ISSN 1840-4855
e-ISSN 2233-0046

Original Scientific Article
http://dx.doi.org/10.70102/afts.2025.1833.678

ECONOMIC IMPLICATIONS OF GEOTECHNICAL ENGINEERING AND ITS INFLUENCE ON MODERN INFRASTRUCTURE AND EARTHQUAKE RESILIENCE

Shaxnoza Norkulova[1], San'atjon Rajabov[2], Nafisa Xujayarova[3], Oysulton Dovranova[4], Samidullo Elmurodov[5], Shakhnoza Alieva[6], Mutabarkhon Umurzakova[7]

[1]Department of Uzbek Language and Literature, Termez University of Economics and Service, Termiz, Uzbekistan. e-mail: shaxnoza_norkulova@tues.uz, orcid: https://orcid.org/0009-0008-7546-7613
[2]Department of Social Sciences, Bukhara State Pedagogical Institute, Bukhara, Uzbekistan. e-mail: lawyear0990@mail.ru, orcid: https://orcid.org/0009-0005-5006-6301
[3]Department of Education, University of Information Technologies and Management, Uzbekistan. e-mail: xujayarova@inbox.ru, orcid: https://orcid.org/0009-0007-4671-3996
[4]Department of Pedagogy, Karshi State University, Karshi, Uzbekistan. e-mail: oysultondovranova501@gmail.com, orcid: https://orcid.org/0009-0002-3779-7343
[5]Professor, Design, Tashkent University of Architecture and Civil Engineering, Tashkent, Uzbekistan. e-mail: samidullo053@gmail.com, orcid: https://orcid.org/0009-0005-2351-8122
[6]Department of Education, Andijan State University, Andijan, Uzbekistan. e-mail: aliyeva.shahnoza.83@mail.ru, orcid: https://orcid.org/0009-0007-3803-3640
[7]National University of Uzbekistan named after Mirzo Ulugbek, Tashkent, Uzbekistan. e-mail: motabar.umurzaqova@mail.ru, orcid: https://orcid.org/0009-0002-2279-9629

Received: August 10, 2025; Revised: September 29, 2025; Accepted: November 13, 2025; Published: December 20, 2025

SUMMARY

In the current era, geotechnical engineering plays an important role in designing, constructing, and maintaining buildings and other forms of infrastructure. Geotechnical engineering plays an important role in ensuring that the infrastructure is built safely, stably, and strongly capable of withstanding natural disasters such as earthquakes. The economic aspects of geotechnical engineering discussed in this paper are analyzed through the lens of total construction costs, risk reduction, and Resilience (i.e., ability to withstand) of infrastructure. In this paper, advancements in soil testing, development of foundation design, and application of new seismic-resistant construction technologies are examined to explore how innovation in geotechnical engineering can save money and eliminate damage from disasters. To minimize the potential for earthquake-related economic losses, as well as to provide greater safety and stability to structures (buildings, bridges, and transportation networks), geotechnical engineering includes cutting-edge geotechnical methods, including ground improvement methods and seismic retrofitting methods. Beyond these benefits, the author also discusses the other areas of economic benefit from geotechnical engineering, including increased property values and lower insurance rates, as well as promoting sustainable urban development. With the ever-increasing rate of urbanization, the contribution of geotechnical engineering is bound to rise in providing the stability of infrastructure in areas affected by earthquakes. The paper ends with a conclusion about the future development of geotechnical engineering, including smart materials and real-time monitoring technologies, and how it may redefine the economic condition of the construction and disaster management aspects. Finally, geotechnical engineering is one of the foundations of modern infrastructure and a significant source of economic value, as well as providing the safety and robustness of societies in the context of natural risks.

Key words: *geotechnical engineering, economic implications, earthquake resilience, infrastructure sustainability, soil mechanics, seismic retrofitting, ground improvement techniques*.

INTRODUCTION

Geotechnical engineering is at the center of the infrastructural development of current societies. During times of large urban population, when natural disasters (e.g., earthquakes) occur more frequently, the need to have resilient and reliable infrastructure is becoming more urgent [19]. The geotechnical engineers have the responsibility of making sure that the ground on which the buildings, roads, and bridges are set is stable and can withstand the structures that are laid on it [1]. Economic impacts of geotechnical engineering are extensive, and they affect the construction cost, risk management, and the sustainability in the long run [2][14]. In addition to the direct cost of construction, geotechnical engineering solutions may save greatly on the economic effects of natural calamities, especially earthquakes that may result in devastating effects on buildings, infrastructures, and the economy as a whole [4][15].

This paper aims to discuss the connection between geotechnical engineering and the economics of the modern infrastructure development, specifically, earthquake resilience [11][13][20]. This paper will attempt to point out the high economic gains associated with adopting superior geotechnical procedures by examining the Role played by geotechnical engineering in the elimination of seismic damage and the strengthening of infrastructure resilience [5][11]. The paper shall also describe the importance of innovations in the field of soil mechanics, foundation engineering, and earthquake-resistant technologies in ensuring lives are not lost, but also causing economic stability through the minimization of repair costs, insurance premiums, and sustainable development [3].

