into driving, linkage, autonomous, and dependent factors. The driving factors possess very high driving strength and weak dependence strength. The factors F5, F6, F9, and F10 are the driving barriers in this case and have the propensity to affect other factors. Conclusively, these factors are crucial to the enhancement of the safety and serviceability of infrastructure constructed on reclaimed land in the Eastern Province of Saudi Arabia. Accordingly, the factors ought to be given due consideration during policy formulation to ensure the safety and serviceability of the huge infrastructure construction being undertaken in the region.

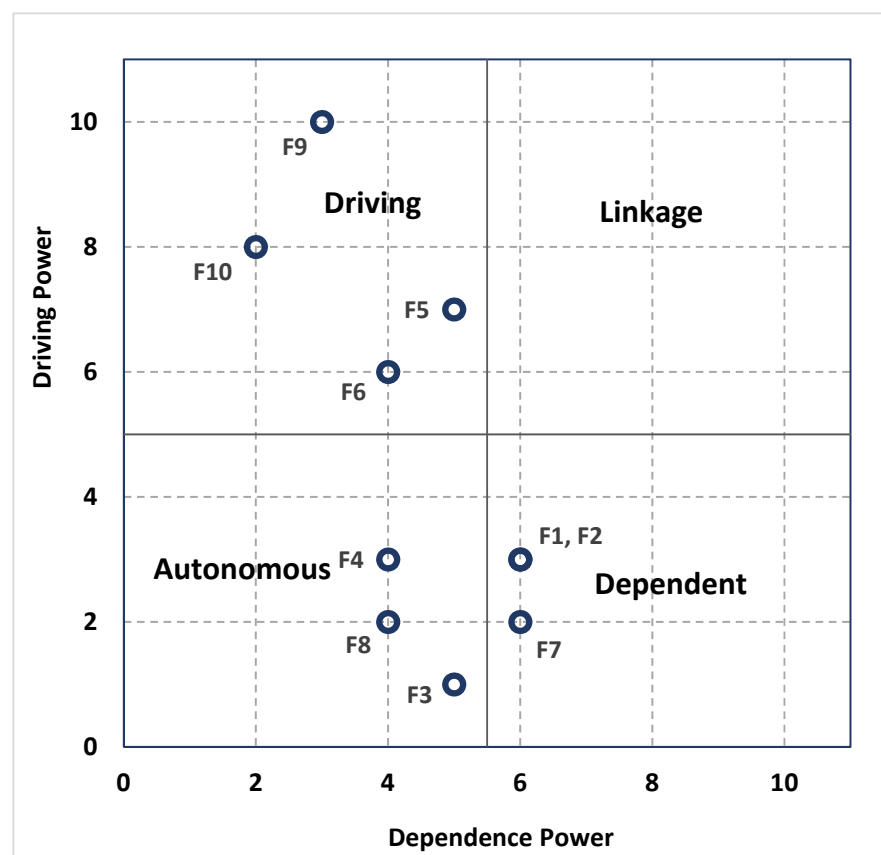


Figure 7. Grouping of the factors based on driving and dependence powers.

In contrast, the dependent factors have weak driving strength but high dependence strength. As presented in Figure 7, F1, F2, and F7 are the dependent factors, and their impact on the enhancement of the safety and serviceability of infrastructure constructed on reclaimed land largely depends on other factors. In essence, if other factors are properly tackled, the dependent factors could be controlled automatically. Therefore, these factors do not play a significant role in controlling the safety and serviceability of infrastructure constructed on reclaimed land. The linkage factors possess high values of driving as well as dependence strengths. Any variable affecting these factors will equally affect other factors directly. Therefore, the linkage factors are regarded as highly sensitive and unstable. In this study, no linkage factors were identified (Figure 7). The autonomous factors lack strong driving and dependence powers. These factors are disconnected from the cluster they were earlier grouped into. Note that, alone, they do not form any significant interrelationship with the other factors, as they are cut-off from their main cluster. As shown in Figure 7, the factors F3, F4, and F8 fall in the autonomous class, having a weak interrelationship with other factors. Thus, they would not influence the improvement of the safety and serviceability of infrastructure constructed on reclaimed land.

7. Discussion

A close observation of the hierarchical structure of all factors is shown in Figure 6. It can be easily seen that the driving factors, which include salt-bearing sabkha soil (F9) and shallow and fluctuating depth of the groundwater table (F10), make up the top level of the hierarchical structure (Level 7). As discussed earlier, sabkha soil has highly expansive behavior, which is adversely extrapolated by the shallow and fluctuating groundwater table in the coastal region. Such soils usually have very low bearing capacity and are not capable of safely carrying the loads applied on them. Conclusively, the aforementioned driving factors play a vital role in causing excessive settlement and shear failure, which affects the safety and serviceability of the infrastructure built on the problematic sabkha soils. Thus, policymakers should give high priority to these factors to improve the safety and serviceability of infrastructure construction on reclaimed land. While the highest priority should be given to the problematic salt-bearing sabkha soil (F9) and shallow and fluctuating depth of the groundwater table (F10), the importance of lack of soil improvement applications (F6) and low bearing capacity of the soil (F5) cannot be overemphasized. A methodical ground improvement to enhance the bearing capacity and reduce the possibility of potential settlement/failure is the only workaround solution for problematic soil like sabkha formations. Different soil improvement techniques are employed to enhance the strength and deformation characteristics of such soils. However, these soil improvement practices were rarely observed in the study area due to lack of awareness and the associated increase in the initial cost of the project. Considering the importance of the problems posed by sabkha soil, a number of studies [37–39] have sought to improving its strength and deformation characteristics. Furthermore, there is a need to investigate the performance of traditional soil improvement materials and practices for severe environmental conditions, i.e., the presence of water and different types of salts.

