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RESEARCH ARTICLE

REDUCTION OF SEISMIC EFFECTS ON BUILDINGS USING GEOTECHNICAL SEISMIC ISOLATION

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Abstract. *The article addresses one of the most relevant challenges in modern construction–ensuring the reliability and stability of buildings in seismically hazardous regions while reducing the cost of protective engineering measures. The aim of the study is to perform numerical modeling of the influence of geometric and physical–mechanical parameters of geotechnical seismic isolation on the dynamic response of buildings under seismic loading. The study investigates artificial foundation layers composed of sand, pebble gravel, and crushed stone. The scientific novelty lies in substantiating optimal configurations of artificial foundation layers and identifying patterns of seismic response reduction depending on geomaterial characteristics. The interaction between the foundation and the superstructure was simulated using the finite element method in PLAXIS with an earthquake accelerogram as input motion. The results show that increasing the height and volume of the artificial foundation layer reduces horizontal accelerations by approximately 16% at both the foundation and the top of the building. The use of coarse-grained sand led to a reduction in acceleration of up to 15% and foundation settlement of up to 9%, while reinforcement with two geogrid layers further reduced vibration amplitudes by up to 28%. The findings confirm the effectiveness of artificial foundation layers in improving the stability and reliability of buildings in seismic regions.*

Keywords: *seismic effects; soils; artificial foundation; accelerograms; dynamic response of buildings; acceleration reduction.*

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ҒЫЛЫМИ МАҚАЛА

ГЕОТЕХНИКАЛЫҚ СЕЙСМООҚШАУЛАУ АРҚЫЛЫ ҒИМАРАТТАРҒА ТҮСЕТІН СЕЙСМИКАЛЫҚ ӘСЕРЛЕРДІ АЗАЙТУ

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Аңдатпа. *Мақала қазіргі заманғы құрылыс саласындағы өзекті мәселелердің бірі – сейсмикалық қауіпті аймақтарда орналасқан ғимараттардың сенімділігі мен орнықтылығын қамтамасыз ету және сонымен қатар инженерлік қорғаныс шараларын жүзеге асыру шығындарын азайту мәселесіне арналған. Зерттеудің мақсаты – геотехникалық сейсмооқшаулаудың геометриялық және физика-механикалық параметрлерінің сейсмикалық әсер кезіндегі ғимараттардың динамикалық жауабына ықпалын сандық модельдеу арқылы бағалау. Зерттеуде құм, малта тас (галька) және қиыршық тас сияқты әртүрлі геоматериалдардан тұратын жасанды негіз қабаттарының тиімділігі қарастырылды. Жұмыстың ғылыми жаңалығы жасанды негіз қабаттарының оңтайлы конфигурацияларын әзірлеу және негіздеу, сондай-ақ геоматериал қабатының сипаттамаларына байланысты сейсмикалық жауаптың төмендеу заңдылықтарын анықтау болып табылады. Жасанды негіз бен ғимараттың үстіңгі конструкциясының өзара әрекеттесуі PLAXIS бағдарламалық кешенінде соңғы элементтер әдісі арқылы модельденді, мұнда сейсмикалық әсер кіріс ретінде жер сілкінісінің акселерограммасы түрінде берілді. Алынған тербелістердің амплитудалық-жиіліктік сипаттамалары жасанды негіз қабатының биіктігі мен көлемі артқан сайын іргетас деңгейінде де, ғимараттың жоғарғы нүктесінде де көлденең үдеулердің шамамен 16%-ға төмендейтінін көрсетті. Ірі түйіршікті құмнан жасалған жасанды негізді қолдану кезінде үдеудің 15%-ға дейін, ал іргетас отырысының 9%-ға дейін төмендеуі байқалды. Сонымен қатар, ірі түйіршікті құм қабатын екі қабат геотор арқылы армирлеу тербелістердің амплитудалық-жиіліктік сипаттамаларын 28%-ға дейін төмендетуге мүмкіндік берді. Алынған нәтижелер жасанды негіз қабаттарын қолданудың сейсмикалық белсенді аймақтарда ғимараттардың орнықтылығы мен сенімділігін арттырудағы оң әсерін растайды.*

Түйін сөздер: *сейсмикалық әсерлер; грунттар; жасанды негіз; акселерограммалар; ғимараттардың динамикалық жауабы; үдеуді төмендету.*

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НАУЧНАЯ СТАТЬЯ

СНИЖЕНИЕ СЕЙСМИЧЕСКИХ ВОЗДЕЙСТВИЙ НА ЗДАНИЯ С ИСПОЛЬЗОВАНИЕМ ГЕОТЕХНИЧЕСКОЙ СЕЙСМОИЗОЛЯЦИИ

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Аннотация. *Статья посвящена одной из наиболее актуальных задач современного строительства – обеспечению надежности и устойчивости зданий, расположенных в сейсмоопасных регионах, при одновременном снижении затрат на реализацию инженерных защитных мероприятий. Целью настоящего исследования является численное моделирование влияния геометрических и физико-механических параметров геотехнической сейсмоизоляции на динамический отклик зданий при сейсмическом воздействии. В работе представлены результаты исследования искусственных оснований, сформированных из различных геоматериалов, включая песок, гальку и щебень. Научная новизна исследования заключается в разработке и обосновании оптимальных конфигураций искусственных оснований, а также в выявлении закономерностей снижения сейсмического отклика в зависимости от характеристик слоя геоматериалов. Взаимодействие искусственного основания и надземной части здания моделировалось методом конечных элементов в программном комплексе PLAXIS с использованием акселерограммы землетрясения в качестве входного воздействия. Полученные амплитудно-частотные характеристики колебаний здания показывают, что с увеличением высоты и объема слоя искусственного основания горизонтальные ускорения уменьшаются примерно на 16% как на уровне фундамента, так и на верхней точке здания. Существенное снижение ускорений (до 15%) и осадки фундамента (до 9%) было зафиксировано при использовании искусственного основания из крупнозернистого песка. Кроме того, армирование слоя крупнозернистого песка двумя слоями геосетки позволило снизить амплитудно-частотные характеристики колебаний до 28%. Полученные результаты подтверждают положительное влияние применения искусственных оснований на повышение устойчивости и надежности зданий в сейсмически активных регионах.*

Ключевые слова: *сейсмические воздействия; грунты; искусственное основание; акселерограммы; динамический отклик зданий; снижение ускорений.*

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CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

The authors declare that no generative artificial intelligence technologies or AI-based tools were used in the preparation of this article.

ҒЫС / ҚАРЖЫЛАНДЫРУ КӨЗІ

Зерттеу жеке қаржыландыру көздерін пайдалана отырып жүргізілді.

МҮДДЕЛЕР ҚАҚТЫҒЫСЫ

Авторлар мүдделер қақтығысы жоқ деп мәлімдейді.

Авторлар мақаланы дайындау барысында генеративті жасанды интеллект технологиялары мен жасанды интеллектке негізделген технологияларды пайдаланбағанын мәлімдейді.

БЛАГОДАРНОСТИ/ИСТОЧНИК ФИНАНСИРОВАНИЯ

Исследование проводилось с использованием частных источников финансирования.

КОНФЛИКТ ИНТЕРЕСОВ

Авторы заявляют, что конфликта интересов нет.

Авторы заявляют о том, что при подготовке статьи не использовались технологии генеративного искусственного интеллекта и технологии, основанные на искусственном интеллекте.

1 INTRODUCTION

The seismic safety of buildings and structures remains one of the central challenges of modern structural and geotechnical engineering, particularly in regions characterized by high seismic activity and complex soil conditions. Rapid urbanization, increasing building density, and the expansion of construction into seismically hazardous areas significantly amplify potential seismic risks. Recent destructive earthquakes have demonstrated that traditional approaches to seismic-resistant design, primarily focused on strengthening the superstructure, are often insufficient to ensure the required level of safety and serviceability (**Tuleyev et al., 2024**). This has led to growing recognition of the critical role of soil–structure interaction and the dynamic behavior of foundation soils in shaping the overall seismic response of buildings (**Kirgizbayeva et al., 2025**).

Conventional seismic protection strategies are mainly based on structural solutions such as base isolation devices, energy dissipation systems, and enhanced structural stiffness (**Seiitkassymuly et al., 2025**). While these methods are effective, they are frequently associated with high costs, technological complexity, and limitations in application, especially for low- and mid-rise buildings or for the retrofit of existing structures. In this context, geotechnical seismic isolation (GSI) has emerged as a promising alternative or complementary approach. GSI systems aim to reduce seismic effects at the foundation level by modifying the mechanical and dynamic properties of the soil medium beneath or around the structure, thereby attenuating seismic wave propagation and reducing inertial forces transmitted to the superstructure.

Previous studies have shown that the performance of geotechnical seismic isolation depends on multiple factors, including the geometry and configuration of the isolation layer, its thickness and spatial extent, the depth of installation, and the physical–mechanical properties of the employed geomaterials. Artificial foundation layers composed of sand, gravel, crushed stone, rubber–soil mixtures, and geosynthetically reinforced soils have been reported to exhibit varying degrees of effectiveness in reducing seismic accelerations, settlements, and structural demands. However, despite the growing body of experimental and numerical research, there remains a lack of systematic understanding of how the geometric parameters and material characteristics of soil cushions influence the dynamic response of buildings under realistic seismic loading conditions.