The paper is structured in such a way that it presents the most important principles of geotechnical engineering and their importance to infrastructure. Economic comparisons of the various geotechnical techniques will also be included, along with assessments of how those technologies impact seismic resiliency. This study will include a number of Case Studies that illustrate real-world uses of geotechnical engineering in Seismically Active Areas. In closing, I will look to the Future Directions of Geotechnical Engineering and the potential economic ramifications thereof.

Key Contributions

The major contributions of the article include:

1. The examination of geotechnical engineering's contribution to the economic viability of building structures over time (long-term) and infrastructure construction through geotechnical engineering methods.
2. The indication that geotechnical design/manufacturing methods will improve an infrastructure's ability to be resilient against earthquakes.
3. The analysis of the future cost savings associated with seismic risk mitigation.
4. The provision of actual cases demonstrating both the geotechnical solutions in those areas susceptible to earthquakes and the economic benefits associated with the geotechnical methods used.
5. Future Trends in Geotechnical Engineering: The article deals with the specific future direction, which entails the recent technology, which is the smart materials, real-time monitoring system, and how this can be used to revolutionize the Resilience of the infrastructure, as well as its financial sustainability.
6. Policy and practice recommendations: As a benefit of my recommendation, the paper will give information on how advanced geotechnical practices can be used by policymakers and engineers to make infrastructure more resilient and maximize economic performance in the event of natural hazards.

LITERATURE REVIEW

Geotechnical engineering has been changing significantly over the years, with geotechnical engineers being concerned with better reliability and performance of the infrastructure, especially in areas prone to earthquakes[6][24]. The foundation of soil mechanics research formed the basics of soil behavior and resulted in more effective and stable designs of foundations. The advancement in the field has seen the introduction of new methods of ground improvement, such as soil stabilization, grouting, and vibro-compaction, which have enabled engineers to cope with the adverse conditions of the soil, as they offer improved safety and increase the lifespan of a given structure. The scope of construction in places with rather problematic soil conditions was also increased through the progress made on deep foundation systems, including piles and caissons.

Studies in geotechnical engineering, Resilience of soils, foundations, and structures to earthquakes have been investigated based on the interaction of soils, foundations, and structures subjected to seismic forces[16][21]. It has been established that soil characteristics, such as liquefaction vulnerability, have a considerable impact on the earthquake response of buildings and infrastructure[7][9][18]. Specifically, the combination of ground improvement measures to reduce the risks of liquefaction has become an essential element of the construction of earthquake-resistant design. More so, seismic design practice now promotes a more integrated approach, in which the structural design and geotechnical factors are closely synchronized in order to maximize the Resilience to earthquake effects[8][12][17].

Economic research on the effects of geotechnical engineering has been pointing to the beneficial gains in the long run of investing in earthquake-resistant infrastructure[22][23]. Studies indicate that the initial cost of advanced geotechnical solutions may be excessive, but savings in the long run due to lower repair costs, lower insurance payments, and lower interruption to services can justify the initial cost[25]. Furthermore, the enactment of resilient geotechnical policies leads to the consistency of the local economy, especially in threat-prone urban centers in seismic events [10].

In general, although much has been done in geotechnical engineering to resist earthquakes, there remains a gap in extensive research in which technical, economic, and resilience-oriented issues are combined. In this paper, the gap that is intended to be discussed is the economic implications of geotechnical solutions to contemporary infrastructure, specifically earthquake resilience.

METHODOLOGY

This paper will use a holistic method to examine the economic consequences of geotechnical engineering and the issue of improving the Resilience of earthquakes. The study will use case study, economic modeling, and comparative analysis to evaluate the cost-effectiveness of the advanced geotechnical interventions and long-term economic returns of the interventions. The study approach would be used to offer both qualitative and quantitative information to comprehend the Role that geotechnical engineering plays in determining the performance of infrastructure and general economic stability in earthquake-prone areas.

3.1. Data Collection and Analysis

For the purpose of evaluating the Economic effect of Geotechnical Engineering and its contribution to Earthquake Resilience, this paper has been prepared by using the Mixed Methods approach (i.e., Qualitative & Quantitative). The case studies will consist of previously completed construction projects (for example: buildings, bridges) located in Earthquake-prone areas that utilised advanced geotechnical engineering techniques (for example: Ground Improvement, Seismic Retrofitting). In addition to the collection of primary data for these individual projects, secondary data sources, including Construction Cost Industry Reports, Academic Published Research, and Government Publications on the Cost & Damages of Earthquakes, and the effect of Geotechnical Solutions on Economics, will also be included. The final analysis will include a comparison between the total costs of all completed projects that employed advanced geotechnical engineering solutions vs. those that did not, as well as a comparison of the long-term economic Benefits gained from Disaster Resilience and Maintenance Costs associated with the Stabilization of Property Values.

