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Impact of Geotechnical Engineering on Infrastructure Lifespan and Maintenance Costs

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Author's contribution

The sole author designed, analysed, interpreted and prepared the manuscript.

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Review Article

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ABSTRACT

Aim: To examine the impact of geotechnical engineering on infrastructure lifespan and maintenance costs.

Problem Statement: The roles of geotechnical engineering in civil engineering infrastructures cannot be underestimated. It cuts across sub-divisional professions such as structural engineering, geology, mechanical engineering, construction engineering, environmental engineering, hydraulic engineering and so on. However, the study has great influence on the lifespan of infrastructure and their maintenance costs. Thus, more studies and literature surveys are still needed to reveal crucial information to geotechnical engineers, government, private sectors and related organizations.

Significance of Study: This technical review critically examines the need to study the influence of geotechnical engineering on infrastructure lifespan and maintenance costs.

Methodology: Recent relevant published articles, books and journals in the area of geotechnical engineering in relation to its impacts on the lifespan of infrastructure and their relevant maintenance costs were consulted.

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Discussion: In this technical review paper, the fundamental knowledge of geotechnical engineering and its interrelationship with infrastructure lifespan and their maintenance costs was examined. Applications of geotechnical engineering in relation with practicing fields were listed to include underground structures, roads and airports, supporting ground structures and excavations, subgrades and ground structures, foundation engineering and assessments of slope stability. Infrastructure life cycle was stated to comprise of four phases which include planning, preparation, procurement and implementation. Reference was made to a study on the effects of geotechnical risks on cost and schedule in infrastructure projects. It was concluded that slope Instability was the most significant risk factor based on both cost and schedule impacts having mean values of 3.06 and 3.02 respectively with reference to the survey results achieved from 47 professionals in the construction industry. The findings were recommended for governmental agencies and industry professionals whose professionalism is into infrastructure projects in order to recognize how geotechnical conditions influence time and cost overruns.

Conclusion: Geotechnical engineering has great influence on the lifespan of infrastructure and their maintenance costs.

Keywords: Geotechnical engineering; infrastructure lifespan; maintenance costs; geomaterials; life cycle cost analysis.

1. INTRODUCTION

The systematic application of methods that enables the construction in, on, or with geomaterials such as rock and soil is termed geotechnical engineering. It is a sub-discipline of civil engineering and involves using earth material (that is rock and soil) to improve and defend life and society [1]. Geotechnical engineering was stated to be largely empirical in nature until about the last 100 years and was dependable on careful observation and reflection. Notable scientific development in this area within civil engineering has been attained in the post-World War II era and continues till present day using sensors, data visualization, advanced soil testing and high-performance computers. Geotechnical engineering has been observed to be a vital component of almost all infrastructure connected endeavors be it military or civilian. Geotechnical engineering depends on the continuous adoption of engineering judgment which can be best developed via careful study of past failures and successes, and experience years. Experiences are transferred from one generation to the next via continuous mentorship and education which causes continued improvement of the profession [2].

Almost all civil engineering construction and structure has interrelation with soil. Also, their subsequent design is a function of either the soil or rock properties. This is based on the fact that everything, except space structures like satellites, is located on the earth. Additionally, the entire structure will be in a state of dilemma if there are problems with the foundation. The intrinsic soils variability and the surrounding environmental conditions at a typical project location usually leads to geotechnical solutions development with reference to engineering judgement and expertise [3]. This site-specific attribute and its complexity together with a risk-averse design mindset makes the application of generic sustainability practices to be difficult to all geotechnical projects which requires high level of customization to the industry with unique exhibition. The roles of geotechnical engineers are critical in almost all constructed project. The utilization of natural rock and soil differentiate geotechnical engineering from other engineering branches in which the materials to be used are specified by many engineers. In the case of a geotechnical engineer, the existing material in the ground is used and its properties cannot be generally controlled. Geotechnical operations are of high significance in relation to geomaterials properties investigation, soil sampling, groundwater level control and flow together with hydrological and environmental interactions [4].

