International Journal of GEOMATE
(Geotechnique, Construction Materials and Environment)
ISSN: 2186-2982 (P), 2186-2990 (O), Japan
Vol. 31, Issue 144, August, 2026, PP.20-29; DOI: 10.21660/2026.144.5431

SEISMIC RELIABILITY OF BUILDINGS WITH GEOTECHNICAL SEISMIC ISOLATION (GSI)

Raikhan K. Shegenbayeva[1], Yerik T. Bessimbayev[2], Kylyshbay A. Bissenov[1], Abzal T. Shegenbayev[1], Talal Awwad[3], Svetlana N. Buganova[4], *Sayat Niyetbay[2,4,5]

[1] Institute of Engineering and Technology, Korkyt Ata Kyzylorda University, Kyzylorda 120000, Kazakhstan; [2] Construction and Building Materials Department, Institute of Architecture and Civil Engineering, Satbayev University, 22 Satbayev Street, Almaty 050013, Kazakhstan;[3] Soils and Foundations Department, Emperor Alexander I St. Petersburg State Transport University, 190031 Saint Petersburg, Russia; [4] School of Construction, International Educational Corporation, Ryskulbekov Street, 28 Almaty 050043, Kazakhstan; [5] LLP Kazakh Leading Academy of Architecture and Civil Engineering, Ryskulbekov Street, 28 Almaty 050043, Kazakhstan

*Corresponding Author, Received: 13 Jan. 2026, Revised: 20 March 2026, Accepted: 12 April 2026

ABSTRACT: The article is devoted to the study of the seismic reliability of a building with geotechnical seismic isolation (GSI) under earthquakes of a given intensity. The aim of the work is the numerical modeling of the seismic reliability of buildings with geotechnical seismic isolation, including the analysis of geotechnical parameters, dynamic modeling, probabilistic assessment of the risk of foundation deformations, and the dynamic behavior of the building under earthquakes of a given intensity. The results of the study of geotechnical seismic isolation (GSI) parameters made of various geomaterials such as sand, gravel, and crushed stone are presented, along with the results of numerical modeling of the dynamic behavior of the building, the results of reliability assessment in terms of settlement, and the probabilities of exceeding the allowable acceleration at the foundation and at the top of the building, as well as the patterns of reducing the seismic response depending on the characteristics of geotechnical seismic isolation (GSI). The interaction of geotechnical seismic isolation and the superstructure was modeled in the Plaxis 2D program using the finite element method with an earthquake accelerogram corresponding to the Kobe earthquake (1995, Mw 6.9) with a duration of 20 s. The analysis of the amplitude–frequency characteristics of the building vibrations shows that as the height and volume of geotechnical seismic isolation (GSI) increase, horizontal accelerations at the top and at the foundation level decrease by 16%. A significant reduction of acceleration by 15% and of foundation settlement by 9% is observed when geotechnical seismic isolation (GSI) is constructed from coarse sand. Reinforcement of geotechnical seismic isolation (GSI) made of coarse sand with a geogrid shows a reduction in the amplitude–frequency characteristics of building vibrations by up to 28%. The analysis of the reliability coefficients of geotechnical seismic isolation (GSI) in terms of settlement and the probabilities of exceeding acceleration also shows a significant reduction in the limit of allowable acceleration at the top of the structure from 27% to 7.84%, and the reliability coefficient for acceleration β_{at} = 1.42, which increases by 73%. The results confirm the positive effect of using a geotechnical seismic isolation system as an economically advantageous design alternative to the traditional seismic isolation system.

Keywords: Earthquake; Geotechnical Seismic Isolation; Soil Cushion Made of Geomaterial; Building Settlement; Accelerograms

1. INTRODUCTION

One of the priority tasks of modern construction and geotechnical design is to ensure the seismic resistance of buildings and structures located in areas with increased seismic hazard. In the context of growing urbanization, active development of seismically active territories, and the tightening of regulatory requirements, the need to develop and implement new, efficient methods of seismic protection has become especially relevant. The devastating earthquakes of recent decades—such as the Sichuan earthquake (2008), the Hatib earthquake in Indonesia (2018), and the Türkiye earth-quake (2023)—have clearly demonstrated that traditional approaches to earth-quake-resistant construction require serious reconsideration, particularly with regard to the soil–structure interaction and the dynamic behavior of foundation soils.

Among innovative methods of protecting buildings from seismic impact, special attention in recent years has been given to geotechnical seismic isolation (GSI) systems capable of partially reflecting, absorbing, or transforming seismic waves before they reach the building foundation, while ensuring sufficient reliability and efficiency during installation and operation. Unlike conventional seismic isolation systems such as rubber–metal bearings or friction pendulum isolators, GSI acts directly at the foundation level, attenuating seismic waves before they affect the superstructure. This approach offers a simpler and more reliable technological solution for mitigating seismic loads compared to the abovementioned structural isolation methods[1,2].

Analytical and experimental studies on geotechnical seismic isolation by Hing Ho Tsang (2009), Banović Ivan (2018), A. Tsiavos (2019), and others, conducted using various granular and structured materials, have proven the efficiency of this technology for dissipating seismic energy before it is transmitted to the superstructure. Analytical investigations by Hing Ho Tsang[3,4], Ivan Banović [5], Anastasius [6], Xiong and Tsang [7], and Forcellini [8] on the design of geotechnical seismic isolation systems in fig. 1 have drawn considerable scientific interest, emphasizing the need for new experimental and numerical studies to promote the active implementation of GSI systems in engineering practice.