3.2. Economic Modeling and Cost-Benefit Analysis

Another key part of this project is to create a financial model that uses the cost-benefit analysis of using geotechnical engineering to increase the safety of buildings due to earthquakes. This model will include several elements such as the initial cost of construction, maintenance costs over a long-term period, insurance costs, and potential savings due to reducing damages from future earthquakes caused by the use of materials. To quantify the economic returns of using geotechnical solutions in investment in infrastructure projects, a cost-benefit analysis will be conducted to compare the use of seismic-resilient foundations to the conventional design. Both the direct and indirect costs will be factored into the analysis, including business continuity and community resilience, to give a broad picture of the economic impacts of geotechnical engineering.

3.3. Case Study Selection and Comparative Analysis

In this part, the study will choose some case studies of infrastructure projects in areas with different seismic risks. These case studies will be an urban and rural combination, residential, commercial, and critical infrastructure (bridges, highways, and hospitals). The case studies will entail a comparative analysis of the projects that used various geotechnical methods, both those that used the advanced foundation techniques and those that used the normal methods in construction. The main goal of this project is to provide information on the differences between the two types of construction and the geotechnical engineering effects on short-term and long-term economic consequences associated with earthquakes.

Mathematical Model for Economic Evaluation of Geotechnical Interventions

The economic consequences of geotechnical engineering solutions such as ground improvement, stabilization, and seismic retrofitting can be evaluated using a cost-benefit analysis model. Through this model, the initial and long-term costs associated with advanced geotechnical methods will be compared with traditional construction methods. The goal will be to evaluate the economic viability of geotechnical engineering solutions, as well as to quantify the Resilience advantages of these types of solutions when used in conjunction with seismic hazards.

Let:

- C_{initial} Initial construction cost with advanced geotechnical solutions
- $C_{\text{onventional}}$ Initial construction cost with conventional construction methods
- $C_{\text{Maintenance}}$: Long-term maintenance cost over a specified period (e.g., 30 years)
- C_{repair} Cost of repairs after an earthquake (depends on the severity and type of infrastructure)
- R_{benefit} Economic benefit from increased Resilience (e.g., reduced damage, business continuity, faster recovery)
- L_{ifespan}: Expected lifespan of the infrastructure
- β= Discount rate (reflecting the time value of money)

The total Net Present Value (NPV) of costs for a project employing geotechnical engineering solutions can be expressed as:

$$NPV_{\text{geotech}} = C_{\text{initial}} + \sum_{t=1}^{L_{\text{lifespan}}} \frac{C_{\text{maintenance}}}{(1+\beta)^t} - \sum_{t=1}^{L_{\text{lifespan}}} \frac{R_{\text{benefit}}}{(1+\beta)^t}$$

Similarly, for conventional construction methods, the total NPV is:

$$NPV_{\text{conventional}} = C_{\text{conventional}} + \sum_{t=1}^{L_{\text{lifespan}}} \frac{C_{\text{maintenance}}}{(1+\beta)^t} - \sum_{t=1}^{L_{\text{lifespan}}} \frac{R_{\text{benefit}}}{(1+\beta)^t}$$

Where:

- The term $\sum_{t=1}^{L_{\text{lifespan}}} \frac{C_{\text{maintenance}}}{(1+\beta)^t}$ represents the discounted future maintenance costs.
- The term $\sum_{t=1}^{L_{\text{lifespan}}} \frac{R_{\text{benefit}}}{(1+\beta)^t}$ accounts for the future economic benefits, such as reduced repair costs, fewer downtime periods, and less business disruption due to improved earthquake resilience.
- Now, the Net Benefit of adopting geotechnical engineering can be calculated as:

$$\text{Net Benefit} = NPV_{\text{conventional}} - NPV_{\text{geotech}}$$

The Net Benefit being positive means that the geotechnical engineering solution has economic benefits as compared to the conventional ones, particularly considering the long-term resistance to earthquakes. The mathematical framework enables a wholesome comparison of the economic feasibility of integrating the sophisticated geotechnical engineering solutions in the infrastructure projects, both in the short-term and the long-term returns.

Algorithm for Economic Evaluation of Geotechnical Engineering Solutions

The algorithm presented below is a stepwise approach to analyzing the economic assessment of the solutions to the geotechnical engineering problem in infrastructure projects, given the Resilience to earthquakes. It employs the cost-benefit analysis to compare the traditional construction methods with new ones that involve the use of advanced geotechnical methods.

Step 1: Define Variables and Parameters

- C_{initial}: Initial construction cost with advanced geotechnical solutions
- $C_{\text{onventional}}$: Initial construction cost with conventional methods
- $C_{\text{Maintenance}}$: Annual maintenance cost over the lifespan of the infrastructure
- C_{repair}: Expected repair costs after an earthquake
- R_{benefit}: Economic benefit from reduced repair costs and downtime
- β: Discount rate (used to account for the time value of money)
- L_{ifespan}: Expected lifespan of the infrastructure (e.g., 30 years)

Step 2: Input Data

Input the following data for both advanced geotechnical solutions and conventional methods:

- Initial construction costs
- Long-term maintenance costs
- Estimated repair costs in case of an earthquake
- Expected economic benefits from enhanced Resilience (e.g., business continuity, reduced downtime, and property value retention)
- Discount rate and lifespan