Typical examples of geotechnical engineering applications in relation with practice as a field include underground structures, roads and airports, supporting ground structures and excavations, subgrades and ground structures, foundation engineering and assessments of slope stability. Foundation engineering is a subdivision of geotechnical engineering which adopts structural engineering, soil mechanics and project serviceability necessities in designing and constructing foundations for offshore, onshore and in-land structures. Foundation engineering can be seen as an “imaginative” technique rather than a routine step because well-constructed and designed foundations progressively perform excellently during a project lifetime [5]. A foundation engineer major goal and task is to form a construction-feasible, technically sound and economically viable design of the foundation system in order to support the superstructure. The structural units that transit different load combinations to the underlying soils or rocks from the superstructure is referred to as the foundation systems or elements. The loads may be tolerated individually by the Foundation units via the contribution of other elements such as basement floors, walls or slabs. The foundation principal function is to moderate and spread the structural units (i.e. column, wall or piers) with highly concentrated stresses with the normal magnitude(10–200 MPa) and move them to the subsoil using the normal tolerable compression stresses(0.05–0.5 MPa).With respect to this, the baseplate of steel columns, road pavement and roots of plants and trees are considered as foundations or footings [6].

Additionally, geotechnical engineering forms an essential section of extractive industries such as underground mining, open cast and hydrocarbon extraction. It is also important for the evaluation of natural hazards like landslides and earthquakes [7-10]. Geotechnical engineering practices comprise of team effort engaging other disciplines which include structural engineering, hydraulics, geology, construction management, transportation and earthquake engineers, and other relevant branches. The final design of any project is symbolic of different professions collaboration [8]. Geology complexity in most cases strongly indicates the handling of complex and variable materials by geotechnical engineer including the materials properties which usually change over time and are importantly functions of the changing water pressures in the ground. A geotechnical engineer is assigned with the role of specifying certain soils and rocks properties before and after treatment to recommend them for construction purposes [9].

Many solutions are still approximate despite the notable improvement in geotechnical engineering. This resulted from the dominant environmental conditions and soils natural inherent inhomogeneity. Furthermore, the sensitivity of soils to local environmental conditions is usually high when compared with other prefabricated building materials like concrete or steel. Consequently, it would be essential to have comprehensive knowledge about natural soil deposits and their environment interactions alongside response to local conditions in order to enable more accurate forecast of behavior geomaterials in project and their engineering performance. The improved focus on environmental sustainability has resulted to a flow in studies that execute the systematic environmental impact assessments of geotechnical engineering systems [10]. The life cycle assessment (LCA) is a major framework used in the quantification of system or product impacts over its life cycle. LCA is a multitalented technique which can be adopted for a variety of projects that provide a framework for the evaluation and comparison of the tradeoffs of possible design alternatives for a typical geotechnical application. Various constraints of geotechnical systems implementation are in existence despite the growing interest in LCA due to its advantages.

The Decisions made in the course of geotechnical design is contributory to the general environmental impact from infrastructure and construction activities and to their total monetary cost. Structures of different kinds possess various impacts during their life cycles and their impact is hardly ever distributed equally over the life cycle stages [11]. However, there is possibility of environmental impact and monetary cost reduction by geotechnical engineers in the entire structures' life cycles with the implementation of sustainability as a key factor when decisions are made. A wide variety of factors in all project types are determinants of cost escalations and schedule delays. These factors may have devastating effects on project performance. Once the amount of money spend is more than the estimated amount, then cost overrun sets in while schedule delay occurs when the time spent to complete a project is more than the preplanned period [12].