The rationale for selecting the GSI modeling approach has been clarified in the revised manuscript. The GSI technique was chosen due to its ability to dissipate seismic energy within the soil layer and significantly reduce the transmission of accelerations to the superstructure, as demonstrated in previous studies [9]. In addition, compared to traditional base isolation systems, GSI represents a cost-effective and practically applicable solution, especially for low- and mid-rise structures, which justifies its use in the present study [10].

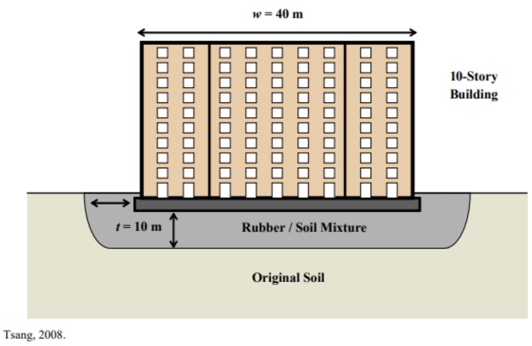


Fig.1 Scheme of the seismic isolation method using a layer of rubber–soil mixture

According to researchers, the effectiveness of GSI systems depends on many factors, including vertical, inclined, or horizontal arrangement, rectangular or circular shape, distance from the building, thickness, and depth of installation. A significant role in the reliability and constructability of GSI is played by the use of various materials beneath the foundation, including sand, gravel, stone pebbles, rubber–soil mixtures (RSM) [11–16], geofoam, and geosynthetic materials [17].

There is an increasing interest in experimental and numerical modelling of the effectiveness of various configurations of geotechnical seismic isolation using different geomaterials [18–23].

In recent years, the application of probabilistic reliability analysis of seismically isolated buildings has made it possible to evaluate seismic resistance considering uncertainties in soil and structural vibrations, as well as to obtain a quantitative assessment of the probability of exceeding the limit state of the structural system. This approach accounts for uncertainties in various parameters considered in the analysis and design of structures according to safety criteria [24].

The reliability of the foundation and structural elements designed in accordance with the Eurocodes permits the use of probabilistic calculation methods that take into account statistical heterogeneity of foundations, anisotropy, plastic and rheological properties of materials and soils, spatial, geometric and physical nonlinearity of structures, the random nature of loads, and other factors[25–28].

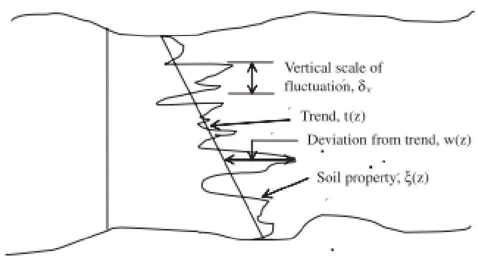


Fig.2 Statistical description of soil variability

The use of the stochastic finite element method for analyzing the bearing capacity of a foundation on spatially varying soil (Fig. 2) made it possible to obtain a quantita-tive assessment of uncertainty factors (Fig. 3) based on random field theory and Monte Carlo simulation.

The reliability assessment of load-bearing structural elements of a multi-storey building is based on the probabilistic description of both the applied loads and the material resistance that determines the structural capacity.

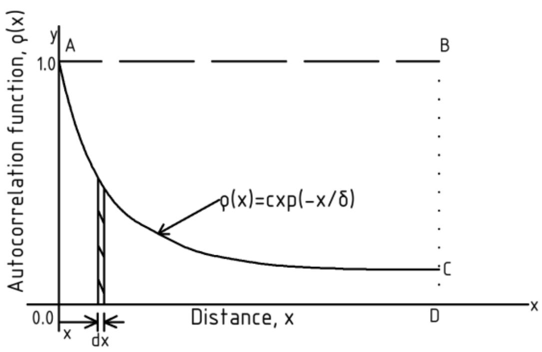


Fig.3 Derivation of the theoretical variance reduction function for the exponential autocorrelation function.

In engineering practice, these parameters are treated as random variables, since their formation is influenced by numerous uncontrolled factors such as variations in material properties, construction technology, climatic and operational effects, and local geotechnical conditions. This intrinsic variability necessitates the use of stochastic analysis methods.

Within the framework of the classical probabilistic approach, the random variables describing the structural resistance R and the resultant load S are approximated by normal distributions. This assumption is justified by the central limit theorem, as the resulting parameters represent the sum of a large number of independent or weakly dependent contributing factors. The normal distribution enables a rigorous formalisation of structural reliability and a quantitative evaluation of the probability of failure.

When modelling the stochastic response of the structure, a normal probability distribution is used around the mean values obtained from the data presented in the article. The probability of exceeding the allowable settlement of the structure is expressed as (1):

$$P(s > s_{lim}) = 1 - \Phi\left(\frac{s_{lim} - \mu(s)}{\sigma_s}\right), \quad (1)$$

where μ(s) is the mean settlement value, σ_s is the standard deviation, slim is the allowable (limit) settlement, and Φ is the standard normal distribution function.

The corresponding reliability index β_s for settlement is defined by the following expression (2):

$$\beta_s = \frac{s_{lim} - \mu(s)}{\sigma_s} \quad (2)$$

Similarly, the probability of failure P_f according to the criterion of exceeding the allowable foundation acceleration under seismic loading is computed as (3):

$$P_f(a_{fund} > a_{lim}) = 1 - \Phi\left(\frac{a_{lim} - \mu(a_{fund})}{\sigma_{af}}\right) \quad (3)$$

where μ(afund) and σaf are the mean value and standard deviation of the vertical acceleration at the foundation, and alim is the allowable design (code-specified) accel-eration value.