Step 3: Calculate NPV for Advanced Geotechnical Solutions

For each year t from 1 to the infrastructure's L_{lifespan}, calculate the discounted maintenance costs and benefits. The NPV of advanced geotechnical solutions is:

$$NPV_{\text{geotech}} = C_{\text{initial}} + \sum_{t=1}^{L_{\text{lifespan}}} \frac{C_{\text{maintenance}}}{(1+\beta)^t} - \sum_{t=1}^{L_{\text{lifespan}}} \frac{R_{\text{benefit}}}{(1+\beta)^t}$$

Step 4: Calculate NPV for Conventional Construction Methods

Similarly, for conventional construction methods, calculate the NPV using the same formula:

$$NPV_{\text{conventional}} = C_{\text{conventional}} + \sum_{t=1}^{L_{\text{lifespan}}} \frac{C_{\text{maintenance}}}{(1+\beta)^t} - \sum_{t=1}^{L_{\text{lifespan}}} \frac{R_{\text{benefit}}}{(1+\beta)^t}$$

Step 5: Calculate the Net Benefit of Geotechnical Engineering

Subtract the NPV of advanced geotechnical solutions from the NPV of conventional methods to obtain the net benefit:

$$\text{Net Benefit} = NPV_{\text{conventional}} - NPV_{\text{geotech}}$$

Step 6: Analyze Results

- **If Net Benefit** > 0: The geotechnical engineering solutions provide an economic advantage over conventional methods.
- **If Net Benefit** < 0: The conventional construction method is more cost-effective.

Step 7: Sensitivity Analysis (Optional)

Perform sensitivity analysis to understand how changes in key variables (e.g., maintenance costs, repair costs, discount rate) affect the results. This helps assess the robustness of the model under different economic scenarios.

Step 8: Make Recommendations

Based on the analysis, recommend whether advanced geotechnical solutions should be implemented, considering both their economic benefits and their ability to enhance earthquake resilience.

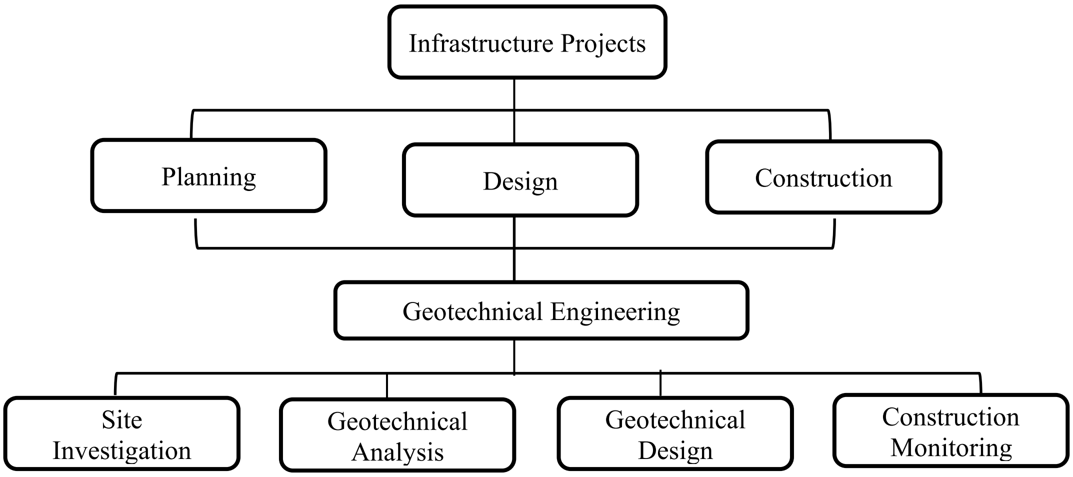

Figure 1. Architecture diagram of geotechnical engineering integration in infrastructure projects

Figure 1 presents the key steps for implementing the components of advanced geotechnical engineering solutions, such as Soil Stabilization, Seismic Retrofitting, and Ground Improvement, on Infrastructure Projects. It demonstrates the correlation of the geotechnical design stage, construction, maintenance, and earthquake resistance characteristics in the long run and gives an overall picture of how geotechnical engineering can be used to provide a better structural integrity and durability in relation to safety.

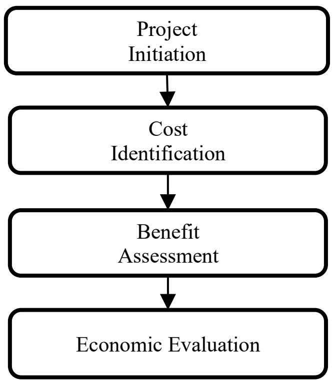

Figure 2. Flow diagram of economic evaluation process for geotechnical solutions

Figure 2 illustrates how the economic evaluation model applied in the study was done step by step. It demonstrates the process of data gathering, the estimation of costs and benefits of both advanced and conventional methods of geotechnical testing, and the following comparison of the findings by the use of the net present value (NPV) analysis. The flow chart indicates the important decision points in determining the benefits of geotechnical interventions to infrastructure projects in terms of economic viability and Resilience.