Poor contract management, poor estimates, delay in payment, inadequate planning, inaccurate design drawings and design changes are among the major causes of schedule and cost overruns. Infrastructure projects are of supreme importance because they make provision for essential services to industry and individuals together with considerable inputs to the economy and societal growth [13]. Rail systems, wastewater treatment facilities, bridges, power generation and supply facilities, tunnels and roads are generally referred to as infrastructure investments which can be

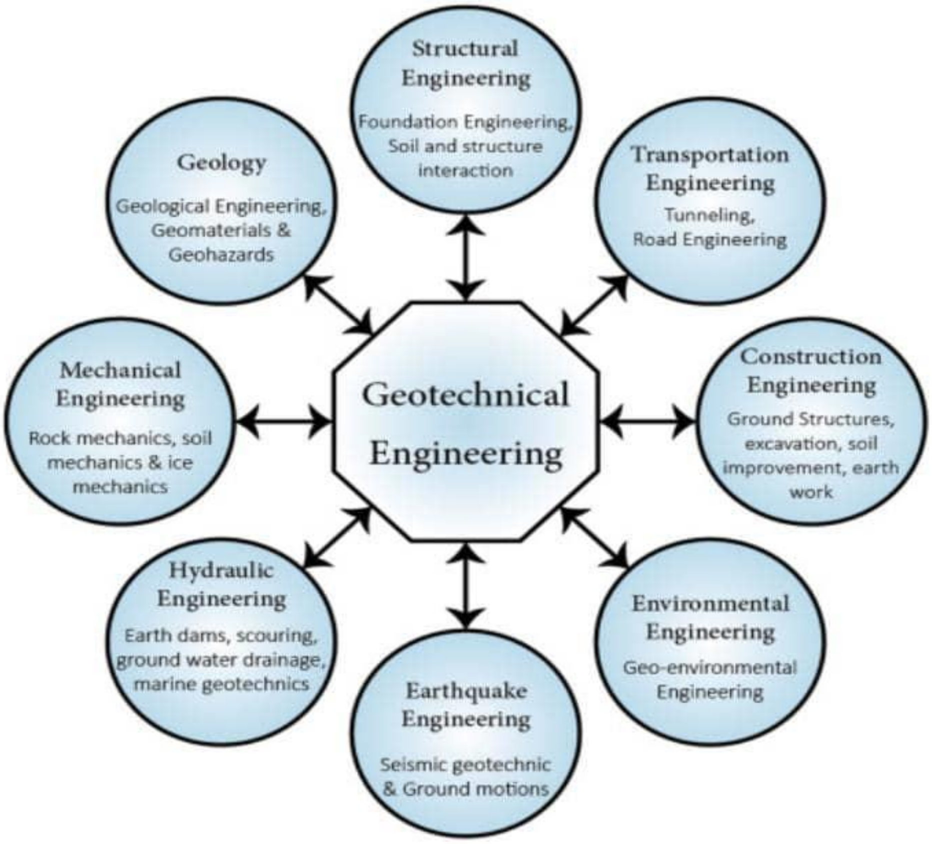

Fig. 1. Related branches of geotechnical engineering and their overlap

attributed as long-lived requiring broad primary cost and having complications in valuing. The influence of geotechnical situation on infrastructure projects could be overwhelming since geotechnical conditions may not always be foreseen and could be very dramatic. The unidentified character of some infrastructure projects like tunnel construction makes it complicated to recognize all possible geotechnical conditions before the execution phase [14]. Fig. 1 shows several branches that are related to geotechnical engineering and their overlap.

2. IMPACT OF GEOTECHNICAL ENGINEERING ON INFRASTRUCTURE LIFE CYCLE SPANS

Based on perspective of public sector, infrastructure life cycle spans an asset whole life starting from the initial planning to the final disposal of asset. The sequential stages include comprise planning, preparation, procurement, design, construction, operation, maintenance and disposal [7]. These stages should be adequately considered (both environmentally and economically) when efficiency is the main target. For example, higher life cycle costs may arise when much attention is not given to the asset utilization phase while much focus is on initial costs minimization (such as design, planning and construction costs). To achieve this, it is important to implement techniques that utilize a life cycle perspective to measure both economic and environmental impacts such as life cycle cost analysis (LCCA), which determines economic impacts and life cycle assessment (LCA), which evaluates the environmental impacts. The asset life cycle usually handles the infrastructure construction, design and its operation. This also explains the whole of the asset life cycle beginning from need identification to its disposal [15]. This is due to the fact that any inefficient or efficient decision in the entire life cycle affects the public services quality. Thus, an infrastructure life cycle comprises four phases which are sequentially planning, preparation, procurement and implementation as indicated in Fig. 2.