The reliability index corresponding to this criterion is defined as (4):

$$\beta_{af} = \frac{a_{lim} - \mu(a_{fund})}{\sigma_{af}} \quad (4)$$

For the assessment of the dynamic response of the upper floors of the building, the following expression is used in an analogous manner (5):

$$P_f(a_{top} > a_{lim}) = 1 - \Phi\left(\frac{a_{lim} - \mu(a_{top})}{\sigma_{at}}\right) \quad (5)$$

μ(atop) and σat are the mean value and standard deviation of the accelerations at the top floor.

The corresponding reliability index is given by (6):

$$\beta_{at} = \frac{a_{lim} - \mu(a_{top})}{\sigma_{at}} \quad (6)$$

The relationships presented in Equations (1)–(6) make it possible to transition from a stochastic description of structural parameters to a quantitative evaluation of the probability of exceeding normative limit-state criteria and to the calculation of reliability indices using the formal safety-factor method. This approach enables the integration of random factors into the analysis process, provides the ability to compare different limit states by their associated risk levels, supports the calibration of design safety factors based on a target reliability level, and accounts for the combined behaviour of structural elements, particularly under seismic and geotechnical actions.

The relevance of the study is determined by the need to enhance the reliability and stability of buildings using probabilistic calculation methods that consider the statistical heterogeneity of soils and structural materials under random natural loading conditions.

The use of geotechnical seismic isolation (GSI) methods opens new opportunities in the design of foundations and subgrade systems, while also expanding the range of available passive protection measures for structures[29,30].

Despite the growing body of research on geotechnical seismic isolation (GSI) and soil-based damping mechanisms, several important aspects remain insufficiently investigated. Existing studies predominantly focus on deterministic evaluations of structural response, such as reductions in acceleration or displacement, while probabilistic reliability interpretations are comparatively limited. In particular, the quantitative relationship between GSI parameters, stochastic variability of soil properties, and reliability indices of buildings under seismic loading has not been comprehensively established.

Furthermore, previous investigations often emphasize either dynamic response analysis or geotechnical performance, whereas integrated frameworks combining finite-element seismic modelling with reliability-based assessment of limit states are rarely reported. The influence of different geomaterials and reinforcement schemes on failure probabilities associated with settlement and acceleration criteria also remains inadequately clarified.

A critical analysis of recent studies indicates that, although significant progress has been achieved in evaluating the effectiveness of GSI systems, most investigations remain limited to deterministic approaches and do not adequately address the influence of uncertainties in soil properties and seismic input parameters. Moreover, the lack of integrated methodologies combining advanced numerical modelling with probabilistic reliability assessment highlights a clear research gap, which is addressed in the present study.

Therefore, a systematic reliability-oriented evaluation of buildings incorporating GSI, accounting for uncertainties in both geotechnical and dynamic parameters, is still required.

The main objective of this work is the numerical modelling of the seismic reliability of buildings incorporating geotechnical seismic isolation, including the analysis of geotechnical parameters, dynamic modelling, and probabilistic assessment of foundation deformation risks and the dynamic behaviour of the structure under earthquakes of specified intensity.

2. RESEARCH SIGNIFICANCE

This study significantly advances the state of the art in seismic design by providing a comprehensive numerical and probabilistic assessment of buildings equipped with geotechnical seismic isolation (GSI). By integrating dynamic finite-element modeling with reliability analysis, the research quantifies the influence of different geomaterials and reinforcement schemes on settlement, acceleration response, and failure probability. In particular, the study considers a homogeneous cohesive soil layer representative of stiff ground conditions, characterized by key geotechnical parameters such as density, shear modulus, cohesion, and Poisson's ratio, defined within a nonlinear constitutive framework. The GSI layer is modeled using deformable geomaterials (e.g., rubber–soil mixtures and geosynthetic-based interfaces) with enhanced energy dissipation capacity. The reinforcement scheme includes the implementation of a geotechnical isolation layer beneath a shallow rigid foundation, combined with structural idealization of multi-store buildings using elastic beam-column elements, allowing for the simulation of soil–structure interaction effects under seismic loading. The findings demonstrate that GSI can substantially reduce seismic demand and improve structural reliability, offering a cost-effective and practical alternative to conventional base isolation systems for buildings in seismically active regions.

3. MATERIALS AND METHODS

3.1 Methods

The research methods include theoretical analysis, numerical modelling using the finite element method in PLAXIS 2D, interpretation of the obtained results, as well as the reliability assessment of the building using probabilistic methods that account for statistical heterogeneity and random external actions.

For the implementation of the numerical modelling, the software package PLAXIS 2D (v.2023) was selected as one of the most widely used and scientifically validated tools in the field of soil dynamics and seismic process modelling. The software is based on the finite element method and provides capabilities for dynamic time-domain analysis, the application of nonlinear soil models such as Mohr–Coulomb, the use of real accelerograms or response spectra, and the implementation of special boundary conditions to reduce wave reflections.

Within this study, a comprehensive approach is applied to investigate the effectiveness of geotechnical seismic isolation (GSI) constructed from various geomaterials, as well as to evaluate their reliability under earthquakes of specified intensity.

3.1.1 Materials

The building is a 10-storey structure with a height of 39 m and plan dimensions of 15.5 × 27 m. The structural system is a reinforced concrete frame–shear wall system (monolithic frame with stiffness diaphragms). The foundation is a 1.2 m-thick raft foundation made of concrete grade B25. The adopted geometric and structural parameters are assumed to represent a typical mid-rise residential building widely used in seismic regions. The selected dimensions and structural configuration are consistent with common design practice and reflect realistic conditions for buildings constructed in areas with increased seismic hazard, including urban environments similar to those of Central Asia.