On the other hand, the dependent factors shown in Figure 7 (F1, F2, and F7) are inconsequential factors, whose impact on the improvement of the safety and serviceability of infrastructure construction on reclaimed land is controlled by the driving factors. The effect of dependent factors could be easily eliminated if the performance of related driving factors is improved. For example, the performance of improper soil investigation before construction (F1), which is a dependent factor, is highly influenced by the problematic salt-bearing sabkha soil (F9) and fluctuating depth of the groundwater table (F10), which are driving factors. The soil investigation for sabkha soil is not straightforward. There is a need to investigate the strength and deformation behavior of the soil with different types, proportions, and forms of the salts present in the soil. The dissolution of the salts with a raised groundwater table significantly decreases the strength of sabkha soil. Similarly, improper foundation system (F2) and poor compaction work (F7) are highly influenced

by the low bearing capacity (F5), lack of soil improvement applications (F6), and presence of the salts in the soil (F9). The adoption of an isolated shallow foundation is never recommended for low-strength expansive soils, as it will lead to undesirable differential settlement. In addition, the effective compaction of such problematic soil is not possible without proper ground improvement applications. Therefore, either effective ground improvement methods or deep foundations should be adopted, even for a small-scale important project. However, these solutions cannot be adopted for individually owned houses due to the increased costs involved.

The factors categorized as autonomous (presented in Figure 7) are insufficient time for the soil to settle before construction (F3), lack of quality fill material (F4), and poor gradation of the soil (F8). These autonomous factors are merely related to other factors; they are relatively impartial and not affected by other factors. Thus, these factors have low driving and dependence power. In many cases, the soil in the foundation zone is poorly graded sand and does not need a long time for settlement, as in the case of clayey soil. Likewise, the quality of fill material is totally independent of the in-situ soil.

Limitations and Future Study

Although a clear procedure has been provided for the content analysis and identification of the factors, the interrelationships of the variables are comparatively weak, as the inter-linkage logic varies from case to case. This paper is, in fact, the first in a series with the objective of determining the governing factors that impede the safety and serviceability of infrastructure built on reclaimed land. This study will be further extended to include the formulation of a framework to effectively handle the driving impediments and ensure sustainable construction.

8. Conclusions

The rapid population growth and economic boom in the Gulf region has propelled a huge demand for social and physical infrastructure development, particularly along the coastline. To date, large areas of land have been duly reclaimed to meet these social infrastructure needs. However, the safety and serviceability of infrastructure construction on reclaimed land has been a major cause of concern in the industry and is linked to various constraints that must be addressed methodically. Thus, this study determined the ten most crucial geotechnical factors that affect the safety and serviceability of infrastructure construction on reclaimed lands in the Eastern Province of Saudi Arabia. Subsequently, the interpretive structural modeling technique was used to create the hierarchical formation of the governing factors. Furthermore, the MICMAC classification technique was applied to classify the factors into distinct groups according to their driving and dependence strengths.

The results of this study indicate that the presence of problematic “salt-bearing sabkha soil” is the most crucial factor hindering the safety and serviceability of infrastructure construction in the reclaimed areas. The study also highlighted the factors having strong driving and dependence strengths for the enhancement of the safety and serviceability of infrastructure construction. The strong driving factors include “shallow and fluctuating depth of the groundwater table”, “lack of soil improvement applications”, and “low bearing capacity of the soil”. On the other hand, the strongly dependent factors include “improper soil investigation before construction”, “inappropriate foundation system”, and “poor compaction work”. The outcomes of this study offer momentous information to policymakers to revisit the existing guidelines, standards, and regulations in order to ensure strict compliance with safety, serviceability, and overall quality regulations for infrastructure construction.

Thus, this study promotes the enhancement of safety, serviceability, and quality of the infrastructure construction in the Eastern Province of Saudi Arabia. The establishment of a hierarchical structure of the governing factors identifies the critical impediments to be addressed. Detailed data on the critical factors and their effects allows construction industry practitioners to obtain necessary information required for their involvement in effectively

ensuring the safety, serviceability, and quality of the infrastructure construction. If these critical factors are methodically addressed, the enhancement of the safety and serviceability of infrastructure construction could help to promote cleaner production in the region's construction sector. In essence, policy formulators can be guided to develop efficient strategies capable of protecting infrastructure construction from safety and serviceability problems. In particular, this paper amply deepens the literature about managing the construction of infrastructure on reclaimed land in the coastal areas of Saudi Arabia and in similar areas around the Gulf region.

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