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Comparative Analysis of the Damping Properties of Soil-Rubber Geomaterials for Seismic Isolation of Road Structures

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Abstract

The article focuses on the investigation of the effectiveness of soil-rubber composites used as damping layers for geotechnical seismic isolation in road structures. The main objective is to minimize the adverse impact of seismic waves on infrastructure by introducing an intermediate, energy-absorbing layer between the natural soil base and the foundation of the structure. This innovative approach aims to enhance the seismic resilience of transport systems, especially in earthquake-prone regions.

Laboratory experiments were conducted using accelerometric analysis methods to measure the amplitude and frequency of vibrations transmitted through natural soil and soil modified with rubber crumb. The results demonstrated that the inclusion of rubber particles significantly improves the damping properties of the soil. Specifically, the soil-rubber layer reduced peak ground acceleration by approximately 33% compared to unmodified natural soil. This confirmed the composite material's ability to absorb and dissipate seismic energy effectively.

Additionally, the study emphasizes the environmental benefits of using rubber crumb derived from recycled tires. This approach not only provides a technically efficient solution for seismic isolation but also contributes to sustainable waste management by reusing non-biodegradable materials that would otherwise pose environmental hazards.

The developed methodology offers a practical and cost-effective strategy for improving the reliability and safety of road structures in seismically active areas. The experimental data support the implementation of soil-rubber composite technology in engineering practice as an innovative solution that combines structural performance with environmental sustainability.

Keywords: seismic isolation, damping layer, road structures, accelerometric analysis.

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Техникалық ғылымдар. Сәулет және құрылыс

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Жол құрылыстарының сейсмикалық оқшаулауына арналған топырақ-резеңке геоматериалдарының демпферлік қасиеттерінің салыстырмалы талдауы

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Түйіндеме
Мақала жол құрылыстары үшін геотехникалық сейсмоизоляцияда қолданылатын топырақ-резеңке композиттерінің тиімділігін зерттеуге арналған. Зерттеудің негізгі мақсаты – құрылымның іргетасы мен табиғи топырақ негізі арасындағы энергияны сіңіретін аралық қабатты енгізу арқылы сейсмикалық толқындардың инфрақұрылымға әсерін азайту. Бұл инновациялық тәсіл әсіресе сейсмикалық белсенді аймақтарда көлік жүйелерінің сейсмиялық төзімділігін арттыруға бағытталған.
Лабораториялық тәжірибелер акселерометриялық талдау әдістері арқылы жүргізілді, бұл табиғи топырақ пен резеңке түйіршіктері қосылған топырақ арқылы берілетін тербелістердің амплитудасы мен жиілігін өлшеуге мүмкіндік берді. Нәтижелер резеңке бөлшектердің қосылуы топырақтың демпферлік қасиеттерін едәуір арттыратынын көрсетті. Атап айтқанда, топырақ-резеңке қабаты пішінді үдеуді табиғи топырақпен салыстырғанда шамамен 33%-ға азайтты, бұл материалдың сейсмикалық энергияны тиімді сіңіріп, сейілту қабілетін дәлелдейді.
Сонымен қатар, зерттеу қайта өңделген шиналардан алынған резеңке түйіршіктерін пайдаланудың экологиялық артықшылықтарын көрсетеді. Бұл әдіс техникалық жағынан тиімді ғана емес, сонымен қатар қайта өңделмейтін қалдықтарды қолдану арқылы экологиялық тұрақтылықты арттыруға ықпал етеді.
Зерттеу барысында жасалған әдістеме сейсмикалық қауіпті аймақтардағы жол құрылымдарының сенімділігі мен қауіпсіздігін арттыру үшін тиімді әрі үнемді шешім бола алады. Алынған деректер топырақ-резеңке композиттік технологиясын инженерлік тәжірибеде қолдануға ұсынуға негіз береді.
Түйін сөздер: сейсмикалық оқшаулау, демпферлік қабат, жол құрылыстары, акселерометриялық талдау.