The geological profile of the modelled soil mass is represented as a two-layer stratified medium:

– the upper layer consists of fill sand with a thickness of up to 3 m, with a deformation modulus E = 19.9 MPa and a density ρ = 1.88 g/cm³;

– the lower layer consists of fine sand of medium density, ranging from slightly moist to fully saturated, with a thickness of up to 12 m (deformation modulus approximately 19.9 MPa, density 1.88 g/cm³).

The total depth of the modelled domain is 40 m, with a width of 150 m. Such di-mensions allow eliminating the influence of reflected waves from the model bounda-ries on the behaviour of the system in the central zone. The model parameters are se-lected considering quasi-linear wave attenuation conditions along the lateral bounda-ries.

The seismic input is applied in the form of horizontal acceleration at the bottom boundary of the model using an accelerogram of the real Kobe earthquake (1995, magnitude 6.9, intensity 7.3 on the Richter scale), subsequently scaled to a design peak value of 0.25g. The duration of the input motion is 20 s. The use of a spectrally enriched input function enables an adequate representation of the seismic loading conditions corresponding to an intensity of 8–9 on the MSK-64 scale.

Fig. 4 shows the finite element numerical model used in the study, including the soil domain, foundation, and superstructure. The building is represented by a frame–shear wall system placed on a raft foundation, while the soil mass is modeled as a layered medium with defined boundary conditions. The model dimensions and mesh discretization are selected to ensure accurate simulation of soil–structure interaction under seismic loading.

Fig. 5 presents the distribution of total displacements in the soil–foundation–structure system under seismic loading. The results indicate a concentration of maximum displacements beneath the foundation, forming a characteristic deformation zone that reflects the soil response and load transfer mechanism. The displacement contours demonstrate the influence of soil stratification and confirm the development of a localized deformation field governing the settlement behaviour of the foundation.

Formulation of the numerical model and results

Task 1. Calculation of the settlement of the natural foundation soil and determination of the acceleration at the foundation level and at the top of the building under the specified seismic input (based on the Kobe earthquake accelerogram), as well as assessment of the possible increase in foundation loading under seismic actions.

Fig. 6 shows the time histories of accelerations obtained from the dynamic analysis: (a) at the foundation level and (b) at the top of the building. The results demonstrate a noticeable amplification of seismic response along the height of the structure, with higher peak accelerations observed at the upper level compared to the foundation. This behavior reflects the dynamic characteristics of the building and confirms the influence of soil–structure interaction on the distribution of seismic effects.

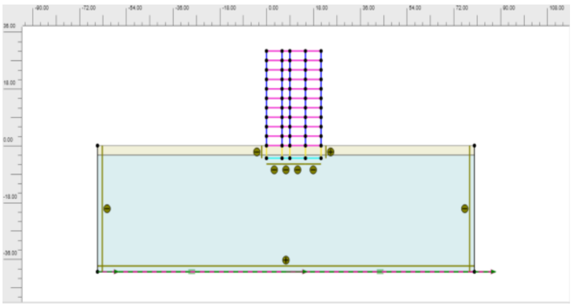


Fig.4 Numerical model.

The acceleration at the top of the building exceeds that at the foundation level by 35%, which may adversely affect the overall structural reliability of the building. Fig. 7 illustrates the distribution of axial forces in the foundation under different loading conditions: (a) basic load case and (b) special seismic load case.

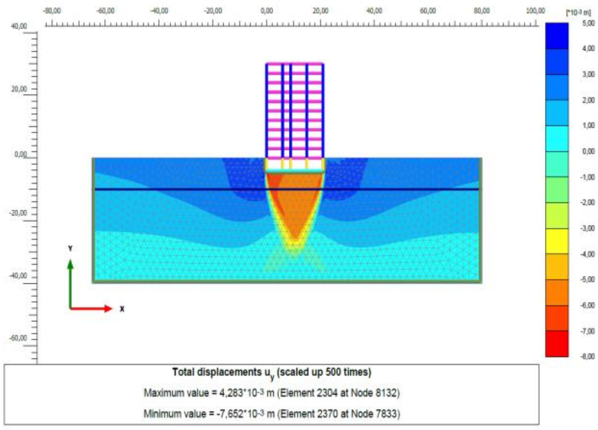
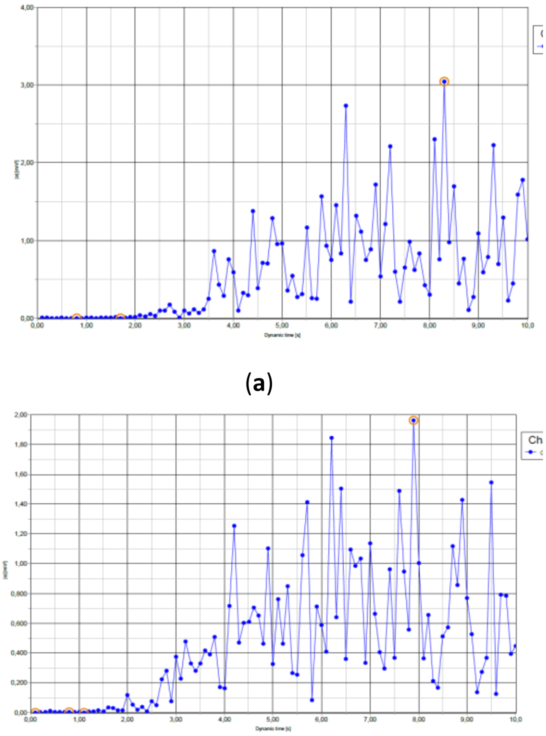