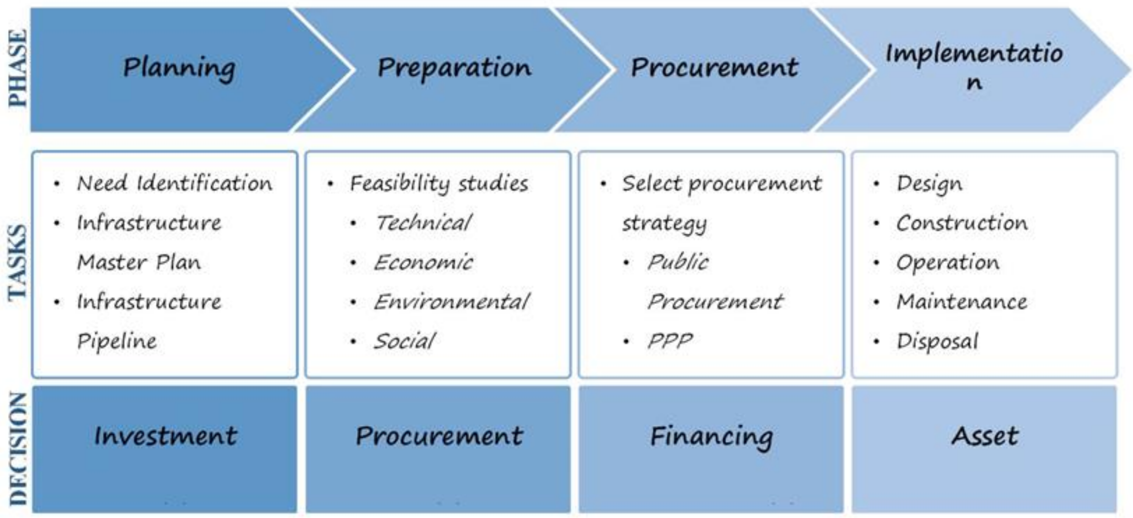

Fig. 2. The phases, tasks and decisions of Infrastructure's life cycle

2.1 Planning Phase

The planning phase begins from the identification of the needs and stops at the project selection as an excellent investment decision. The public sector cost would involve the costs at the planning phase over time which may be considered as being measurable or immeasurable [8]. For instance, different routing opinions and a highway project could be considered for lengthy years. Based on this, some institutional transformations and changes in numerous policies may come into play which may have influenced the road building and the associated infrastructures. Significant changes in the demography and landscape of the beneficiaries will cause changes in the highway economic viability. An investment decision should be taken by the government based on the best option to make provision for the best economic benefits to the intended population based their needs with reduced costs towards the end of the planning phase [12]. Efficiency gains in the course of prioritizing and selecting a particular investment should be irrespective of whether the delivery mode is public-private partnership (PPP) or public procurement. In an ideal situation, this would be executed at the sectoral or local government body like the transport ministry. An informed decision should be made by the central ministry from a portfolio of well-purposed projects via transiting the responsibility of the most excellent investment to give out the need decision or investment decision to the sectoral ministry [7].