A significant gap persists in the quantitative assessment of the combined effects of soil cushion composition, thickness, and reinforcement on both foundation performance and superstructure response. In particular, comparative evaluations of commonly used geomaterials and the role of geosynthetic reinforcement within soil cushions under strong ground motion are still limited. This uncertainty restricts the development of reliable design recommendations and hinders the broader adoption of geotechnical seismic isolation in engineering practice.

A comparison of the present results with the extensive studies conducted by Japanese researchers after the 1995 Kobe earthquake shows a strong consistency in the understanding of seismic damage mechanisms associated with near-fault ground motions and soil amplification effects. Japanese investigations demonstrated that severe structural damage was largely caused by amplified ground motions and velocity pulses, particularly in areas with soft soil deposits. The results of this study complement these findings by showing that geotechnical seismic isolation in the form of engineered soil cushions can effectively reduce the transmission of such amplified motions to the structure. By dissipating part of the seismic energy within the soil mass, the proposed approach leads to lower acceleration demands at both the foundation and superstructure levels. This suggests that, in addition to traditional structural strengthening strategies widely adopted in Japan, purposeful modification of soil–structure interaction represents a practical and cost-effective lesson derived from the Kobe earthquake for improving seismic resilience in similar seismically active regions (**Nishino et al., 2025**).

The present study addresses this gap by performing numerical modeling of buildings equipped with geotechnical seismic isolation in the form of soil cushions composed of different geomaterials. The central hypothesis of the research is that appropriately configured artificial foundation layers can significantly reduce seismic accelerations and settlements while maintaining acceptable foundation loads. The main objective is to evaluate the influence of geometric and physical–mechanical parameters of soil cushions, including material type, thickness, plan dimensions, and geogrid reinforcement, on the dynamic response of a building subjected to seismic excitation. The adopted strategy is based on finite element modeling of the integrated “building–foundation–soil” system under input ground motion represented by a real earthquake accelerogram.

By clarifying the mechanisms through which soil cushions modify seismic response and by identifying efficient configurations of geotechnical seismic isolation, this study aims to contribute to the development of cost-effective and reliable seismic protection solutions. The results are intended to support design decisions, reduce uncertainties in foundation modeling under seismic loading, and expand the practical applicability of geotechnical seismic isolation in seismically active regions.

2 LITERATURE REVIEW

The One of the key priorities of modern structural and geotechnical engineering is ensuring the seismic resistance of buildings and structures located in regions with elevated seismic hazard. Under conditions of increasing urbanization, intensive development of seismically active territories, and the tightening of regulatory requirements, the need to develop and implement new and effective methods for protecting structures against seismic actions becomes particularly critical. Destructive earthquakes of recent decades, such as the Sichuan earthquake (2008), the Hattibe earthquake in Indonesia (2018), and the Turkey earthquake (2023), have clearly demonstrated that conventional approaches to seismic-resistant design require substantial reconsideration, with special emphasis on soil–structure interaction and the dynamic behavior of soils.

Among innovative methods for mitigating seismic impacts on buildings, increasing attention in recent years has been directed toward geotechnical seismic isolation (GSI) systems. These systems are capable of partially reflecting, absorbing, or transforming seismic waves before they reach the foundation of a structure, while also exhibiting sufficient reliability and efficiency during construction and operation.

Analytical studies by (**Feng & Sutter, 2000; Senetakis et al., 2012**) on the design of geotechnical seismic isolation systems have attracted significant scientific interest and highlighted the need for further experimental and numerical investigations to facilitate the broader implementation of GSI systems in engineering practice (**Moldamuratov et al., 2023**).

According to previous studies, the effectiveness of GSI systems depends on a wide range of factors, including vertical, inclined, or horizontal configuration, rectangular or circular geometry, distance from the protected structure, as well as the thickness and depth of installation. A crucial role in the reliability and technological efficiency of GSI systems is played by the materials used beneath the foundation, including sand, gravel, and stone pebbles, rubber–soil mixtures (RSM), geofoam, and geosynthetic materials.

In recent years, a growing body of research has focused on experimental and numerical investigations of the effectiveness of various configurations of geotechnical seismic isolation in the form of soil cushions composed of different geomaterials (**Forcellini, 2020; Tsiavos et al., 2020; Xiong et al., 2011**).

The relevance of this study is обусловлена the need to enhance the reliability and stability of buildings in seismically hazardous regions while simultaneously reducing the costs associated with the implementation of engineering protective measures. The application of geotechnical seismic isolation (GSI) methods offers new opportunities in the design of foundations and substructures and expands the range of available passive seismic protection solutions (**Aldakhov et al., 2025**).

The primary objective of the numerical modeling conducted in this study is to evaluate the influence of geometric and physical–mechanical parameters of geotechnical seismic isolation (GSI) in the form of soil cushions on the dynamic response of buildings subjected to seismic loading. In particular, the study aims to investigate how variations in the thickness, composition, configuration, and position of the isolation layer within the foundation soil mass affect the level of seismic inertial forces transmitted from the ground to the building foundation (**Alenov et al., 2025; Bessimbayev et al., 2022; Okanov et al., 2025**).

The relevance of this problem formulation is further justified by the fact that, in seismically active areas–especially those characterized by alluvial, water-saturated, and stratified soils–traditional calculation schemes based on a simplified "rigid base" assumption lose their reliability (**Moldamuratov et al., 2024**). In such cases, the role of wave propagation dynamics within the soil medium becomes significantly more pronounced, necessitating the transition to modeling the "building–foundation–seismic medium" system as a single interacting system (**Banović et al., 2020; Chen et al., 2025**).

3 MATERIALS AND METHODS

The research methods include theoretical analysis, numerical modeling using the finite element method implemented in PLAXIS 2D, interpretation of the obtained results, and elements of comparison with data from engineering practice.

For the numerical simulations conducted in this study, the PLAXIS 2D software package (v.2023) was selected as one of the most widely used and scientifically validated tools in the field of soil dynamics and seismic process modeling (**S.E. Nietbay et al., 2024; Shadkam et al., 2024**).

The study adopts a comprehensive approach to evaluating the effectiveness of various types of geotechnical seismic isolation, considering variations in material composition, geometry, and depth of installation. Particular attention is given to modeling the behavior of the isolation layer using the finite element method within the PLAXIS environment, which enables the consideration of soil nonlinearity, contact interaction characteristics, and scenario-based seismic loading conditions (**Ilyassova et al., 2025; Moldamuratov et al., 2025**).

The analyzed structure is a 10-story building with a total height of 39 m and plan dimensions of 15.5 × 27 m. The structural system is a frame–shear wall system consisting of a monolithic reinforced concrete frame with stiffness diaphragms. The foundation is a raft slab with a thickness of 1.2 m, constructed from B25-grade concrete.

The geological profile of the modeled soil mass is represented by a two-layer stratified system: the upper layer consists of fill sand with a thickness of up to 3 m; the lower layer is fine sand of medium density, ranging from slightly moist to fully water-saturated, with a thickness of up to 12 m (deformation modulus approximately 19.9 MPa and density of 1.88 g/cm^3).

The total depth of the modeled soil domain is 40 m, with a horizontal extent of 150 m. These dimensions were selected to eliminate the influence of wave reflections from the model boundaries on the behavior of the system in the central region. Model parameters were defined to satisfy quasi-linear wave attenuation conditions at the lateral boundaries.

Seismic loading was applied in the form of horizontal acceleration imposed at the bottom boundary of the computational domain using a recorded accelerogram of the Kobe earthquake (1995) **(Figure 1)**, with a magnitude of 6.9 (7.3 on the Richter scale), scaled to a design peak ground acceleration of 0.25 g. The duration of seismic excitation was 20 s. The use of a real earthquake accelerogram, rather than an idealized or synthetic seismic input, ensures a more realistic representation of ground motion characteristics, including frequency content, amplitude variability, and duration effects, which cannot be fully captured by simplified model earthquakes. This approach allows for a more reliable assessment of structural response under seismic loading conditions representative of regions with seismic intensity levels of 8–9 according to the MSK-64 scale.

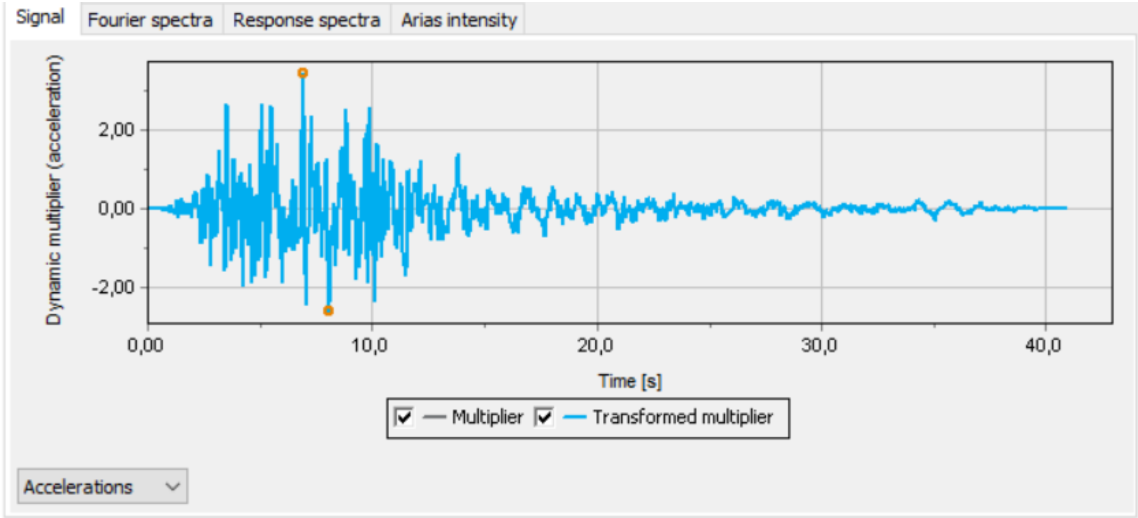

Figure 1 – Accelerogram of the Kobe earthquake (1995) (author's material)