Fig.5 Foundation settlement (141 mm)



(a)

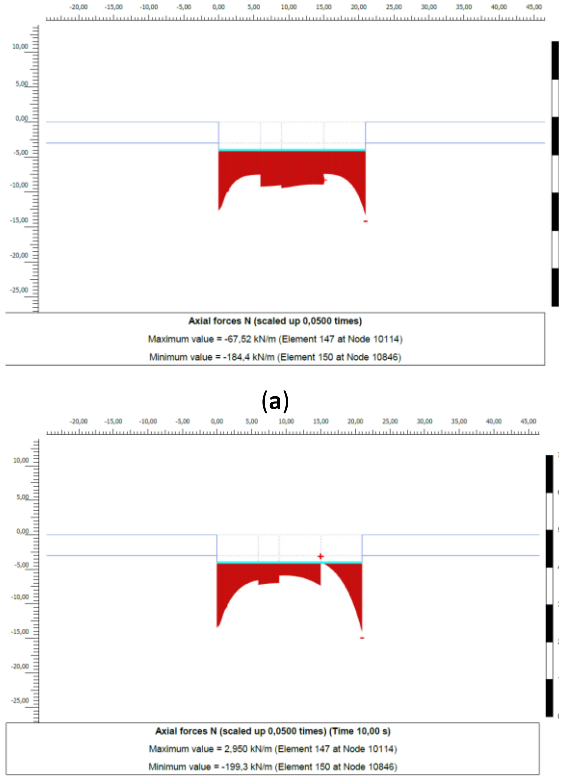
(b)

Fig.6 Accelerations: (a) at the foundation level (1.96 m/s²); (b) at the top of the building (3.04 m/s²).

The results show an increase in axial forces and a redistribution of stresses beneath the foundation during seismic loading, indicating a more non-uniform load transfer mechanism. This confirms that seismic action leads to additional foundation loading, which may affect the bearing capacity and overall reliability of the soil–foundation system.

Under seismic loading, a potential increase in foundation pressure of up to 10% may occur. Task 2. Investigation of seismic isolation using different geomaterials: coarse sand and pebbles. A 3-m-thick geotechnical seismic isolation layer with a plan area equal to 1.5A relative to the building dimension A was considered. For both types of geotechnical seismic isolation, the foundation settlement is nearly the same, with only minor differences. The lowest settlement value was ob-tained for the pebble-based isolation, while the sand-based isolation resulted in a 5% higher acceleration at the top of the building.

Task 3. Investigation of the structural response when using geotechnical seismic isolation with a geogrid layer, characterized by a radial secant stiffness of 360 kN/m at 0.5% strain (250 kN/m at 2% strain), a stiffness ratio of 0.80, junction efficiency of 100%, and a hexagon pitch of 80 mm. The considered configuration included a coarse sand isolation layer reinforced with a geogrid placed at a depth of 1 m within a 2-m-high seismic isolation layer.



(a)

(b)

Fig.7 Foundation loading under seismic analysis: (**a**) basic load case — 18.4 t/m²; (**b**) special (seismic) load case — 19.9 t/m².

The foundation settlement with geogrid-reinforced seismic isolation is 20% lower compared to the case without the geogrid layer.

Table 1. Comparison of foundation settlement, vibration acceleration, and increase in foundation loading for different types of seismic isolation.

No.	Type of seismic isolation	Foundation settlement, mm	Acceleration at foundation level, m/s²	Acceleration at top of building, m/s²	Increase in foundation loading, %
1	Without seismic isolation	141	1.96	3.04	8
2	Coarse sand	129	1.595	2.922	8.6
3	Pebbles	125	1.437	2.754	1.2
4	Sand reinforced with geogrid	114	1.389	2.585	11.5

Table 2. Parameters of the probabilistic reliability assessment of the building structure for different types of foundation conditions.

Variant	μ(s), mm	σ_s, mm	P(s > 100)	β_s	μ(afund), m/s²	σaf	Pf(afund > 2.5)	βaf
Without seismic isolation	141	28,2	92,7 %	-1,45	1,960	0,490	13,52 %	1,10
Sand	129	25,8	87 %	-1,12	1,595	0,399	1,16 %	2,27
Pebbles	125,6	25,11	84,6 %	-1,02	1,437	0,359	0,15 %	2,96
Crushed stone	126	25,2	84,9 %	-1,03	1,676	0,419	2,46 %	1,97
Sand + 2 layers of geogrid	114	22,8	73 %	- 0,61	1,389	0,347	0,069 %	3,20

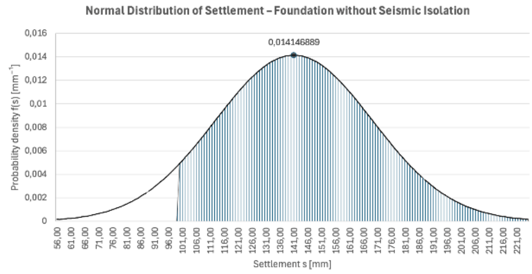
Task 4. Investigation of the probabilistic assessment of foundation deformation risk and the dynamic behaviour of the building under earthquakes of specified intensity. Table 1 shows parameters of the probabilistic reliability assessment of the building structure for different types of foundation conditions.

Table 3. Parameters of the probabilistic reliability assessment of the building structure for different foun-dation types at the top of the structure.