2.2 Preparation Phase

The project picked as a the best investment with complete feasibility studies on legal, market, economic, technical, commercial and environmental and social aspects should be prepared at preparation phase. These are vital studies requiring both the institutional and budget capacities to ensure that the project has involved the appropriate stakeholders so as order to identify the risks and project cost during the preparation phase [13]. A typical example is the identification of the water shed areas, disturbing the adjacent farmland drainage and irrigation and drainage, by the engineering study in the highway project. With this, consultation can be made to the farmers as stakeholders such that an adequate mitigation plan can be arranged to avoid inflicting havoc on the environment. Consulting stakeholders usually have significant influence on the project design. By the end of the preparation phase, a government should be able to state whether to involve the privatized sector would be a good choice in order to make provision for one or multiple services during the project execution [16]. For instance, the invited private sector could be engaged in either construction alone or both construction and maintenance. In another case, the private sector could be invited as subcontractors for some specific services. This kind of decision would be termed procurement decision which basically involves determining the most suitable way to procure the project services. The primary purpose of this kind of decision is to identify if public procurement is a relevant method in asset procurement. Other public procurement principle could be adopted out of which value for money (VFM) is the most prevailing practice [17].

2.3 Procurement Phase

The government's decision determines the procurement phase and explicitly explains the procurement strategy that will be adopted. Generally, each of the procuring agencies has its stated rules and regulations in public procurement. These contracts would be minute and would engage individual tenders for each service. The responsibility of the procuring agency is to manage the multiple-contract such as design of each segment for multiple construction contracts, toll company, resettlement, drainage area mitigation and so on. If it is decided that a private company should be procured, then a PPP law and relevant procedures would be serve as guides. However, there may be some different operational guidelines based on the country of operation as the separation of PPP laws from public procurement laws in common law countries may not be executed [18]. The procuring agency is completely in charge of the main concession contract general management with the private company. However, it is essential for the private company to manage the multiple subcontracts. The best way to spend the public resources allotted to the chosen investment should be determined during the procurement phase using a financing strategy decision. The main aim should be the maximization of benefits to the intended population and the return to the government. In cases where the project delivery mode is a is public-private partnership, then the objective should primarily be for purpose maximization which include environmental, social and financial outcomes and not profit maximization which includes financial benefits alone. In this kind of scenario, the most effective decision involves providing a win-win situation via the optimization of public benefits together with the private proceeds [19-21]. For instance, the same budget allocated to an investment could be programmed as a capital loan, grant or guarantee. This should be handled together with the sectoral ministry, central ministry and procuring authority as the financial strategy decision.

2.4 Implementation Phase

The implementation phase should involve construction, design, operation and maintenance until the disposal of the infrastructure causing asset management strategy decision. However, the maintenance and operation costs are usually underestimated by most countries and do not make provision for either institutional or budget support. In lieu of this, a decline in the infrastructure asset sets in which makes it difficult to rehabilitate in a few years [6]. Subsequently, only construction was targeted by the cost overruns neglecting whole life cycle. The general cost to the public sector emanates from the whole life cycle costs while capital costs are the most expensive having the most multiplicative influences as a result of delays. This is not emanating from capital expenditures. Economies of scale and better risk mitigation come into play when construction is merged with maintenance and operation. For instance, it would take attention to design a highway in order to reduce the costs emanating from the risk of watershed zones damaged in the areas adjacent to the highway if the same contractor is building and operating the highway [4]. The expected results in this regard would strongly indicate that the implementation phase is lacking from weak project management together with asset-monitoring institutions in practice. However, they may put into places the project implementation central monitoring mechanisms. In order to tackle this kind of weakness, project management training and guidelines could be implemented by the countries with the adoption of the monitoring mechanisms and also execute the audits [14].