Task 1. The first stage of the study involved calculating the settlement of the natural foundation and determining the acceleration response at the foundation level and at the top of the building under the prescribed seismic excitation based on the Kobe earthquake accelerogram. In addition, the possible increase in foundation loading under seismic actions was assessed. Numerical simulations were performed using the finite element method within an integrated "soil–foundation–structure" system, which enables realistic modeling of soil–structure interaction under dynamic loading conditions. The adopted computational scheme is shown in **Figure 2.**

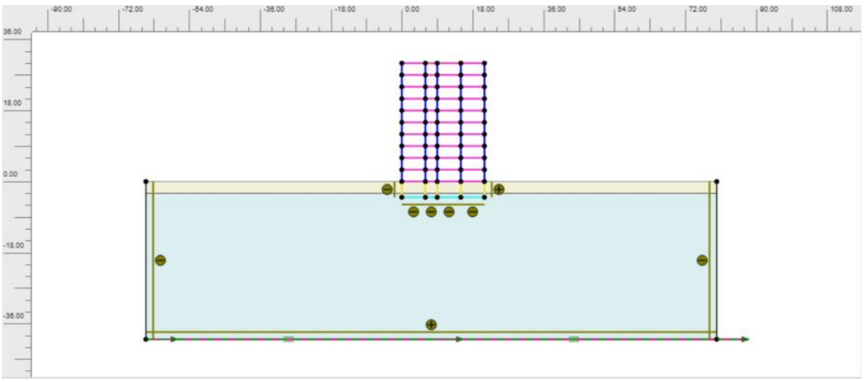

Figure 2 – Numerical model (computational scheme) (author's material)

The results of the static analysis indicate that the calculated settlement of the natural foundation reaches 141 mm, which exceeds the allowable limits specified by relevant design codes. Such excessive settlement confirms the insufficient bearing performance of the natural foundation under the considered loading conditions and highlights the necessity of implementing seismic protection or foundation improvement measures. The calculated foundation settlement is illustrated in **Figure 3.**

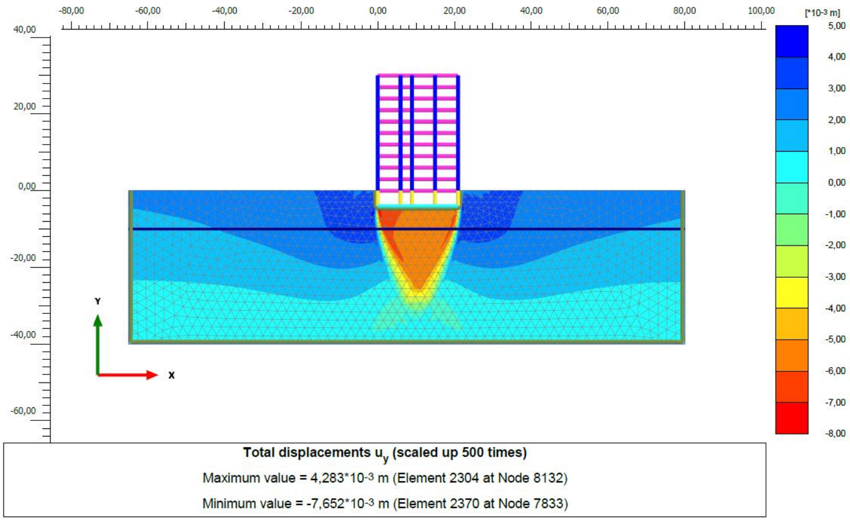

Figure 3 – Foundation settlement (141 mm) (author's material)

The foundation settlement under the design load exceeds the allowable code limits. The dynamic response analysis demonstrates a pronounced amplification of seismic effects along the height of the structure. The peak horizontal acceleration at the foundation level reaches 1.96 m/s², while the acceleration at the top of the building increases to 3.04 m/s². This increase indicates significant transmission and amplification of seismic energy from the foundation to the superstructure, which may lead to elevated inertial forces and structural damage. The acceleration time histories at the foundation level and at the top of the building are presented in **Figure 4(a)** and **Figure 4(b),** respectively.

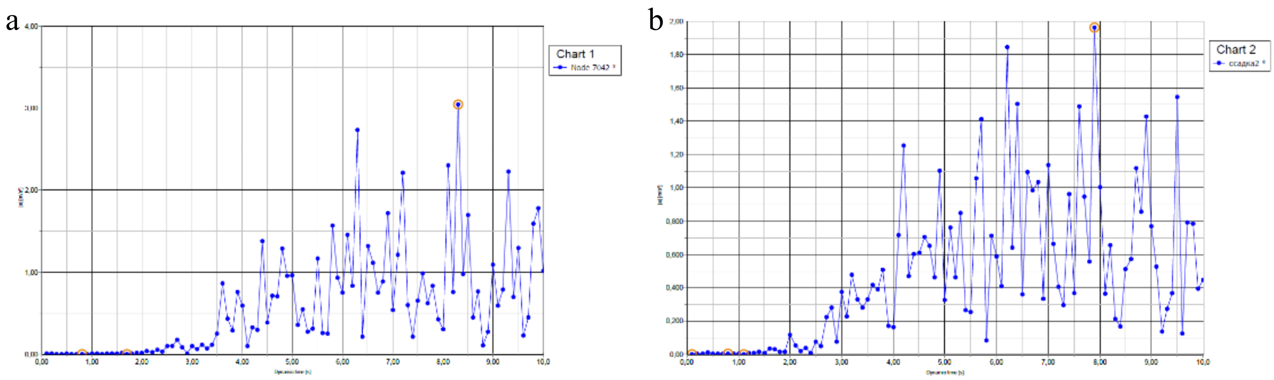

Figure 4 – Acceleration at the foundation level (1.96 m/s²) (a) and
Acceleration at the top of the building (3.04 m/s²) (b) (author's material)

The acceleration at the top of the building exceeds the acceleration at the foundation level by approximately 35%, which may adversely affect the overall structural reliability and increase seismic demands on the load-bearing elements. Task 2. The second stage of the study focuses on investigating the effectiveness of soil cushions composed of different geomaterials, including coarse-grained sand, pebble gravel, and crushed stone. For all variants, a soil cushion thickness of 3 m was adopted, while the plan dimensions of the cushion were taken as 1.5A relative to the building width A. For the case of a coarse sand cushion, the numerical model of the integrated "soil–foundation–structure" system is shown in **Figure 5.**

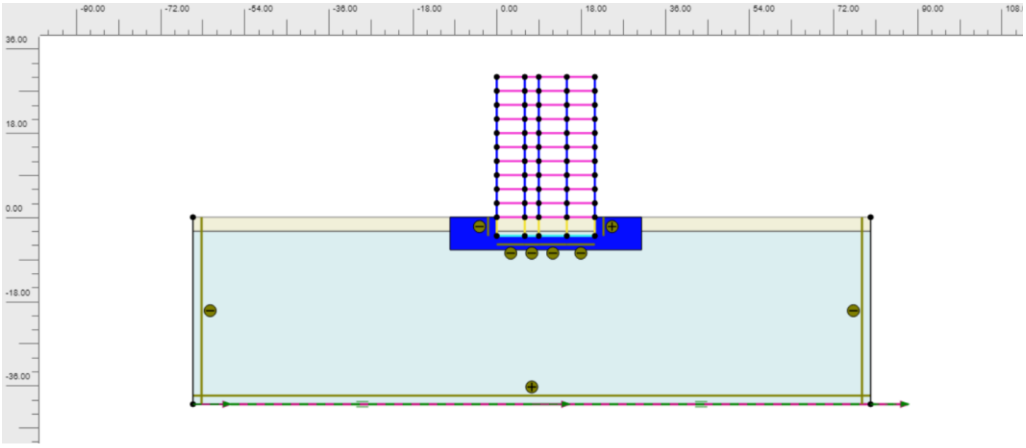

Figure 5 – Numerical model (coarse sand cushion) (author's material)

The physical and mechanical properties assigned to the coarse-grained sand layer in the numerical model were determined based on representative laboratory and reference data. These parameters govern the stiffness, strength, and damping behavior of the soil cushion under seismic loading conditions and are summarized in **Figure 6.**

General | Parameters | Groundwater | Thermal | Interfaces | Initial

Property	Unit	Value
Stiffness		
E'	kN/m²	45,00E3
ν' (nu)		0,3000
Alternatives		
G	kN/m²	17,31E3
E_{oed}	kN/m²	60,58E3
Strength		
c'_{ref}	kN/m²	0,000
φ' (phi)	°	30,00
ψ (psi)	°	0,000
Velocities		
V_s	m/s	92,14
V_p	m/s	172,4

Figure 6 – Physical and mechanical properties of sand (author's material)

The results of the static analysis demonstrate that the introduction of a coarse sand soil cushion leads to a noticeable reduction in foundation settlement. The calculated settlement decreases to −129 mm, which is significantly lower compared to the natural foundation case and indicates improved load distribution and deformation control. The corresponding settlement pattern is illustrated in **Figure 7.**