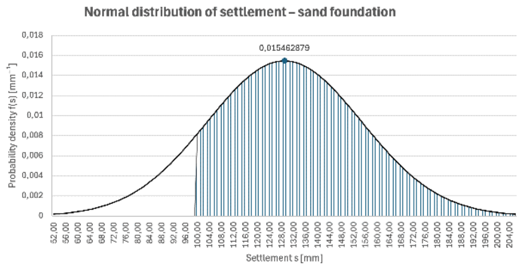
Variant	μ(a_top), м/c²	σ_{at}	Pf (a_top>3,5)	β_{at}
Without seismic isolation	3,040	0,760	27,25 %	0,61
Sand	2,922	0,731	21,44 %	0,79
Pebbles	2,754	0,689	13,93 %	1,08
Crushed stone	2,896	0,724	20,21 %	0,83
Sand + 2 layers of geogrid	2,585	0,646	7,84 %	1,42

4. RESULTS AND DISCUSSION

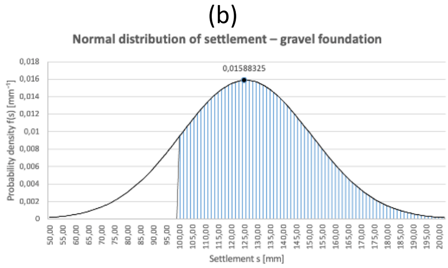
The results of the numerical modelling, performed for a geotechnical seismic isolation (GSI) layer with a width of 1.5A relative to the building width A, show a reduction in foundation settlement with increasing thickness of the soil cushion. The optimal thickness of the soil cushion, at which settlement does not exceed the design limits for this project, is approximately 3.0 m. At the same time, under seismic loading, an increase in foundation loading of about 10% is observed with the greater cushion thickness. Therefore, in foundation design, the design load should be increased to the critical level, i.e., by approximately 10–20%. Based on the assumed μ(s) values provided in the article, all considered variants have a high probability.



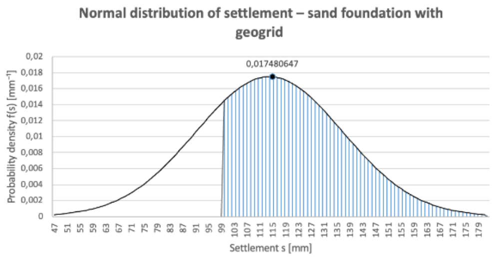
(a)



(b)



(c)



(d)

Fig.8 Normal distribution of foundation settlement: (a) without seismic isolation; (b) with sand-based isolation; (c) with pebble-based isolation; (d) with sand isolation reinforced with two geogrid layers.

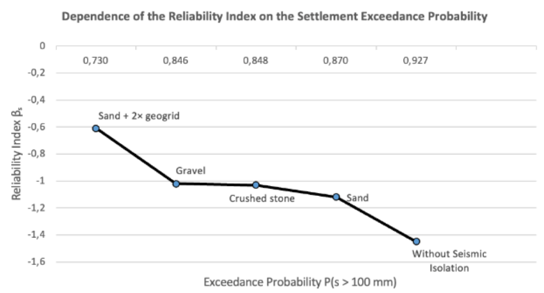


Fig.9. Relationship between reliability indices for settlement and the probabilities of exceeding the allowable limit

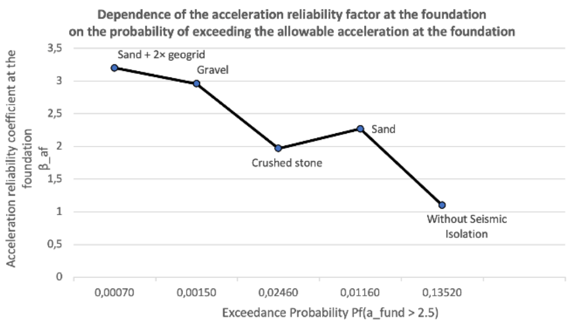


Fig.10. Relationship between reliability indices for foundation acceleration and the probabilities of exceeding the allowable acceleration at the foundation

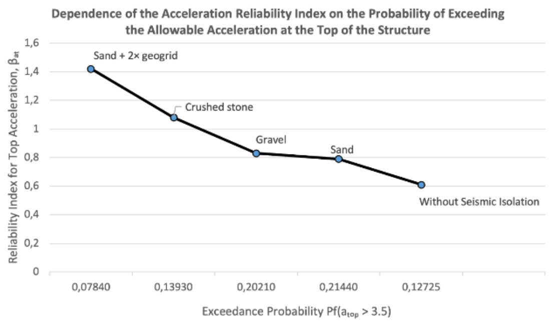


Fig.11. Relationship between reliability indices for top-floor acceleration and the probabilities of exceeding the allowable acceleration at the top of the structure

The high probability of (Pf ≈ 0.73–0.93) exceeding the allowable settlement of 100 mm. Thus, according to the mean values reported in the article, settlement remains the primary issue and requires further improvement: none of the cushion configurations (including the geogrid-reinforced option) ensures meeting the 100-mm criterion with an acceptable probability.

The best settlement performance is observed for the sand + geogrid option (μ = 114 mm), although even in this case Pf ≈ 73%.

The situation is significantly better with respect to accelerations. For the foundation, all variants with a soil cushion produce mean accelerations well below the allowable value of 2.5 m/s²; in the best case (sand + geogrid), the probability of exceedance is nearly zero (Pf ≈ 0.07%), and for the pebble layer it is also very low (Pf ≈ 0.15%).

At the top of the building, the probability of exceeding 3.5 m/s² is also relatively small for all variants (the largest values, Pf ≈ 13–27%, occur for the baseline model without a cushion; with soil cushions, Pf generally decreases to the range of ~8–21%).

Geotechnical seismic isolation (GSI) effectively reduces the dynamic demand (accelerations), and several of the analyzed configurations are suitable for design purposes with respect to acceleration criteria.