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Технические науки. Архитектура и строительство

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Сравнительный анализ демпфирующих свойств грунто-резиновых геоматериалов для сейсмической изоляции дорожных сооружений

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Аннотация
Статья посвящена исследованию эффективности почвенно-резиновых композитов, используемых в качестве демпфирующих слоёв для геотехнической сейсмоизоляции дорожных сооружений. Основной целью является снижение негативного воздействия сейсмических волн на инфраструктуру путём введения промежуточного, поглощающего энергию слоя между естественным грунтовым основанием и фундаментом сооружения. Этот инновационный подход направлен на повышение сейсмостойкости транспортных систем, особенно в сейсмоактивных районах.
Лабораторные эксперименты были проведены с использованием методов акселерометрического анализа для измерения амплитуды и частоты колебаний, передающихся через природный грунт и грунт с добавлением резиновой крошки. Результаты показали, что включение резиновых частиц существенно улучшает демпфирующие свойства почвы. В частности, слой почвенно-резинового композита снижал пиковое ускорение на ~33 % по сравнению с необработанным грунтом, что подтвердило способность материала эффективно поглощать и рассеивать сейсмическую энергию.
Кроме того, исследование подчёркивает экологические преимущества использования резиновой крошки, полученной из переработанных шин. Этот подход является не только технически эффективным решением для сейсмоизоляции, но и способствует устойчивому управлению отходами, повторно используя трудноразлагаемые материалы.
Разработанная методика представляет собой практичную и экономически выгодную стратегию повышения надёжности и безопасности дорожных конструкций в сейсмоопасных зонах. Полученные данные поддерживают внедрение технологии почвенно-резиновых композитов в инженерную практику как инновационного решения, сочетающего структурную эффективность и экологическую устойчивость.
Ключевые слова: сейсмоизоляция, демпфирующий слой, дорожные сооружения, акселерометрический анализ.

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Introduction

Intense seismic activity poses a serious threat to transport infrastructure, especially in regions with high seismicity. In the Republic of Kazakhstan, a significant portion of the territory is located in seismically hazardous zones, particularly the southern and southeastern regions. Historical earthquakes (Almaty 1911, Tashkent 1966, Zhambyl Region 2003, among others) have demonstrated the vulnerability of engineering structures built using traditional technologies. Damage and destruction of road bridges, overpasses, viaducts, and other elements of the transport network during strong earthquakes lead to severe socio-economic consequences. Even when construction standards are followed, conventional design solutions may prove insufficient. Common problems include low density and strength of the subgrade, soil heterogeneity, high groundwater levels, poor drainage, and resonance effects between seismic waves and the natural vibrations of the structure. Statistics show that a significant proportion of structural damage is concentrated in the "soil–foundation" interface. Therefore, it is highly relevant to develop solutions capable of mitigating seismic impacts before the vibrations are transmitted to the superstructure.

The concept of geotechnical seismic isolation offers a fundamentally different approach to seismic protection compared to traditional methods of structural reinforcement. The core idea lies in creating a special damping layer between the building foundation and the natural subgrade, which partially absorbs and dissipates the energy of incoming seismic waves. Such a layer can be composed of soil mixtures with materials possessing enhanced damping properties—such as soil–rubber, soil–bitumen, soil–silicate, soil–cement, and other composite geomaterials. Their effectiveness is ensured by a combination of a low shear modulus (allowing the layer to deform and cushion seismic vibrations) and high internal friction (promoting rapid attenuation of the wave within the layer). As a result, the peak accelerations transmitted to the structure are significantly reduced, thereby limiting horizontal displacements and dynamic loads on the superstructure [1].

In recent years, geotechnical seismic isolation has undergone successful testing in both laboratory and field conditions. Vibration table experiments and numerical modeling have shown that the inclusion of soil–rubber mixture layers can reduce the transmission of seismic energy to the building superstructure by 30–60% [2]. International implementation of such systems already includes real-world projects: for example, damping cushions made of glass beads and sand, gravel–rubber filtering layers beneath foundations, and deformable bases applied in Japan, Italy, China, New Zealand, and South Korea [3–6]. It has been noted that the use of geosynthetic layers, pile rows, and other barrier elements is also effective in attenuating seismic waves within the soil [5, 6]. Recent studies confirm that geotechnical seismic isolation can enhance the seismic resistance of both new and existing structures while remaining economically viable due to the availability of local materials and reduced repair costs [4].