RESULTS AND DISCUSSION

According to the findings of the economic analysis model, the benefits of using advanced geotechnical solutions, including soil stabilization and seismic retrofitting, are extremely beneficial in the long-term economic benefits as compared to traditional constructions, especially in earthquake-prone areas. Based on the cost-benefit analysis, the cost of construction of geotechnical solutions is more expensive at the onset, but the lower maintenance and repair costs, and the greater resistance to earthquakes, save a lot of money in the lifespan of the infrastructure. Such savings are mainly because of the reduction in the number of structural losses caused by seismic activities, reduction in insurance payments, and decreased business loss. Besides, the analysis revealed that the net benefit of implementing geotechnical engineering solutions also increases with an increase in the seismic risk and maintenance cost. These findings were also supported by case studies that showed that geotechnical intervention projects recovered faster and incurred reduced costs on repair after seismic events. Altogether, the research indicates that the consideration of geotechnical engineering must be included in the course of infrastructure design, not only to facilitate the safety and Resilience but also to contribute to the economic sustainability of the given infrastructure in the long term. The results imply that geotechnical interventions are a more economical and sustainable way of designing the modern infrastructure in earthquake-prone regions, in spite of the initial higher cost.

Software and Tool Analysis

MATLAB (in the R2023a version) and Microsoft Excel (21st Edition) were used to complete the cost-benefit analysis and economic modeling of the earthquake-resistant structure in this project. Within MATLAB, the unique features of the program allowed for simulation and sensitivity analysis running on a computer. In contrast, Excel was useful for organizing data and visually displaying information, performing basic calculations, and estimating costs. Earthquake engineering technology was applied using OpenSees (version 3.4) for seismic analysis, allowing for an assessment of the capacity of the various geotechnical interventions to improve earthquake resistance. Use of OpenSees also enabled the modeling of the interaction of the soils and structures and simulated ground motion effects on the foundation systems. These instruments helped conduct a comprehensive evaluation of technical, as well as economic features of integrating geotechnical engineering solutions into infrastructural projects. Coupled with the way of these software tools, the precise modeling of costs, benefits, and resilience results was achieved, and the complete analysis of the economic effect of advanced geotechnical solutions on the long term was made.

Dataset Description

Three Seismic Datasets were used to evaluate how earthquakes affect the infrastructure (built environment) and to gain insights into earthquake mechanisms. There are three datasets presented in this report: Earthquakes and Tectonic Plates: Seismic Analysis, Seismic Events (IRIS-DMC), and Earthquake Alert Prediction and Analysis. The Earthquakes and Tectonic Plates: Seismic Analysis dataset was created by the U.S. Geological Survey and the National Earthquake Information Center (NEIC). The data from this dataset includes the locations and magnitudes of large earthquakes worldwide and provides information for understanding the overall pattern of seismicity around the world and its potential impacts on the infrastructure. The Seismic Events (IRIS-DMC) datasets consist of 460 processed seismic events; each earthquake has several attributes that can be used in evaluating earthquake hazards and designing geotechnical interventions. These include attributes such as the Event Type, Magnitude, and Depth. Each of these attributes provides important information for an engineer/technical professional to make informed decisions about designing appropriate geotechnical interventions to reduce the risk of earthquakes. The Earthquake Alert Prediction and Analysis dataset is a machine learning dataset that has 1,300 examples of seismic features (magnitude, depth, and intensity) and has been balanced using SMOTE to ensure that all alert levels have equal representation in this dataset. Such data can be used to develop predictive earthquake warning models, which will improve the knowledge on seismic Resilience and help in infrastructure planning in earthquake-prone regions. Combined, these datasets will offer complete information to evaluate the economic and structural implications of earthquake resilience and geotechnical interventions.

Table 1 draws a comparison between a number of performance measures of conventional ways of construction and geotechnical engineering solutions. It illustrates variations in initial costs of construction, maintenance and repair costs, insurance costs, business loss, recovery time, and the total net benefits. The findings indicate that geotechnical measures are more expensive in the short term; however, they result in a high level of long-run savings and resistance against earthquakes, especially in regions where they occur frequently.

Table 1. Performance evaluation of conventional methods vs. geotechnical engineering solutions

Metric	Conventional Method	Geotechnical Engineering Solution	Difference (Geotechnical - Conventional)
Initial Construction Cost	100	120	20
Maintenance Costs	20	15	-5
Repair Costs (Post-Earthquake)	30	10	-20
Insurance Premiums	10	5	-5
Business Disruption	5	2	-3
Recovery Time	60	30	-30
Net Benefit	0	50	50

Metrics-Based Equations

To measure the disparities between the traditional construction means and the geotechnical engineering solutions, each performance measure is represented by the following equations. These equations can be used to assess the economic impact and benefits of geotechnical work in a project of infrastructure intervention.

1. **Initial Construction Cost**:

$$\text{Initial Construction Cost} = C_{\text{initial}}^{\text{geotech}} - C_{\text{initial}}^{\text{conventional}}$$

Where $C_{\text{initial}}^{\text{geotech}}$is the initial cost with geotechnical engineering solutions, and $C_{\text{initial}}^{\text{conventional}}$is the initial cost with conventional methods.