5. CONCLUSION

A comprehensive study of the effectiveness of geotechnical seismic isolation (GSI) for buildings has been carried out using numerical modelling of the interaction be-tween the structure, the foundation soil, and the damping layer under seismic loading.

The scientific novelty of the work lies in a systematic approach to evaluating the effi-ciency of GSI through numerical modelling and probabilistic assessment of foundation deformation risks and the dynamic behaviour of buildings subjected to earthquakes of specified intensity.

The numerical analysis demonstrated that implementing a 3.0-m-thick GSI layer between the foundation slab and the underlying soil allows one to:

– reduce the peak ground acceleration (PGA) by 35–47%,

– decrease the maximum horizontal displacement at the building top by 30–42%,

– confine deformation within the isolation layer.

The probabilistic analysis of exceeding normative limit-state criteria and the computed reliability indices provided a quantitative assessment of the stochastic structural response considering random influencing factors:

– all GSI variants result in mean accelerations significantly below the allowable limit of 2.5 m/s²;

– the sand-based GSI reinforced with a geogrid shows an almost negligible probability of exceeding the settlement limit (Pf ≈ 0.07%);

– the reduction in dynamic demand (accelerations) in the range of ~8–21% confirms the effectiveness of GSI under certain geotechnical conditions;

– all considered GSI configurations exhibit a high probability (Pf ≈ 0.73–0.93) of ex-ceeding the allowable settlement.

The study shows that the highest efficiency is demonstrated by combined solutions incorporating sand–gravel mixtures and geosynthetic reinforcement layers.

The observed reduction in accelerations is primarily governed by energy dissipation and wave scattering within the deformable GSI layer, which reduces the transmission of seismic waves from the soil to the superstructure. At the same time, the increase in settlement is associated with the shear deformation mechanism and reduced stiffness of the isolation layer, leading to concentration of strains beneath the foundation. These results highlight the trade-off between seismic isolation efficiency and deformation compatibility of the foundation system.

The limitations of the present study include the assumption of simplified soil stratification, the use of idealized material models, and the consideration of a limited number of seismic input motions. In addition, long-term effects such as material degradation, cyclic accumulation of deformations, and construction-related uncertainties were not explicitly considered. Further research should focus on experimental validation, advanced constitutive modelling, and the evaluation of GSI performance under a wider range of seismic and geotechnical conditions.

The numerical modelling of GSI systems confirms their high effectiveness and supports their integration into modern engineering practice as an accessible, reliable, and adaptable technology for mitigating seismic risks to buildings.

6. REFERENCES

1. Ahmad F., Kumar P., Kumar D.R., Wipulanusat W., Samui P., Geotechnical evaluation of embankment stability in seismic zones using Monte Carlo and subset simulations within an LRFD framework aided by machine learning. Results in Engineering, 27, 2025, pp.106320. https://doi.org/10.1016/J.RINENG.2025.106320
2. Gallardo J.A., de la Llera J.C., Epistemic uncertainty in the seismic performance assessment of isolated buildings due to high damping rubber bearing model selection. Engineering Structures, 348, 2026, pp.121734. https://doi.org/10.1016/J.ENGSTRUCT.2025.121734
3. Tsang H.H., Analytical design models for geotechnical seismic isolation systems. Bulletin of Earthquake Engineering, 21(8), 2023. https://doi.org/10.1007/s10518-022-01469-x
4. Tsang H.H., Pitilakis K., Mechanism of geotechnical seismic isolation system: Analytical modeling. Soil Dynamics and Earthquake Engineering, 122, 2019, pp.171-184. https://doi.org/10.1016/J.SOILDYN.2019.03.037
5. Banović I., Radnić J., Grgić N., Foundation size effect on the efficiency of seismic base isolation using a layer of stone pebbles. Earthquake and Structures, 19(2), 2020. https://doi.org/10.12989/eas.2020.19.2.103
6. Tsiavos A., Haladij P., Sextos A., Alexander N.A., Analytical investigation of the effect of a deformable sliding layer on the dynamic response of seismically isolated structures. Structures, 27, 2020, pp.2426-2436. https://doi.org/10.1016/j.istruc.2020.08.016
7. Xiong W., Tsang H.H., Lo S.H., Shang S.P., Wang H.D., Zhou F.Y., Geotechnical Seismic Isolation System - Experimental Study. Advanced Materials Research, 163-167, 2010, pp.4449-4453. https://doi.org/10.4028/www.scientific.net/AMR.163-167.4449
8. Forcellini D., Assessment of geotechnical seismic isolation (GSI) as a mitigation technique for seismic hazard events. Geosciences, 10(6), 2020. https://doi.org/10.3390/geosciences10060222
9. Jauhari N., Hegde A., Performance Evaluation of Single and Multiple Trenches in Screening Ground Vibrations. Lecture Notes in Civil Engineering, 2023. https://doi.org/10.1007/978-981-19-6998-0_29
10. Banović I., Radnić J., Grgić N., Numerical Model for Dynamic Analysis of Structures with Seismic Base Isolation Using A Layer of Stone Pebbles. Ingegneria Sismica, 38(1), 2021.
11. Tsiavos A., Alexander N.A., Diambra A., Ibraim E., Vardanega P.J., Gonzalez-Buelga A., A sand-rubber deformable granular layer as a low-cost seismic isolation strategy in developing countries: Experimental investigation. Soil Dynamics and Earthquake Engineering, 125, 2019, pp.105731. https://doi.org/10.1016/j.soildyn.2019.105731
12. Pitilakis K., Karapetrou S., Tsagdi K., Numerical investigation of the seismic response of RC buildings on soil replaced with rubber–sand mixtures. Soil Dynamics and Earthquake Engineering, 79, 2015, pp.237-252. https://doi.org/10.1016/j.soildyn.2015.09.018
13. Brunet S., de la Llera J.C., Kausel E., Non-linear modeling of seismic isolation systems made of recycled tire-rubber. Soil Dynamics and Earthquake Engineering, 85, 2016, pp.134-145. https://doi.org/10.1016/j.soildyn.2016.03.019
14. Pistolas G.A., Pitilakis K., Anastasiadis A., A numerical investigation on the seismic isolation

potential of rubber/soil mixtures. Earthquake Engineering and Engineering Vibration, 19(3), 2020. https://doi.org/10.1007/s11803-020-0589-3