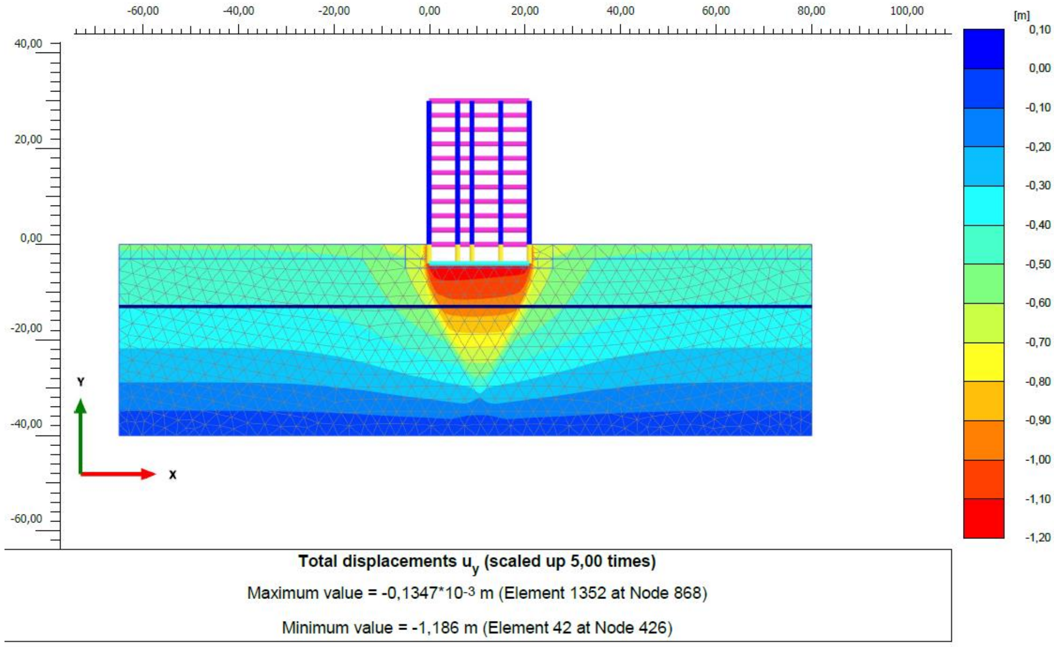

Figure 7 – Foundation settlement (−129 mm) for the coarse sand cushion (author's material)

The dynamic response analysis shows a substantial decrease in horizontal accelerations after introducing the coarse sand cushion. The peak acceleration at the foundation level is reduced to 1.595 m/s², while the acceleration at the top of the building decreases to 2.922 m/s². These results confirm the damping effect of the soil cushion and its ability to attenuate seismic energy transmitted to the superstructure. The acceleration responses are presented in **Figure 8(a)** and **Figure 8(b).**

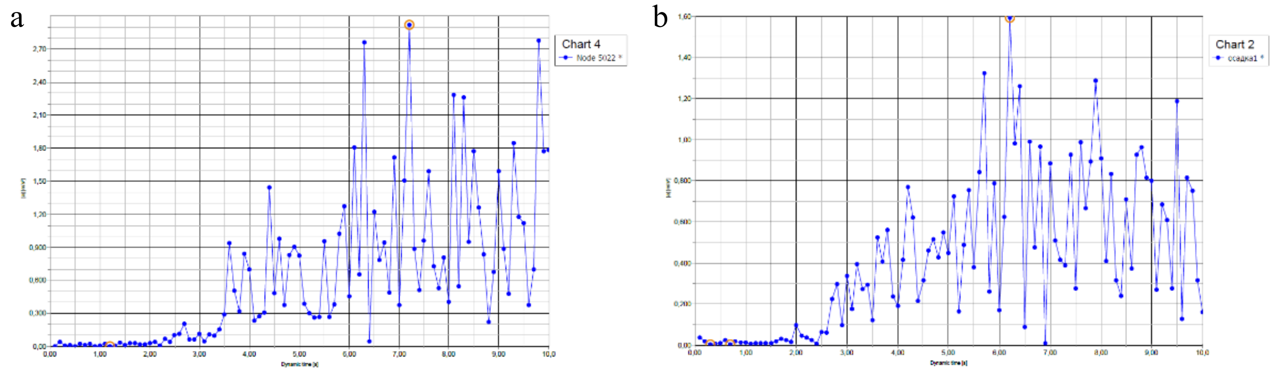

Figure 8 – Acceleration at the foundation level (1.595 m/s²) (a) and
Acceleration at the top of the building (2.922 m/s²) (b) (author's material)

An assessment of the foundation loading indicates that the introduction of the soil cushion affects the stress state of the foundation under seismic conditions. The foundation pressure under the main load combination is 18.7 t/m², while under the special (seismic) load combination it increases to 20.5 t/m². This increase reflects the influence of seismic actions and should be considered in foundation design. The distribution of foundation loads for both load combinations is shown in **Figure 9(a)** and **Figure 9(b).**

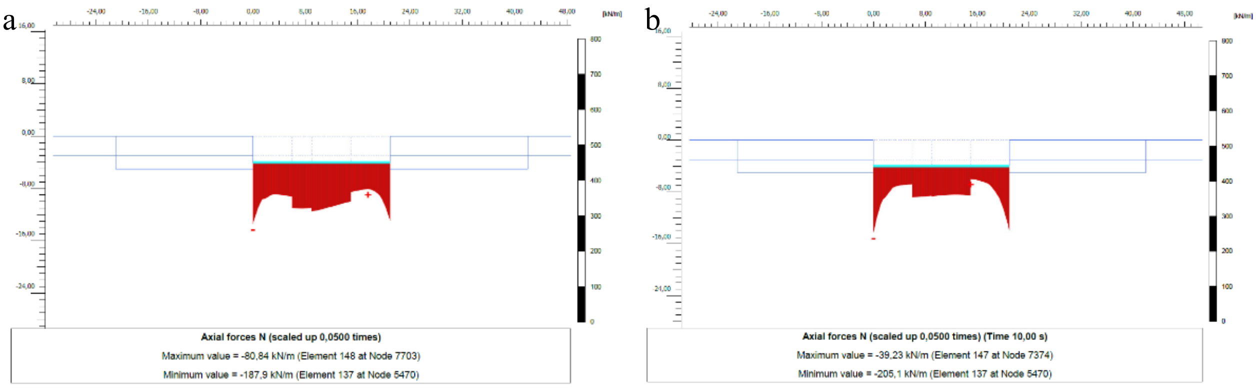

Figure 9 – Foundation load under the main load combination: 18.7 t/m² (a)
Foundation load under the special (seismic) load combination: 20.5 t/m² (b) (author's material)

For the pebble gravel cushion, a numerical model of the integrated "soil–foundation–structure" system was developed to evaluate its seismic performance. The adopted computational scheme reflects the geometric configuration of the building, foundation, and isolation layer and is presented in **Figure 10.**

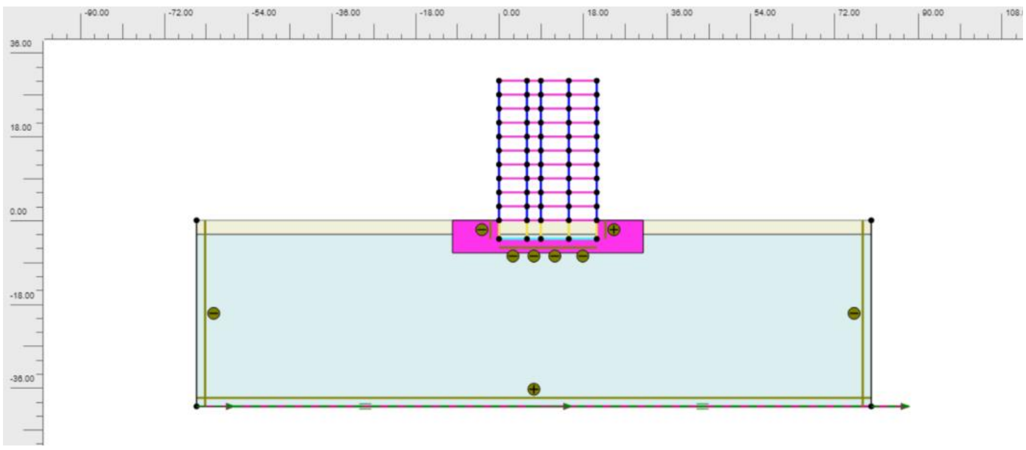

Figure 10 – Numerical model (pebble gravel) (author's material)

The physical and mechanical properties assigned to the pebble gravel material were selected to represent its stiffness, strength, and damping characteristics under dynamic loading conditions. These parameters govern the seismic response of the isolation layer and are summarized in **Figure 11.**

General | Parameters | Groundwater | Thermal | Interfaces | Initial

Property	Unit	Value
Stiffness		
E'	kN/m²	60,00E3
ν' (nu)		0,3000
Alternatives		
G	kN/m²	23,08E3
E_{oed}	kN/m²	80,77E3
Strength		
c'_{ref}	kN/m²	10,00
φ' (phi)	°	20,00
ψ (psi)	°	0,000
Velocities		
V_s	m/s	101,4
V_p	m/s	189,8

Figure 11 – Physical and mechanical properties of pebble gravel (author's material)

The results of the static analysis indicate that the use of a pebble gravel cushion leads to a foundation settlement of −125.57 mm, which is slightly lower than that obtained for the coarse sand cushion. This reduction demonstrates the higher stiffness and improved load-bearing behavior of the pebble gravel layer. The calculated settlement distribution is shown in **Figure 12.**