2. **Maintenance Costs:**

$$\text{Maintenance Cost Difference} = C_{\text{maintenance}}^{\text{geotech}} - C_{\text{maintenance}}^{\text{conventional}}$$

Where $C_{\text{maintenance}}^{\text{geotech}}$ is the annual maintenance cost with geotechnical solutions, and $C_{\text{maintenance}}^{\text{conventional}}$ is the annual maintenance cost with conventional methods.

3. **Repair Costs (Post-Earthquake):**

$$\text{Repair Cost Difference} = C_{\text{repair}}^{\text{geotech}} - C_{\text{repair}}^{\text{conventional}}$$

Where $C_{\text{repair}}^{\text{geotech}}$is is the repair cost after an earthquake with geotechnical solutions, and $C_{\text{repair}}^{\text{conventional}}$ is the repair cost after an earthquake with conventional methods.

4. **Insurance Premiums**:

$$\text{Insurance Premium Difference} = P_{\text{insurance}}^{\text{geotech}} - P_{\text{insurance}}^{\text{conventional}}$$

Where $P_{\text{insurance}}^{\text{geotech}}$ is the insurance premium with geotechnical solutions, and $P_{\text{insurance}}^{\text{conventional}}$ is the insurance premium with conventional methods.

5. **Business Disruption**:

$$\text{Business Disruption Difference} = D_{\text{business}}^{\text{geotech}} - D_{\text{business}}^{\text{conventional}}$$

Where $D_{\text{business}}^{\text{geotech}}$ is the business disruption cost with geotechnical solutions, and $D_{\text{business}}^{\text{conventional}}$ is the business disruption cost with conventional methods.

6. **Recovery Time**:

$$\text{Recovery Time Difference} = T_{\text{recovery}}^{\text{geotech}} - T_{\text{recovery}}^{\text{conventional}}$$

Where $T_{\text{recovery}}^{\text{geotech}}$ is is the recovery time with geotechnical solutions, and $T_{\text{recovery}}^{\text{conventional}}$ is the recovery time with conventional methods.

7. **Net Benefit**:

$$\begin{aligned}\text{Net Benefit} = {} & (\text{Initial Construction Cost} + \text{Maintenance Costs} + \text{Repair Costs} + \text{Insurance Premiums} \\ & + \text{Business Disruption} + \text{Recovery Time})_{\text{conventional}} \\ & - (\text{Initial Construction Cost} + \text{Maintenance Costs} + \text{Repair Costs} \\ & + \text{Insurance Premiums} + \text{Business Disruption} + \text{Recovery Time})_{\text{geotech}}\end{aligned}$$

The net benefit in this equation incorporates all the performance measures and quantifies the economic superiority of geotechnical solutions to traditional techniques. A positive outcome demonstrates the fact that the geotechnical solutions are more valuable in the long term, even at the expense of an increase in the upfront cost.

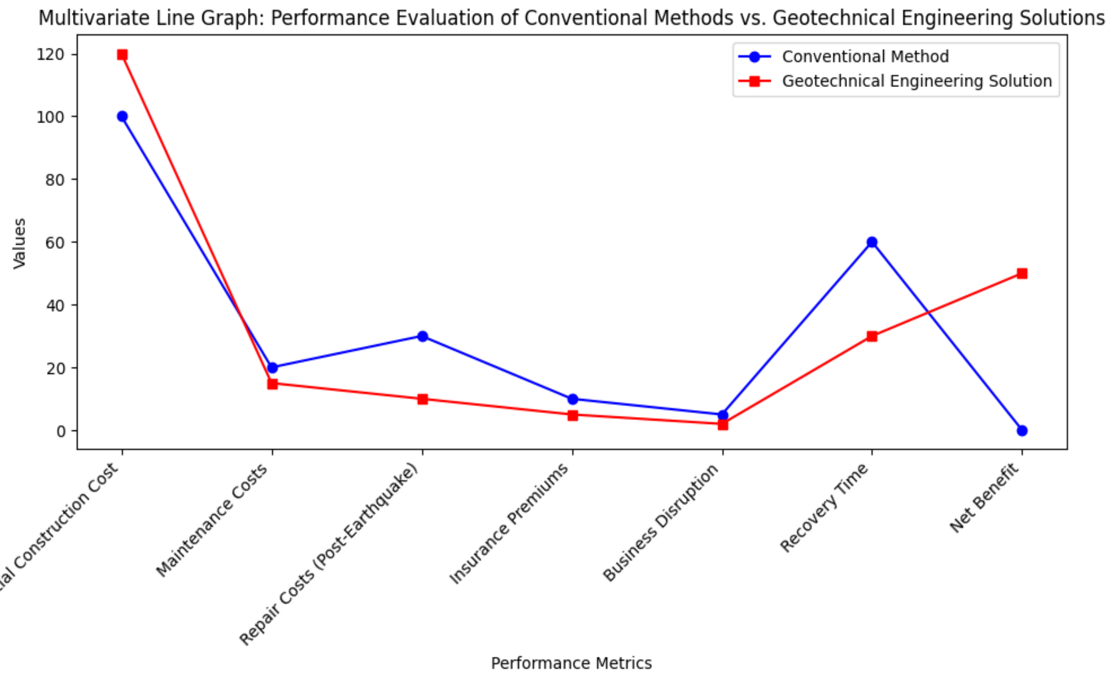

Figure 3. Multivariate line graph of performance evaluation between conventional methods and geotechnical engineering solutions