Particular interest lies in the use of recycled materials, such as rubber crumb from used tires, in damping layers. This approach addresses two key issues: first, it enhances the seismic protection of structures; second, it facilitates waste utilization, thereby reducing environmental impact. Crumb rubber derived from worn-out vehicle tires is characterized by low density and high damping capacity, making it an ideal component for seismic isolation layers [7]. According to research, the use of such tire-derived aggregate (TDA) layers can significantly reduce dynamic forces. For example, in numerical models of tunnels backfilled with tire crumb, reductions in deformations and internal forces of 50–75% were achieved [7]. Other studies have noted that an optimal crumb content of 30% in soil mixtures provides the highest seismic energy absorption. Thus, the incorporation of tire waste into seismic protection not only addresses the challenge of disposal but also delivers substantial benefits for ensuring structural reliability, aligning with the principles of sustainable development in construction.

Despite the obvious advantages, the widespread implementation of geotechnical seismic isolation in Kazakhstan is currently hindered by the lack of regulatory frameworks and standardized solutions adapted to local soil conditions. Nevertheless, the increasing seismic risks and limited budgets for structural reinforcement underscore the need for cost-effective and efficient seismic protection technologies. The geotechnical soil–rubber layer is one such technology: it is inexpensive, easy to implement, and compatible with existing design practices. The aim of this study is to experimentally assess the damping capacity of a soil–rubber layer in reducing seismic impacts on the foundations of road structures. To achieve this goal, a laboratory methodology based on accelerometric analysis was developed and applied to evaluate vibration transmission through soil foundation models with different additive compositions. The study emphasizes both the scientific novelty (the use of accelerometric methods and innovative materials) and the practical relevance of the obtained results for seismic-prone regions.

Methods

The object of the study is the soil foundations of road structures that are subject to dynamic loads during seismic events. The subject of the study is the damping properties of a composite geomaterial based on soil and rubber crumb, used as an intermediate layer between the natural subgrade and the foundation structure. The experimental part of the research was carried out under laboratory conditions using tools for vibrational dynamic analysis.

A composite mixture was prepared using natural soil (representing the mineral composition of the foundation) and rubber crumb derived from recycled automobile tires. The component ratio was set at 80% soil and 20% rubber additive by weight. This proportion was selected based on literature recommendations and technological considerations to ensure sufficient workability of the mixture and a pronounced damping effect. For control testing, additional specimens made of pure soil without additives (natural soil) were also prepared to enable comparative analysis with the soil–rubber mixture.

The prepared components were thoroughly mixed until a homogeneous composition was achieved (Figure 1). The resulting mixture was then placed into a standard cylindrical mold in layers. Each layer had a thickness of approximately 50–60 mm. Compaction was performed using the standard Proctor method with the laboratory unit UG-F: 40 blows were applied to the surface of each layer using a special tamping weight (2.5 kg) dropped from a height of 300 mm. After compacting a layer, its surface was slightly loosened to ensure bonding with the subsequent layer, which was then added on top. This procedure was repeated until the mold was filled; the top layer was leveled flush with the mold's rim. This method of mechanical compaction allowed the modeling of dense soil and soil–rubber states that closely resemble real foundation conditions.

Figure 1. Preparation of the soil–rubber mixture [author's material]

The compacted specimen was carefully removed and placed into a larger-diameter testing container simulating a structural foundation. An accelerometer (BC111, standard ICP, sensitivity 10 mV/g, operating frequency range 0.5–15,000 Hz) was installed at the base of the container (beneath the specimen). The sensor was mounted in such a way as to capture vibrations transmitted through the specimen to the foundation.

To induce oscillations, an impact pulse was applied: a 469 g weight was dropped from a height of 250 mm onto the top surface of the specimen. The falling weight generated a short-duration impulse analogous to a seismic wave propagating downward through the foundation model. The accelerometer positioned below the specimen recorded the transmitted signal (Figure 2).