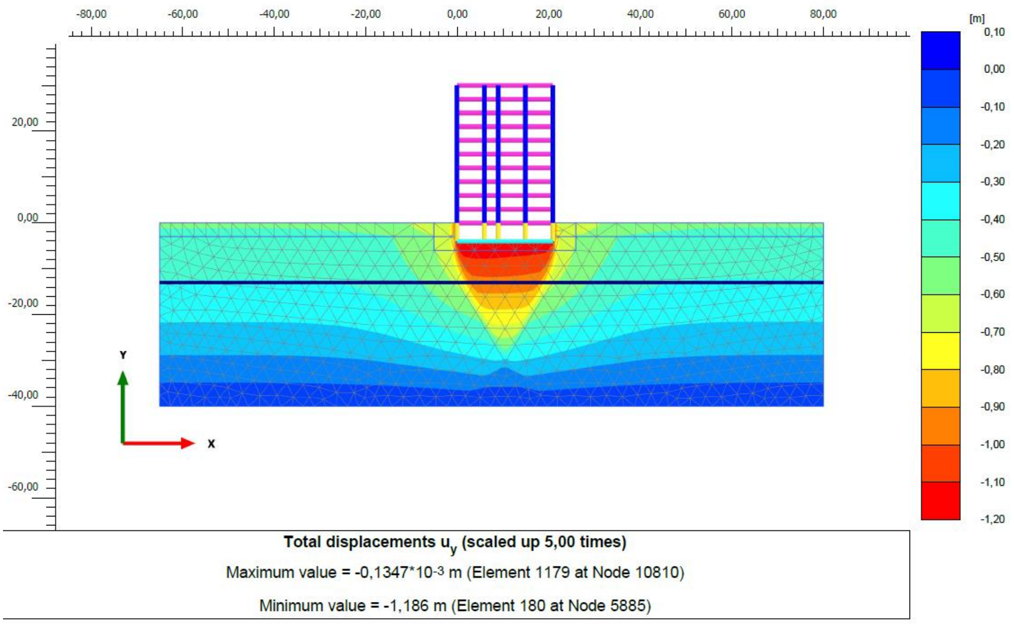

Figure 12 – Foundation settlement (−125.57 mm) (author's material)

The dynamic response analysis reveals a further decrease in horizontal accelerations compared to the coarse sand case. The peak acceleration at the foundation level is reduced to 1.437 m/s², while the acceleration at the top of the building decreases to 2.754 m/s². These results confirm the enhanced seismic attenuation capacity of the pebble gravel cushion. The acceleration responses at the foundation level and at the top of the structure are illustrated in **Figure 13(a)** and **Figure 13(b)**, respectively.

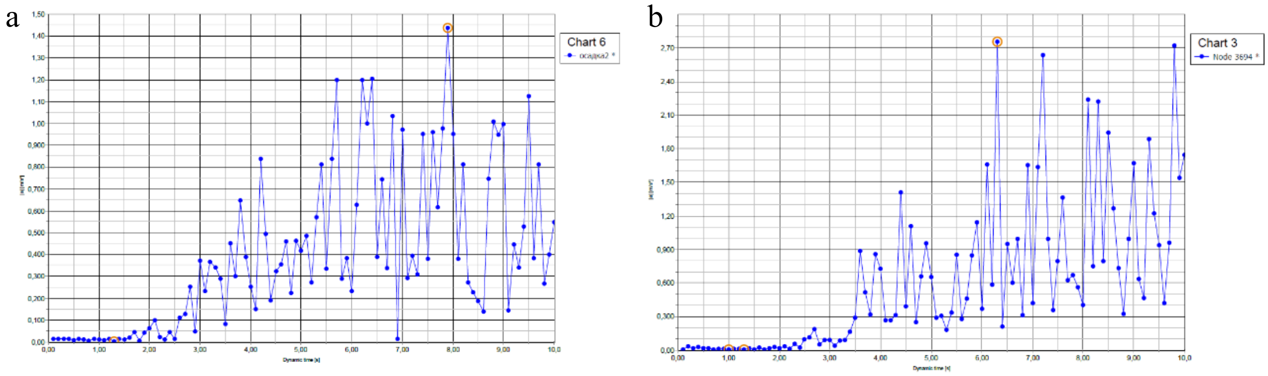

Figure 13 – Acceleration at the foundation level (1.437 m/s²) (a)
and Acceleration at the top of the building (2.754 m/s²) (b) (author's material)

An assessment of foundation loading shows that the foundation pressure under the main load combination reaches 20.3 t/m², while under the special (seismic) load combination it slightly increases to 20.4 t/m². The relatively small difference between these values indicates a stable load response of the foundation system when subjected to seismic excitation. The corresponding foundation load distributions are presented in **Figure 14(a)** and **Figure 14(b).**

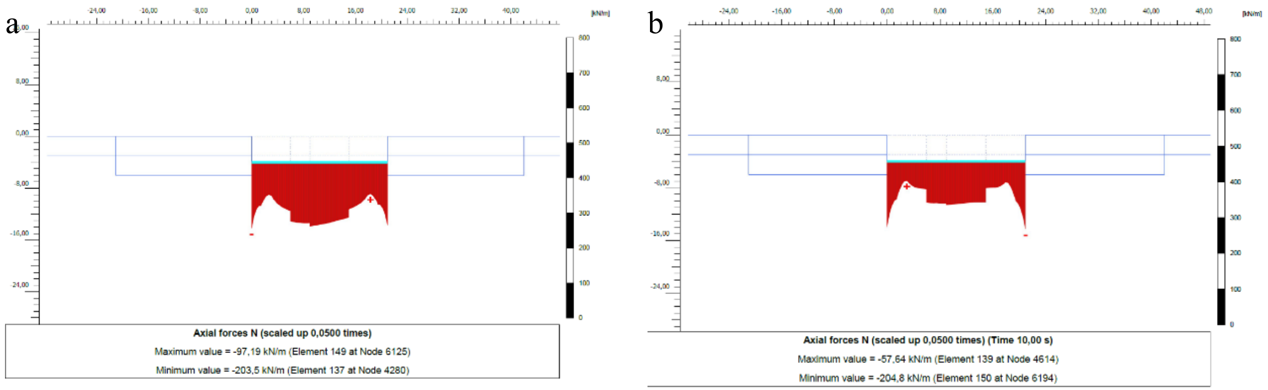

Figure 14 – Foundation load under the main load combination: 20.3 t/m² (a) and
foundation load under the special (seismic) load combination: 20.4 t/m² (b) (author's material)

For the crushed stone cushion, a numerical model of the integrated "soil–foundation–structure" system was developed to assess its seismic performance. The adopted computational scheme reflects the geometric configuration of the building, foundation, and isolation layer and is presented in **Figure 15.**

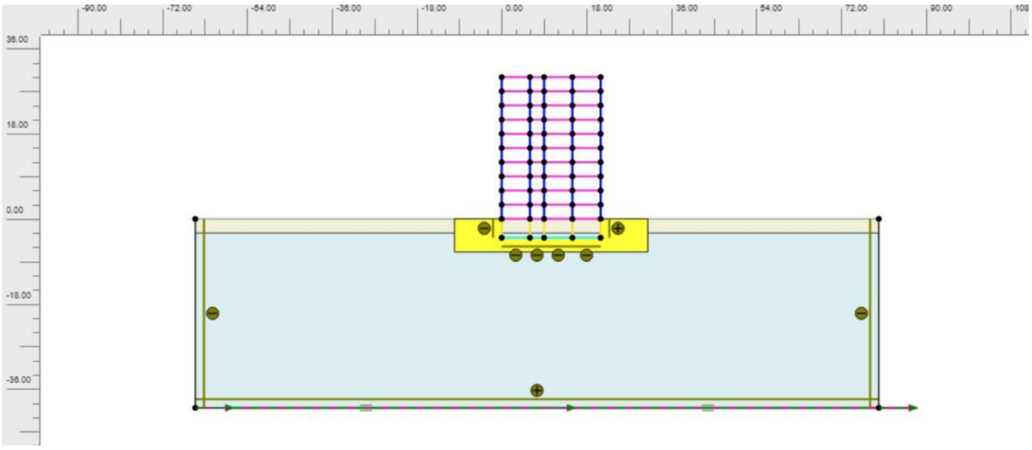

Figure 15 – Numerical model (computational scheme) (author's material)

The physical and mechanical properties assigned to the crushed stone material were selected to represent its stiffness, strength, and deformation characteristics under dynamic loading conditions. These parameters play a key role in defining the seismic response of the foundation system and are summarized in **Figure 16.**

General | Parameters | Groundwater | Thermal | Interfaces | Initial

Property	Unit	Value
Stiffness		
E'	kN/m²	100,0E3
ν' (nu)		0,3000
Alternatives		
G	kN/m²	38,46E3
E_{oed}	kN/m²	134,6E3
Strength		
c'_{ref}	kN/m²	10,00
φ' (phi)	°	20,00
ψ (psi)	°	0,000
Velocities		
V_s	m/s	131,0
V_p	m/s	245,0

Figure 16 – Physical and mechanical properties of crushed stone (author's material)

The results of the static analysis indicate that the foundation settlement for the crushed stone cushion reaches −126 mm. This value is comparable to those obtained for the coarse sand and pebble gravel cushions, indicating a similar level of deformation control under static loading conditions. The calculated settlement distribution is shown in **Figure 17.**