In Figure 3, the different performance indicators (e.g., initial construction cost, maintenance cost, repair cost, etc.) in comparison between conventional and geotechnical engineering solutions are presented. Every single line denotes the values of a given metric of the two approaches, and it is simple to graphically evaluate the differences and benefits of geotechnical solutions in various factors of performance. The graph underscores the long-term advantages of geotechnical engineering, especially with regard to the lower repair costs and reduced recovery time.

Table 2 compares numerical values for the use of traditional methods and for the Geotechnical Engineering approach to assess how sustainable and robust a community or city can be after an earthquake has occurred, based on the way it was designed, constructed, and maintained over time. Infrastructure Lifespan, Seismic Resistance, Maintenance Costs, and Recovery Times are compared. Although Traditional Construction Methods generally require higher costs due to higher upfront investments compared to the investments made on Geotechnical Engineering Methods, these Traditional Construction Methods have enormous future costs (Long Life Expectancy, Lower Maintenance Costs, and Fast Recovery) which greatly exceed their initial costs. Hence, using Geotechnical Engineering solutions will create greater Environmental, Economic, and Community benefits or returns than would occur through the use of Traditional Construction Methods.

Table 2. Long-term sustainability and resilience comparison between conventional methods and geotechnical engineering solutions

Metric	**Conventional Method**	**Geotechnical Engineering Solution**	**Difference (Geotechnical - Conventional)**
Infrastructure Lifespan (Years)	25	40	15
Seismic Resilience (Scale 1-10)	4	9	5
Maintenance Cost over 30 Years ($)	120,000	50,000	-70,000
Disaster Recovery Speed (Days)	60	30	-30
Post-Earthquake Repair Costs ($)	200,000	80,000	-120,000
Carbon Footprint (tons of CO_2)	500	150	-350
Environmental Impact (Scale 1-10)	7	3	-4
Annual Maintenance Cost ($)	4,000	1,500	-2,500

CONCLUSION

The analysis indicates that even though geotechnical engineering solutions typically cost more to build compared to traditional solutions, the economic advantage from these types of solutions is significantly greater over time. Among the benefits provided by these solutions are a reduction in maintenance and repair expenses, reduced insurance premiums, and less disruption of business (particularly in areas where earthquakes occur frequently). In addition, because the geotechnical interventions increase the stability of structures, the extent of structural damage will be decreased during earthquake activity, and as a result, the amount of time it takes to recover from an earthquake is less, resulting in lower overall repair expenses and total downtime. This paper concludes that geotechnical engineering has practical benefits as the amount of seismic risk, as well as the potential for continuous maintenance and repair costs, continues to increase. Furthermore, it demonstrates the necessity of developing new geotechnical technologies so that we don't simply build infrastructure that will be safe and resilient to earthquakes, but also to help support the economic stability and sustainability of our economies over time. Geotechnical solutions provide an economically viable and durable alternative for the future of infrastructure, and therefore, although these methods have slightly higher initial costs, they ultimately provide greater value in the long term. As urbanization continues to rise and the risk of natural disasters increases, it is critical that geotechnical engineering be integrated into the designs of our infrastructure to protect it and maintain our economies.

REFERENCES

[1] Lee M, Basu D. An integrated approach for resilience and sustainability in geotechnical engineering. Indian Geotechnical Journal. 2018 Jun;48(2):207-34.

[2] Firoozi AA, Firoozi AA. Geotechnical innovations for seismic-resistant urban infrastructure. Journal of Civil Engineering and Urbanism. 2024;14(3):346-55. https://dx.doi.org/10.54203/jceu.2024.39

[3] Nayak A, Mishra N. Urban Soil Erosion Modelling and Infrastructure Vulnerability Assessment Using RUSLE–GIS and Remote Sensing Techniques. Journal of Smart Infrastructure and Environmental Sustainability. 2026;3(1):9-17.

[4] Okem ES, Nwokediegwu ZQ, Umoh AA, Biu PW, Obaedo BO, Sibanda M. Civil engineering and disaster resilience: A review of innovations in building safe and sustainable communities. International Journal of Science and Research Archive. 2024;11(1):639-50. https://doi.org/10.30574/ijsra.2024.11.1.0107

[5] DuPont A, Brunet T. Assessing the structural integrity of aging infrastructure using non-destructive techniques. International Academic Journal of Innovative Research. 2023;10(3):27–33. https://doi.org/10.71086/IAJIR/V10I3/IAJIR1022

[6] Haeri SM. The role of geotechnical engineering in sustainable and resilient cities. Scientia Iranica. 2016 Aug 1;23(4):1658-74.