Figure 2. General view of the experimental setup [author's material]

Signals from the sensor were transmitted to a multi-channel spectrum analyzer ZET 017-U8 (dynamic range: 80 dB, frequency range up to 20 kHz), which was connected to a computer running ZetLab software. The recording parameters were selected to reliably capture the entire vibration process—from the moment of impact to the complete attenuation of oscillations. The duration of each impact recording was 1.0 second, including approximately 0.5 seconds before the impact (background and impact moment) and 0.5 seconds after the impact to capture the decaying vibrations. As a result, each experiment produced an accelerogram—a time-history plot of acceleration—reflecting the response of the foundation model to the impact load.

To improve the reliability of the results, each configuration was tested through a series of repeated trials. Specifically, three independent tests were conducted for the natural soil (three weight drops from the same height and mass), and similarly, three tests for the soil–rubber mixture. Before each repeated impact, the specimen was reinstalled, and the system was reset, or a newly prepared identical specimen was used to eliminate the influence of structural changes or damage accumulation from previous impacts. In total, six experiments were conducted under identical conditions (three for soil, three for soil–rubber). For each series, the average peak acceleration recorded by the accelerometer was calculated. Data processing and averaging were performed using ZetLab software with built-in statistical analysis tools. Reproducibility of the accelerogram waveform was also monitored—they showed high similarity within each set of three trials, confirming the reliability of the testing methodology.

The obtained accelerograms (Figures 3–8) were displayed on the computer screen and saved for subsequent analysis (examples of oscillograms are provided in Appendix 1 of the source materials). The primary parameter used for comparison was the peak acceleration amplitude—the maximum acceleration value transmitted through the specimen. This parameter characterizes the proportion of seismic impact energy that the damping layer transfers to the foundation: a lower amplitude indicates more effective vibration attenuation. Additionally, the nature of vibration decay (the rate of amplitude decrease on the accelerogram) was analyzed; however, the present article focuses primarily on comparing peak acceleration values for different materials.

Figure 3. Accelerogram of natural soil without additives. Experiment 1

Figure 4. Accelerogram of natural soil without additives. Experiment 2

Figure 5. Accelerogram of natural soil without additives. Experiment 3

Figure 6. Accelerogram of soil–rubber mixture. Experiment 1

Figure 7. Accelerogram of soil–rubber mixture. Experiment 2

Figure 8. Accelerogram of soil–rubber mixture. Experiment 3

Results

Table 1 presents the measured peak vibration amplitudes recorded by the accelerometer beneath the specimens made of natural soil and soil–rubber composite under three repeated impact tests. It is evident that in all cases, the model with the soil–rubber layer transmitted significantly less vibration than the model consisting of pure soil. For example, in Experiment No. 1, the peak acceleration through natural soil was 5.91 (in arbitrary acceleration units, close to m/s^2), while for the soil–rubber layer it was only 3.78. In Experiment No. 2, the values were 7.00 and 4.04, respectively, and in No. 3 – 7.47 and 3.91. On average, the amplitude reduction due to the addition of rubber crumb was approximately 33–34% compared to the control soil. These data clearly confirm the pronounced damping effect of the soil–rubber composite: the addition of 20% rubber results in only two-thirds of the seismic energy being transmitted to the foundation compared to conventional soil.

Table 1. Results of Experimental Studies. Peak Vibration Amplitude

Experiment	Natural Soil	Soil–Rubber Composite
1	5,91	3,78
2	7	4,04
3	7,47	3,91

Data analysis (Figure 9) shows that natural soil exhibits significantly higher vibration amplitude values compared to the soil–rubber composite. In the first experiment, the amplitude for natural soil was 5.91, in the second – 7.00, and in the third – 7.47. In contrast, the amplitude values for the soil–rubber mixture were noticeably lower: 3.78, 4.04, and 3.91, respectively.