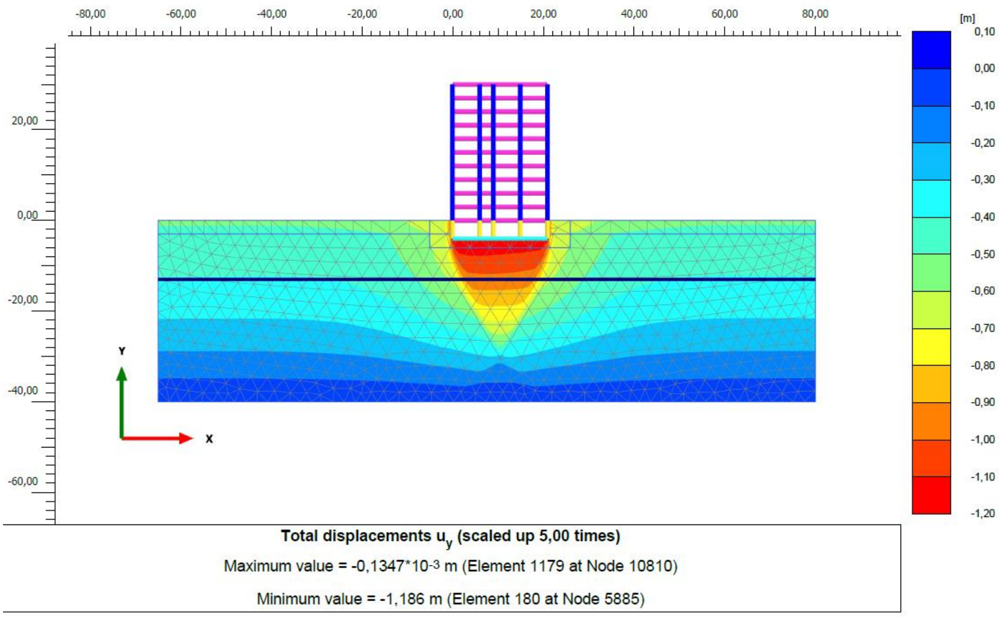

Figure 17 – Foundation settlement (−126 mm) (author's material)

The dynamic response analysis shows that the peak horizontal acceleration at the foundation level reaches 1.676 m/s², while the acceleration at the top of the building increases to 2.896 m/s². Compared to the other geomaterials considered, the crushed stone cushion exhibits slightly higher acceleration values at the superstructure level, reflecting differences in stiffness and energy dissipation capacity. The acceleration responses are illustrated in **Figure 18(a)** and **Figure 18(b)**.

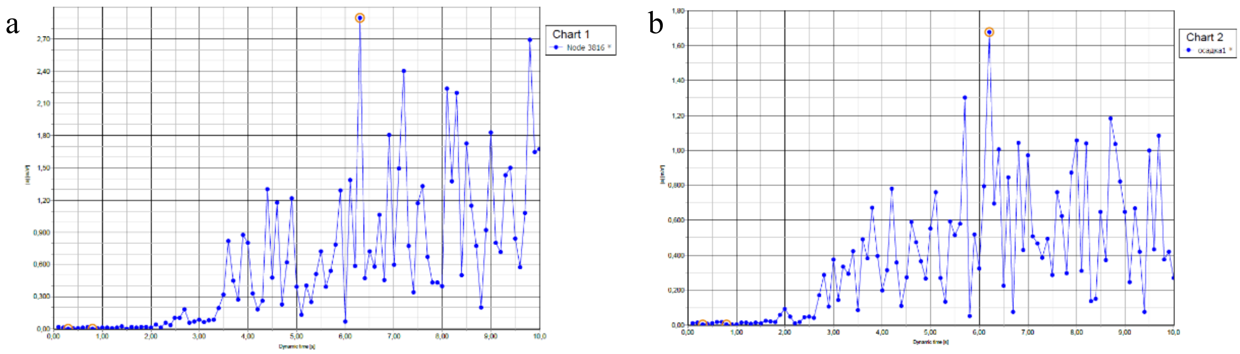

Figure 18 – Acceleration at the foundation level (1.676 m/s²)(a) and acceleration at the top of the building (2.896 m/s²) (b) (author's material)

An assessment of foundation loading reveals that the foundation pressure under the main load combination reaches 22.7 t/m². Under the special (seismic) load combination, the foundation load decreases to 17.8 t/m², indicating a redistribution of stresses within the foundation system during seismic excitation. The corresponding load distributions are presented in **Figure 19(a)** and **Figure 19(b).**

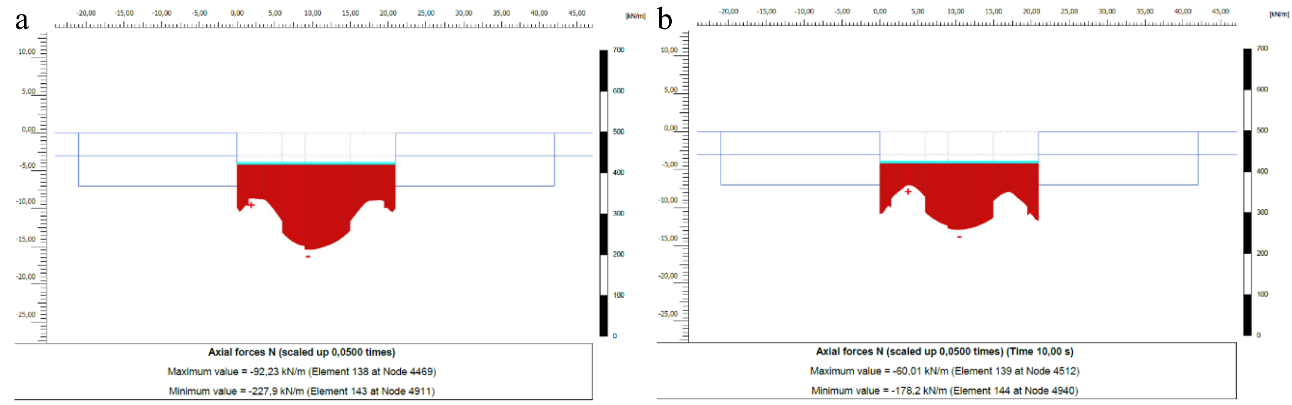

Figure 19 – Foundation load under the main load combination: 22.7 t/m² (a) and foundation load under the special (seismic) load combination: 17.8 t/m² (b).) (author's material)

A comparative analysis of all three soil types shows that the foundation settlement values are nearly identical, with only minor differences observed. The lowest settlement was recorded for the pebble gravel cushion, while the crushed stone cushion exhibited an acceleration at the top of the building that was approximately 5% higher than the corresponding values obtained for the other geomaterials. Task 3. The next stage of the study investigates the seismic response of the building when a soil cushion reinforced with geogrid interlayers is introduced. A configuration consisting of a coarse sand cushion reinforced with geogrids placed at depths of 1 m and 2 m within the soil cushion was considered for further numerical analysis.

To further enhance the seismic performance of the soil cushion, a configuration consisting of coarse sand reinforced with two geogrid layers was investigated. The numerical model of the integrated "soil–foundation–structure" system, incorporating geogrid layers placed at depths of 1 m and 2 m within the soil cushion, is presented in **Figure 20.**

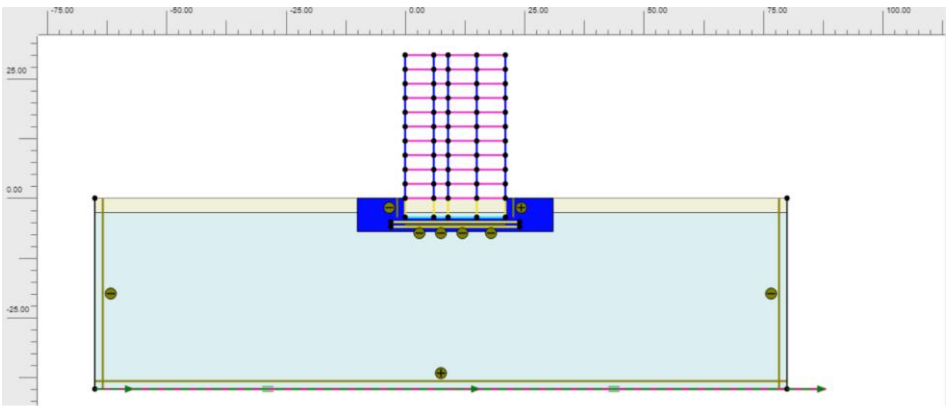

Figure 20 – Numerical model of the coarse sand cushion reinforced with two geogrid layers) (author's material)

The main physical and mechanical characteristics of the geogrid reinforcement adopted in the numerical analysis were selected to represent its tensile stiffness and interaction with the surrounding soil. These parameters govern the load transfer and stress redistribution mechanisms within the reinforced soil cushion and are shown in **Figure 21.**