[7] Al-Mutairi Y. Development of sustainable and resilient infrastructure systems using recycled materials and advanced techniques. International Academic Journal of Science and Engineering. 2023;10(4):31–35. https://doi.org/10.71086/IAJSE/V10I4/IAJSE1037

[8] Nikolaou S, Antonaki N, Kourkoulis R, Gelagoti F, Georgiou I, Gazetas G. Geotechnical engineering challenges in the path to resilient infrastructure. InGeo-Risk 2017 2017 Jun 4 (pp. 206-215).

[9] Zhang J, Song X. The AI-assisted traditional design methods for the construction sustainability: A case study of the Lisu ethnic minority village. Natural and Engineering Sciences. 2024 Sep 1;9(2):213-33. https://doi.org/10.28978/nesciences.1569562

[10] Reddy KR, Janga JK, Kumar G. Sustainability and resilience: A new paradigm in geotechnical and geoenvironmental engineering. Indian Geotechnical Journal. 2025 Aug;55(4):2510-31.

[11] Otieno J, Wanjiru G. Seismic Innovations: Strengthening Tall Buildings with Advanced Earthquake-Resistant Technologies. Association Journal of Interdisciplinary Technics in Engineering Mechanics. 2024 Sep 30;2(3):18-21.

[12] Abbas M, Elbaz K, Shen SL, Chen J. Earthquake effects on civil engineering structures and perspective mitigation solutions: a review. Arabian Journal of Geosciences. 2021 Jul;14(14):1350.

[13] Choudhary M, Deshmukh R. Integrating Cloud Computing and AI for Real-time Disaster Response and Climate Resilience Planning. Cloud-Driven Policy Systems. 2023:7-12.

[14] Syahbana AJ, Irsyam M, Delfebriyadi D, Tanjung MI, Misliniyati R, Ridwan M, Aldiamar F, Hanifa NR, Beddu A, Himawan A. Role of the Indonesian society for geotechnical engineering in the development of sustainable earthquake-resilience infrastructure in the recent years. InSustainable Geo-Technologies for Climate Change Adaptation 2022 Oct 3 (pp. 185-194). Singapore: Springer Nature Singapore.

[15] Basu D, Misra A, Puppala AJ. Sustainability and geotechnical engineering: perspectives and review. Canadian geotechnical journal. 2015;52(1):96-113. https://doi.org/10.1139/cgj-2013-0120

[16] Bocchini P, Frangopol DM, Ummenhofer T, Zinke T. Resilience and sustainability of civil infrastructure: Toward a unified approach. Journal of Infrastructure Systems. 2014 Jun 1;20(2):04014004. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000177

[17] Porter KA. Should we build better? The case for resilient earthquake design in the United States. Earthquake Spectra. 2021 Feb;37(1):523-44. https://doi.org/10.1177/8755293020944186

[18] Franchin P, Cavalieri F. Probabilistic assessment of civil infrastructure resilience to earthquakes. Computer-Aided Civil and Infrastructure Engineering. 2015 Jul;30(7):583-600. https://doi.org/10.1111/mice.12092

[19] McDonald GW, Smith NJ, Kim JH, Brown C, Buxton R, Seville E. Economic systems modelling of infrastructure interdependencies for an Alpine Fault earthquake in New Zealand. Civil Engineering and Environmental Systems. 2018 Oct 2;35(1-4):57-80. https://doi.org/10.1080/10286608.2018.1544627

[20] Krawinkler H, Deierlein GG. Challenges towards achieving earthquake resilience through performance-based earthquake engineering. InPerformance-based seismic engineering: Vision for an earthquake resilient society 2014 May 26 (pp. 3-23). Dordrecht: Springer Netherlands.

[21] Das JT. Assessment of sustainability and resilience in transportation infrastructure geotechnics. The University of Texas at Arlington; 2018.

[22] Ansal A, editor. Recent advances in earthquake geotechnical engineering and microzonation.

[23] Rogers CD, Bouch CJ, Williams S, Barber AR, Baker CJ, Bryson JR, Chapman DN, Chapman L, Coaffee J, Jefferson I, Quinn AD. Resistance and resilience–paradigms for critical local infrastructure. InProceedings of the Institution of Civil Engineers-Municipal Engineer 2012 Jun (Vol. 165, No. 2, pp. 73-83). Thomas Telford Ltd. https://doi.org/10.1680/muen.11.00030

[24] Clarke B, Middleton C, Rogers C. The future of geotechnical and structural engineering research. InProceedings of the Institution of Civil Engineers-Civil Engineering 2016 Feb (Vol. 169, No. 1, pp. 41-48). Thomas Telford Ltd. https://doi.org/10.1680/jcien.15.00029

[25] Toprak S, Zulfikar AC, Mutlu A, Tugsal UM, Nacaroglu E, Karabulut S, Ceylan M, Ozdemir K, Parlak S, Dal O, Karimzadeh S. The aftermath of 2023 Kahramanmaras earthquakes: Evaluation of strong motion data, geotechnical, building, and infrastructure issues. Natural Hazards. 2025 Jan;121(2):2155-92.