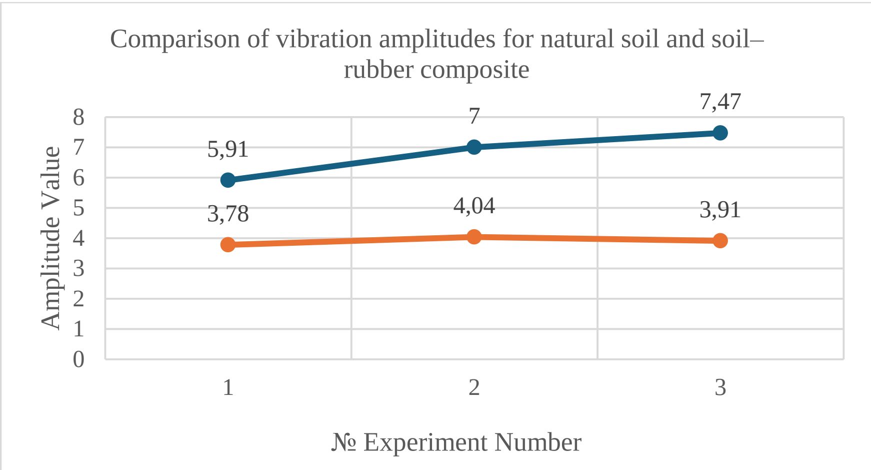

Figure 9. Comparison of Vibration Amplitudes for Natural Soil and Soil–Rubber Composite: red line – natural soil, red line – soil–rubber composite [author's material]

Thus, it is evident that the addition of rubber crumb to the soil structure effectively reduces the amplitude of seismic waves. On average, the soil–rubber composite reduces the amplitude by more than 33% compared to natural soil, confirming its damping properties and applicability in geotechnical seismic isolation for protecting road structures.

The presented data are consistent with previously obtained results, further confirming that soil–rubber mixtures exhibit a stable damping effect and significantly reduce the level of vibrational impact on structures.

Discussion

Analysis of the obtained accelerograms shows that, in addition to reducing the peak acceleration value, the soil–rubber layer also alters the vibration behavior. A noticeably faster attenuation of vibrations over time was observed: oscillations in the soil–rubber specimen diminished earlier than in the pure soil sample (the amplitude dropped to negligible levels over a shorter time period). This indicates increased energy dissipation in the rubber-containing mixture, which corresponds to the well-known properties of polymeric materials—their ability to effectively disperse deformation energy as heat due to internal friction and viscoelastic characteristics. In contrast, vibrations in the natural mineral soil persist longer, as dry, dense soil possesses lower internal damping capacity.

The obtained experimental results are consistent with findings from other studies. Previous research has reported that the use of rubber crumb in soil layers can reduce seismic accelerations and structural deformations by several tens of percent. For example, in the works of Tsang et al. [8] and Ranjbar et al. [9], shake table tests showed that the structural response was reduced by 30–60% due to the addition of 10–30% rubber into sand. In the present study, the observed 33% reduction falls within this same range, confirming the effectiveness of the selected composition. Variations in the magnitude of the effect may be attributed to differences in rubber grain size distribution and content, the properties of the base soil, as well as the scaling factor of the laboratory model. Nonetheless, the qualitative conclusion remains consistent: the rubber component significantly reduces the transmission of seismic energy through the soil.

The inclusion of a rubber fraction affects the dynamic properties of the soil in a complex manner. First, the effective shear modulus of the composite is reduced: rubber is significantly softer than mineral particles, so the mixture deforms more easily under dynamic loading, allowing larger shear displacements at lower forces. As a result, part of the energy is dissipated in harmless deformations of the layer (similar to a spring damper) and is not transmitted upward into the structure. Second, internal friction and dissipative losses increase: the "soil–rubber" interfaces and the rubber material itself absorb vibrational energy, converting it into heat. The results demonstrate that due to these mechanisms, the soil–rubber composite acts as a seismic wave filter, blocking the most hazardous peak oscillations. Notably, even a relatively small rubber content (20%) resulted in a one-third reduction in amplitude. It can be expected that increasing the rubber crumb content to an optimal level (e.g., 30% by weight) could further enhance the damping effect, as reported in international studies [8, 9]. However, an excessive proportion of the soft phase may compromise the strength and stiffness of the foundation, thus requiring a balanced approach and further research to determine the optimal composition.