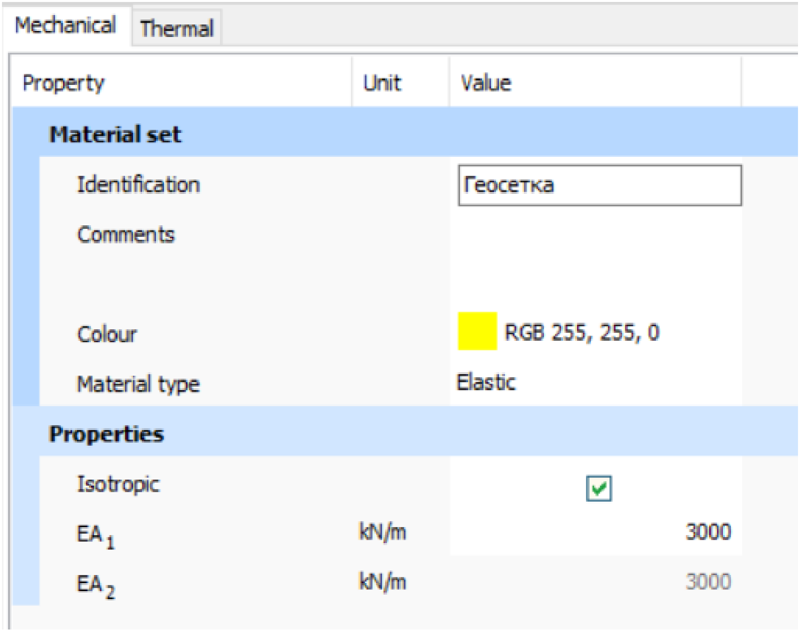

Figure 21 – Characteristics of the geogrid layers) (author's material)

The results of the static analysis indicate that the introduction of geogrid layers leads to a noticeable improvement in foundation performance. The calculated foundation settlement is reduced to −114 mm, which is approximately 10% lower compared to the unreinforced coarse sand cushion. This reduction demonstrates the effectiveness of geogrid reinforcement in controlling deformations of the foundation system. The corresponding settlement distribution is illustrated in **Figure 22.**

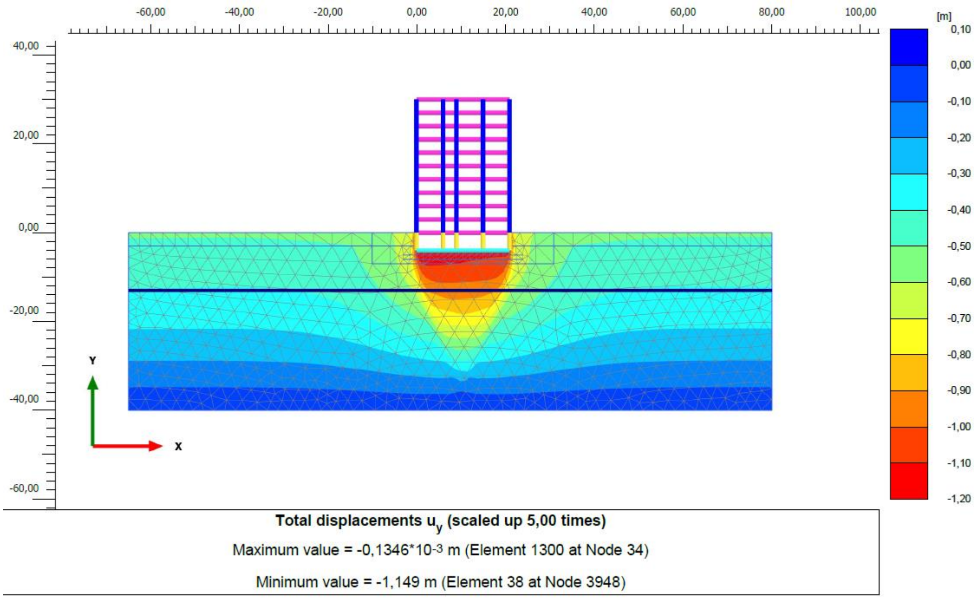

Figure 22 – Foundation settlement (−114 mm) for the coarse sand cushion reinforced with geogrid layers) (author's material)

The dynamic response analysis reveals a further reduction in seismic accelerations due to the combined effect of the soil cushion and geogrid reinforcement. The peak horizontal acceleration at the foundation level decreases to 1.389 m/s², while the acceleration at the top of the building is reduced to 2.585 m/s². These results confirm the enhanced damping capacity of the reinforced soil cushion. The acceleration responses are presented in **Figure 23(a)** and **Figure 23(b).**

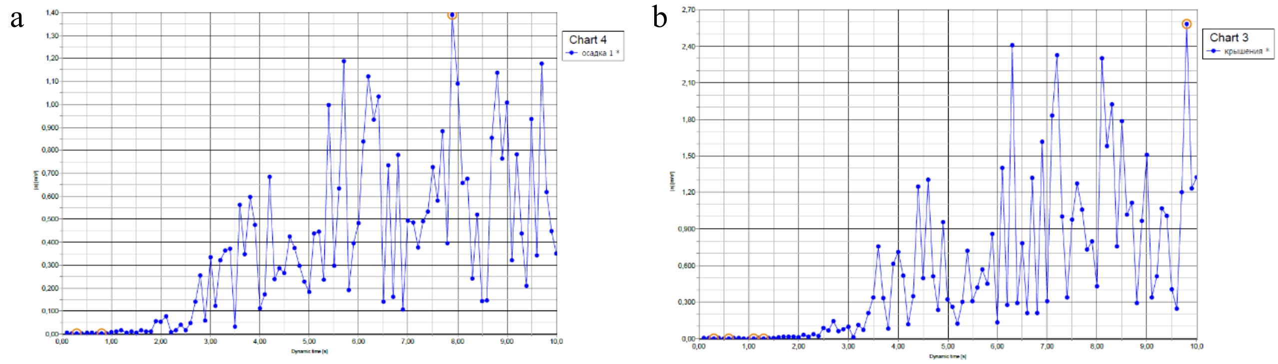

Figure 23 – Acceleration at the foundation level (1.389 m/s²) (a) and
acceleration at the top of the building (2.585 m/s²) (b)) (author's material)

A reduction in acceleration is observed for the foundation system reinforced with geogrid layers. An assessment of foundation loading shows that the foundation pressure under the main load combination reaches 21.0 t/m². Under the special (seismic) load combination, the foundation load increases to 24.9 t/m², reflecting the mobilization of additional forces within the reinforced soil system during seismic excitation. The corresponding load distributions are shown in **Figure 24(a)** and **Figure 24(b).**

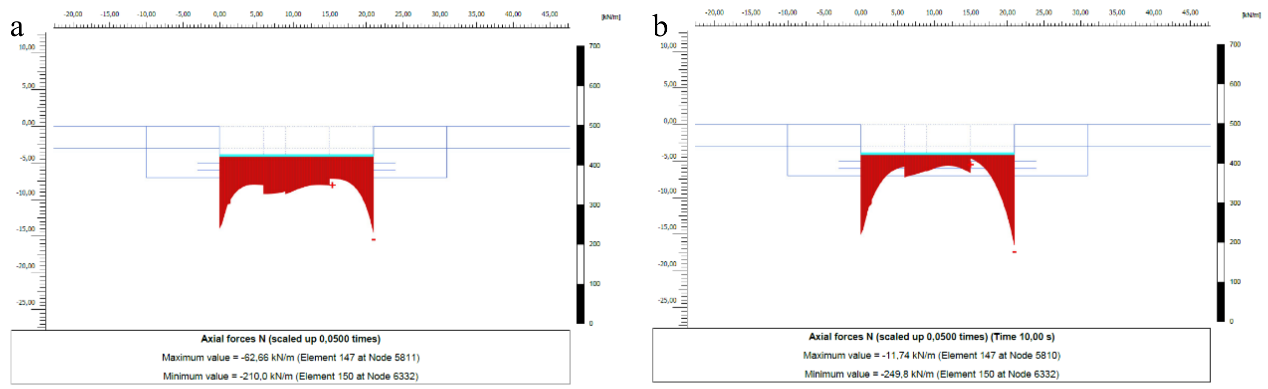

Figure 24 – Foundation load under the main load combination: 21.0 t/m² (a) and
foundation load under the special (seismic) load combination: 24.9 t/m² (b)) (author's material)

An analysis of internal forces in the geogrid layers indicates that tensile forces reach 2.509 kN/m under the main load combination and increase significantly to 46.49 kN/m under seismic loading. This substantial increase highlights the active role of geogrid reinforcement in stress redistribution and energy dissipation within the soil cushion during seismic excitation. The distribution of tensile forces in the geogrid layers is illustrated in **Figure 25(a)** and **Figure 25(b).**

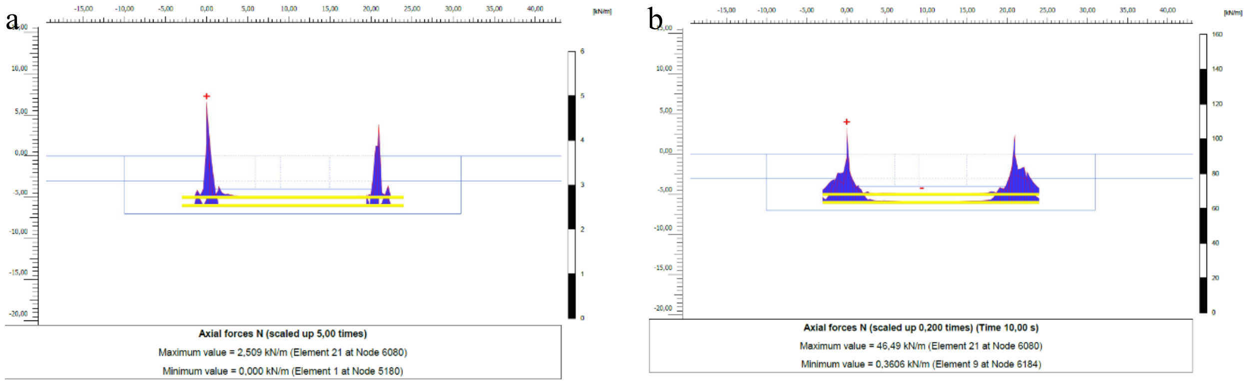

Figure 25 – Forces under the main load combination: 2.509 kN/m (a) and forces under the special (seismic) load combination: 46.49 kN/m (b)) (author's material)

4 RESULTS AND DISCUSSION

The numerical simulation results clearly demonstrate that the thickness and spatial dimensions of the soil cushion play a decisive role in governing the seismic response of the "foundation–structure" system. For a soil cushion width equal to 1.5A (where A is the building width), a consistent reduction in foundation settlement is observed as the cushion thickness increases **(Figure 26).** This trend is associated with the redistribution of stresses within the foundation soil and the increased ability of the isolation layer to accommodate deformations induced by seismic loading.