3. IMPACT OF GEOTECHNICAL ENGINEERING ON INFRASTRUCTURE MAINTENANCE COSTS AND SCHEDULE

The study conducted by Koc et al. [16] investigated the impacts of geotechnical risks on maintenance cost and schedule for infrastructure projects. Schedule impact index (SII), cost impact index (CII) and frequency index (FI) of geotechnical risks were utilized as the yardsticks to evaluate the importance of each level on the risk. About forty-seven professionals were referenced to conduct a survey from a heavy civil construction sector. The importance of each risk based on cost and schedule was evaluated using Importance Index Theory (IIT). The risk factors of the infrastructure examined were chemically reactive ground, contaminated material, eroding/mobile ground conditions, sensitiveness of public consideration, slope instability, soft compressible soil, seismic risk, presence of rock/boulders, subsidence (subsurface voids), unsuitable material, highly compressive soils, Caverns/voids, karst formations, settlement of adjacent structure, soft clays, organic silts, or peat, existing structures likely to be impacted by the work, underground artificial debris, liquefaction, lateral spreading, ground water infiltration, rock faults/fragmentation, replace in situ material with borrowed material, groundwater/water table, settlement in general, settlement of bridge approaches, landslides and scour of bridge piers [18-20].

Koc et al. [16] found that slope Instability was the most significant risk factor based on both cost and schedule impacts having mean values of 3.06 and 3.02 respectively with reference to the survey results achieved from 47 professionals in the construction industry. Soft clays, peat, organic silts and soft compressible soil were recognized as the second and third most significant risk factors with respect to schedule and cost respectively. Additionally, the most regularly encountered risk factors were identified to be groundwater infiltration. The use Pearson correlation analysis has been proved to be a strong tool in revealing the relationship between schedule and cost impacts in numerous risk factors. Table 1 shows the results presented by Koc et al. [16] in which bold values is indications of existence of a strong positive correlation within the corresponding risk factor. Additionally, the correlation analysis revealed the existence of strong relationship between the occurrence frequency and schedule impact and also between cost impact and occurrence frequency. The result revealed an association of increase in the frequency with a rise in its impact on schedule and cost having respective coefficients to be 0.906 and 0.846.

Table 1. The results of geotechnical risk factors as presented by Koc et al. [16]

Risk Factors	Mean Schedule Impact	Mean Cost Impact	Mean Frequency	Correlation
R1- Caverns/voids	1,74	1,96	1,55	**0,718**
R2- Chemically reactive ground	1,64	1,72	1,40	**0,915**
R3- Liquefaction	2,40	2,34	2,04	0,662
R4- Karst formations	1,60	1,70	1,55	**0,788**
R5- Rock faults/fragmentation	2,51	2,51	2,04	0,646
R6- Lateral spreading	2,36	2,49	2,13	**0,799**
R7- Seismic risk	2,60	2,74	2,11	**0,702**
R8- Underground artificial debris	1,85	1,91	1,70	**0,762**
R9- Groundwater infiltration	2,51	2,43	2,49	**0,796**
R10- Presence of rock/boulders	2,30	2,28	2,23	0,693
R11- Settlement of bridge approaches	1,60	1,68	1,62	**0,873**
R12- Eroding/mobile ground conditions	2,47	2,49	2,23	**0,869**
R13- Replace in situ material with borrowed material	1,72	1,68	1,66	**0,846**
R14- Unsuitable material	2,38	2,21	2,19	**0,862**
R15- Subsidence (subsurface voids)	1,89	2,15	1,72	**0,771**
R16- Existing structures likely to be impacted by the work	2,23	2,30	2,15	**0,869**
R17- Contaminated material	1,74	1,98	1,94	0,680
R18- Landslides	2,43	2,60	2,17	**0,876**
R19- Settlement of adjacent structure	2,17	2,49	2,06	**0,818**
R20- Sensitiveness of public consideration (e.g., parks)	2,04	2,02	1,96	**0,706**
R21- Soft compressible soil	2,81	2,77	2,64	0,660
R22- Groundwater/water table	2,74	2,77	2,28	**0,773**
R23- Settlement in general	2,74	3,04	2,26	0,672
R24- Soft clays, organic silts, or peat	2,83	2,98	2,55	**0,777**
R25- Highly compressive soils	2,28	2,45	2,02	**0,809**
R26- Scour of bridge piers	2,00	2,09	1,74	0,667
R27- Slope instability	3,02	3,06	2,36	0,679