15. Senetakis K., Anastasiadis A., Pitilakis K., Dynamic properties of dry sand/rubber (SRM) and gravel/rubber (GRM) mixtures in a wide range of shearing strain amplitudes. Soil Dynamics and Earthquake Engineering, 33(1), 2012. https://doi.org/10.1016/j.soildyn.2011.10.003
16. Feng Z.Y., Sutter K.G., Dynamic Properties of Granulated Rubber/Sand Mixtures. Geotechnical Testing Journal, 23(3), 2000. https://doi.org/10.1520/gtj11055j
17. Yegian M.K., Lahlaf A.M., Dynamic Interface Shear Strength Properties of Geomembranes and Geotextiles. Journal of Geotechnical Engineering, 118(5), 1992, pp.760-779. https://doi.org/10.1061/(ASCE)0733-9410(1992)118:5(760)
18. Yegian M.K., Kadakal U., Foundation Isolation for Seismic Protection Using a Smooth Synthetic Liner. Journal of Geotechnical and Geoenvironmental Engineering, 130(11), 2004, pp.1121-1130. https://doi.org/10.1061/(ASCE)1090-0241(2004)130:11(1121)
19. Banović I., Radnić J., Grgić N., Matešan D., The Use of Limestone Sand for the Seismic Base Isolation of Structures. Advances in Civil Engineering, 2018(1), 2018. https://doi.org/10.1155/2018/9734283
20. Okanov D.A., Bryantsev A.A., Niyetbay S.E., Bozkurt M.B., Moldamuratov Zh.N., Determination of the effective parameters of a triangular corrugated web for crane runway beams. Nanotechnologies in Construction A Scientific Internet-Journal, 17(2), 2025, pp.132-150. https://doi.org/10.15828/2075-8545-2025-17-2-132-150
21. Alenov K.T., Bessimbayev Y.T., Bissenov K.A., Shadkam A.S., Niyetbay S.E., Moldamuratov Zh.N., Modelling and efficiency assessment of vertically reinforced slab foundation of multi-storey building. Nanotechnologies in Construction A Scientific Internet-Journal, 17(2), 2025, pp.151-172. https://doi.org/10.15828/2075-8545-2025-17-2-151-172
22. Guldana A., Niyetbay S., Zhanguzhinov A., Kassabekova G., Jartayeva D., Alimova K., Impact of Airflow Disturbance from Human Motion on Contaminant Control in Cleanroom Environments: A CFD-Based Analysis. Buildings, 15(13), 2025, pp.2264. https://doi.org/10.3390/buildings15132264
23. Bessimbayev Y.T., Niyetbay S.E., Awwad T., Kuldeyev E.I., Uderbayev S.S., Zhumadilova Z.O., The Creation of Geotechnical Seismic Isolation from Materials with Damping Properties for the Protection of Architectural Monuments. Buildings, 14(6), 2024, pp.1572. https://doi.org/10.3390/buildings14061572
24. Zhang H., Song C., Wang M., Cheng Y., Yue S., Wu C., A geotechnical seismic isolation system based on marine sand cushion for attenuating ground shock effect: Experimental investigation. Soil Dynamics and Earthquake Engineering, 168, 2023, pp.107854. https://doi.org/10.1016/j.soildyn.2023.107854
25. Jumadilova S.Zh., Khomyakov V.A., Kenebayeva A.K., Moldamuratov Zh.N., The use of geosynthetic materials to increase the bearing capacity of soil cushions. Nanotechnologies in Construction A Scientific Internet-Journal, 16(4), 2024, pp.342-354. https://doi.org/10.15828/2075-8545-2024-16-4-342-354
26. Tuleyev A., Omarov Z., Abakanov T., Lapin V., Tuleyev T., Vibration test of a high-rise monolithic building. International Journal of GEOMATE, 25(109), 2023, pp.149-156. https://doi.org/10.21660/2023.109.m2315
27. Zhamek N., Abakanov T., Awwad T., Khomyakov V., Elzhanov E., Using the Marchetti dilatometer to determine soil stiffness parameters. International Journal of GEOMATE, 28(130), 2025. https://doi.org/10.21660/2025.130.m2424
28. Abu A.Z., Stage analysis of foundation settlement in retained excavations using PLAXIS 2D. International Journal of GEOMATE, 29(136), 2025. https://doi.org/10.21660/2025.136.5231
29. Gallardo J.A., de la Llera J.C., Epistemic uncertainty in the seismic performance assessment of isolated buildings due to high damping rubber bearing model selection. Engineering Structures, 348, 2026, pp.121734. https://doi.org/10.1016/J.ENGSTRUCT.2025.121734
30. Liu Y., Li J., Lin G., Nonlinear seismic assessment for nuclear power plants with structural-geotechnical hybrid isolation strategy. Structures, 67, 2024, pp.107020. https://doi.org/10.1016/J.ISTRUC.2024.107020