The analysis indicates that the optimal soil cushion thickness for the considered building configuration lies in the range of 2.5–3.0 m. Within this interval, foundation settlements remain below the allowable design limits prescribed by relevant standards, ensuring acceptable serviceability performance. Further increases in cushion thickness beyond this range result in only marginal reductions in settlement, indicating diminishing returns in terms of settlement mitigation efficiency.

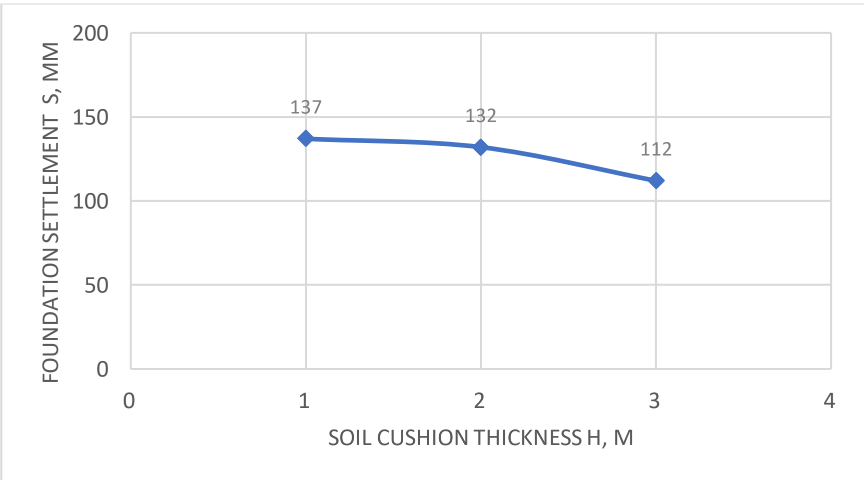

Figure 26 – Relationship between foundation settlement and soil cushion thickness) (author's material)

At the same time, the results reveal an important counteracting effect: under seismic loading conditions, an increase in soil cushion thickness leads to an increase in foundation loads, as shown in **Figure 27**. This increase reaches approximately 10% compared to the reference case and is attributed to changes in stiffness contrast and inertial force redistribution within the isolation system. The soil cushion, while reducing accelerations and deformations, participates actively in the transmission of vertical and horizontal forces to the foundation slab.

From a design perspective, this finding is of critical importance. It suggests that the beneficial effects of soil cushions on seismic response must be balanced against the associated increase in foundation loads. Accordingly, when implementing geotechnical seismic isolation in the form of soil cushions, the normative design loads for foundations should be increased by approximately 10–20% to account for seismic effects and to maintain an adequate margin of structural safety.

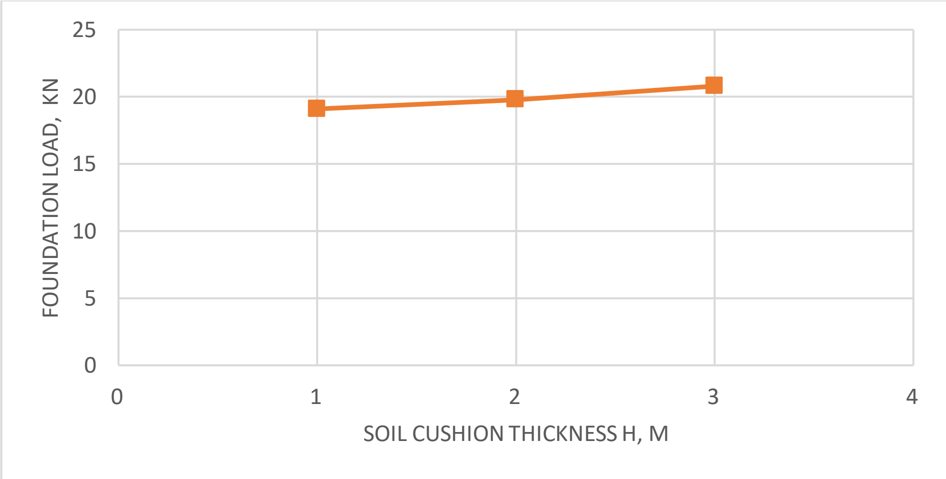

Figure 27 – Relationship between foundation load and soil cushion thickness) (author's material)

An analysis of acceleration records at the foundation level and at the top of the building further confirms the effectiveness of increasing soil cushion thickness. As illustrated in **Figure 28,** a pronounced reduction in horizontal acceleration amplitudes is observed at the foundation level with increasing thickness of the isolation layer. This reduction reflects the ability of the soil cushion to act as a filtering medium, attenuating high-frequency components of seismic motion before they are transmitted to the structure.

A similar trend is observed at the top of the building, where both acceleration amplitudes and displacement demands decrease as the thickness of the soil cushion increases. This behavior indicates a reduction in inertial forces acting on the superstructure and, consequently, a lower demand on structural elements. The observed response can be explained by the transformation of seismic waves as they propagate through the soil cushion, during which part of the seismic energy is dissipated due to material damping and the development of inelastic (plastic) deformations within the isolation layer.

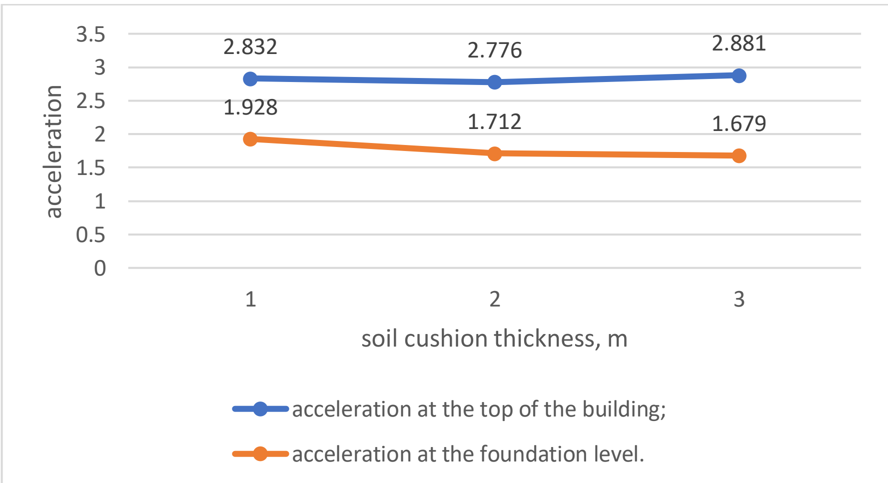

Figure 28 – Dependence of acceleration on soil cushion thickness) (author's material)

Overall, the results demonstrate that properly designed soil cushions not only reduce foundation settlement and seismic accelerations but also modify the dynamic characteristics of the soil–structure system. The combined effect leads to a more favorable seismic response, characterized by lower acceleration demands, reduced displacements, and controlled stress redistribution. These findings highlight the importance of optimizing both the thickness and plan dimensions of soil cushions in geotechnical seismic isolation systems to achieve an optimal balance between seismic performance improvement and foundation load capacity.

5 CONCLUSIONS

1. The numerical analysis demonstrated that the introduction of a damping layer with a thickness of 1.5–2.0 m between the foundation base and the underlying soil allows: a reduction in peak horizontal acceleration (PGA) by 35–47%; a decrease in the maximum horizontal displacements at the top of the building by 30–42%; localization of deformations within the isolation layer; a reduction in the risk of accumulation of plastic deformations in the foundation soil.
2. The study showed that the highest efficiency is achieved by combined solutions incorporating sand–gravel mixtures and geosynthetic interlayers. It was established that the isolation layer should have a horizontal or slightly stratified configuration, with a width of 1.2–1.5 times the foundation width and placement directly beneath the foundation base.
3. The practical significance of the study lies in the fact that the proposed solutions can be integrated into standard design practices, applied in the retrofitting of existing buildings, and adapted to various geotechnical conditions.
4. An analytical comparison of the costs associated with soil-based isolation and conventional seismic protection methods (such as rubber–metal bearings, pendulum-type isolators, and the integration of structural dampers) indicates that the cost of implementing a soil isolation layer typically ranges from 12% to 20% of the total foundation construction cost. In contrast, the installation of structural seismic isolation systems increases the overall project budget by approximately 25–35%. Thus, even in the most cost-intensive configurations (e.g., those employing rubber–sand mixtures and geosynthetics), the expenses associated with geotechnical seismic isolation (GSI) are 30–40% lower than those of structural isolation systems while providing a comparable reduction in inertial seismic loads.
5. Numerical modeling of geotechnical seismic isolation (GSI) for buildings confirms the high effectiveness of the proposed approach and supports its integration into modern engineering practice as an affordable, reliable, and adaptive technology for mitigating seismic risks.

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