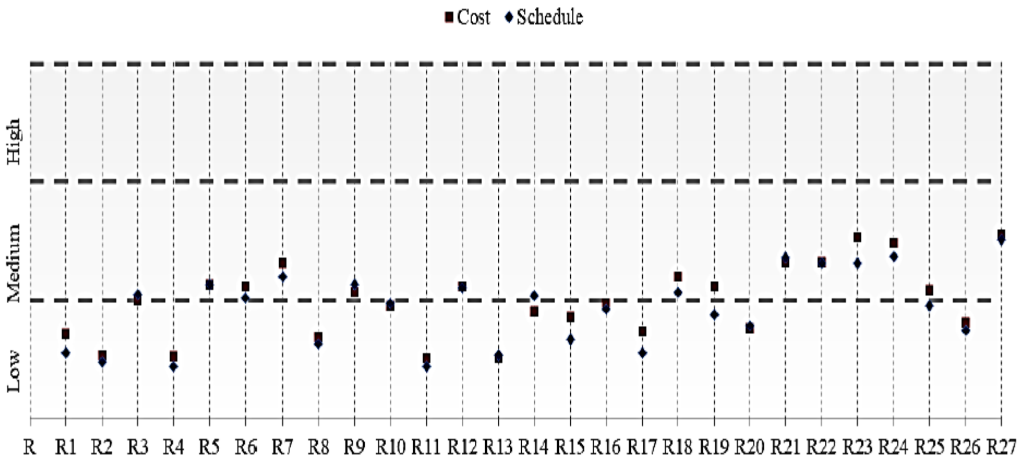

Fig. 3. Impact of geotechnical risk factors on cost and schedule [16]

With reference to the coding of the risk factors stated in Table 1, Fig. 3 is the pictorial representation of the results obtained by Koc et al. [16] showing the impact of each risk factor with reference to cost and schedule indicating the existence of relationship between impact of risks on cost and schedule. The examined geotechnical risk factors were evaluated to have either low (1-2.33) or medium (2.33-3.66) impact on schedule and cost with reference to means. Correlation analysis was adopted in the assessment of the differences in perceptions of respondents with respect to cost and schedule. The results presented by Koc et al. [16,21] revealed that the differences in respondents' perceptions with respect to geotechnical risks impacts on cost and schedule were not significant while the most significant risk factor was organic silts, soft clays or peat when both frequency and impact were concurrently considered. The authors recommended the use of their findings by governmental agencies and industry professionals whose professionalism is into infrastructure projects in order to recognize how geotechnical conditions influence time and cost overruns.

4. CONCLUSION

The roles of geotechnical engineering in civil engineering infrastructures cannot be underestimated. It cuts across sub-divisional professions such as structural engineering, geology, mechanical engineering, construction engineering, environmental engineering, hydraulic engineering and so on. However, the study has great influence on the lifespan of infrastructure and their maintenance costs. Thus, more studies and literature surveys are still needed to reveal crucial information to geotechnical engineers, government, private sectors and related organizations. In this technical review paper, the fundamental knowledge of geotechnical engineering and its interrelationship with infrastructure lifespan and their maintenance costs was examined. Applications of geotechnical engineering in relation with practicing fields were listed to include underground structures, roads and airports, supporting ground structures and excavations, subgrades and ground structures, foundation engineering and assessments of slope stability. Infrastructure life cycle was stated to comprise of four phases which include planning, preparation, procurement and implementation. The results of the study conducted by Koc et al were referenced to reveal the impacts of geotechnical engineering on the lifespan of infrastructure and their maintenance costs. It was concluded that slope Instability was the most significant risk factor based on both cost and schedule impacts having mean values of 3.06 and 3.02 respectively with reference to the survey results achieved from 47 professionals in the construction industry. The use of the findings was recommended for governmental agencies and industry professionals whose professionalism is into infrastructure projects in order to recognize how geotechnical conditions influence time and cost overruns. In conclusion, geotechnical engineering has great influence on the lifespan of infrastructure and their maintenance costs.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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