From an engineering practice perspective, the obtained results are of high importance for the seismic isolation of road structures. A 30% reduction in accelerations transmitted to the foundation implies an equally significant decrease in inertial forces acting on bridge supports, abutments, retaining walls, and other structural elements during an earthquake. This can prevent the attainment of ultimate limit states and reduce the development of cracks and plastic deformations in structural materials. In other words, the soil–rubber damping layer is capable of absorbing part of the destructive energy, thus protecting the superstructure from overloads. This is especially relevant for regions of Kazakhstan where strong seismic events are a real threat, and many existing structures lack sufficient safety margins. The proposed technology is relatively low-cost and technologically feasible: the required rubber crumb is available from local sources (tire recycling), and its placement and mixing do not require complex equipment. According to the literature, such systems are economically efficient and pay off through reduced post-earthquake repair costs [2, 3]. Moreover, the use of waste materials in construction aligns with the principles of “green” engineering and the priorities of sustainable development [10]. Instead of being landfilled, millions of tons of worn-out tires can be given a "second life" as seismic protection elements, providing tangible societal benefits.

Geotechnical seismic isolation using damping layers is not the only method for protecting structures from seismic waves, but it is one of the most versatile and cost-effective. Alternatives include, for example, specialized designs such as pile barriers or wave-blocking screens installed around a structure to deflect seismic energy [5]. Other approaches involve reinforcing foundations with geogrids and geotextiles to enhance the bearing capacity and stability of soil under vibration. However, most of these measures entail substantial costs and complex construction processes. In contrast, a soil–rubber damping layer can be integrated into the construction of a new structure with minimal alterations to the design scheme: it is sufficient to place a layer of the mixture of a specified thickness beneath the foundation or within the fill base. For the reconstruction of existing facilities, this method is also applicable—for example, by introducing thin damping layers during embankment widening or strengthening. Thanks to its implementation simplicity and adaptability to locally available materials, the soil–rubber layer technology appears attractive for large-scale adoption [2, 7]. Naturally, broader application requires further research and the development of regulatory guidelines tailored to regional conditions (e.g., soil types, seismicity, etc.) [11]. Nonetheless, it is already clear that this technology holds strong potential for enhancing the seismic resilience of transport infrastructure both in Kazakhstan and beyond.

Conclusions

The conducted study confirmed the high effectiveness of soil–rubber damping layers within the foundations of road structures for protection against seismic loads. The main findings are summarized below:

- Damping efficiency. Laboratory tests showed that adding approximately 20 % rubber crumb to soil reduces the peak amplitude of transmitted seismic vibrations by about 33 % compared with plain soil. This indicates a significant damping effect of the soil–rubber composite, enabling a reduction in seismic forces acting on structures.
- Measurement methodology. A method for accelerometric analysis of the damping properties of soil composites was developed and successfully applied. Impact excitation combined with accelerogram recording demonstrated the ability to quantitatively assess vibration reduction as waves pass through different layers. This approach can be used in further studies to compare new materials and layer configurations.
- Use of secondary materials. The results confirm the feasibility of employing recycled tire rubber crumb as an effective seismic-isolation material. A soil–rubber layer not only enhances the seismic resilience of structures but also addresses the environmental challenge of waste utilization, thus lowering anthropogenic pressure on the environment. The technology therefore combines engineering reliability with the principles of sustainable construction.
- Simplicity and practicality. Soil–rubber technology is economically attractive and easy to implement: the materials are inexpensive, and the layer can be installed with standard earth-compaction equipment. This makes the method suitable for large-scale deployment in seismically active regions without substantially increasing construction costs. The layer can also be installed in the field under properly organized construction procedures.

Thus, geotechnical seismic isolation based on soil–rubber layers can be considered an effective and innovative solution to improve the seismic safety and durability of highways, bridges, and other transport infrastructure. The results of this study lay a scientific and practical foundation for further development of this approach. They may be taken into account in the development of new regulatory documents and methodological guidelines for seismic protection design in Kazakhstan’s road construction sector.

Future research is planned to expand by conducting numerical simulations of structural dynamic behavior with damping layers under various earthquake scenarios, as well as experimental comparisons of soil–rubber mixtures with other damping materials (such as soil–bitumen, soil–silicate, and soil–cement). Additionally, it would be advisable to organize full-scale field trials on test sections of roads or viaducts in seismically active regions to verify the technology’s effectiveness under real-world conditions. These steps will help confirm the long-term reliability and durability of soil–rubber damping layers and optimize their use in engineering practice.

Conflict of interests. Correspondent the author states that there is no conflict of interest.

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