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Study of the effectiveness of well screens-barriers from mining waste

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Abstract

Geotechnical seismic isolation systems based on borehole screen barriers represent a promising approach for reducing seismic and vibration impacts on foundations and structures. The efficiency of such systems strongly depends on the damping properties of the infill material. This study presents an experimental assessment of the vibration attenuation performance of natural soil, ground–silicate, and fly ash under impulse dynamic loading. Laboratory impact tests were conducted by dropping a mass from a fixed height, while acceleration responses were recorded using a high-sensitivity piezoelectric accelerometer and a spectral analysis system. Peak and average acceleration amplitudes were analyzed to evaluate the damping efficiency of each material. The results demonstrate that natural soil exhibits the weakest damping behavior. Ground–silicate shows a noticeable improvement in vibration attenuation, reducing vibration amplitudes by approximately 60% relative to natural soil. Fly ash exhibits the highest damping efficiency, providing an average vibration reduction of about 80% compared to natural soil and approximately 50% relative to ground–silicate. In addition, fly ash shows the most stable dynamic response across repeated tests. The findings confirm that fly ash-based technogenic materials possess superior damping characteristics and are highly effective as infill for borehole screen barriers. Their application can significantly enhance vibration mitigation and geotechnical seismic isolation performance while simultaneously offering an environmentally sustainable solution through the utilization of industrial waste.

Keywords: geotechnical seismic isolation, borehole barrier screens, fly ash, damping properties, dynamic loading, vibration response

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Түйіндеме
Скважиналық экран-барьерлерге негізделген геотехникалық сейсмооқшаулау жүйелері ғимараттар мен құрылыстардың негіздеріне әсер ететін сейсмикалық және дірілдік ықпалдарды азайтудың перспективалы тәсілі болып табылады. Мұндай жүйелердің тиімділігі экрандарды толтыратын материалдардың демпфирлеу қасиеттеріне тікелей байланысты. Мақалада импульстік динамикалық жүктеме жағдайында табиғи топырақтың, грунтосиликаттың және жылу электр станцияларының золасының дірілді бәсеңдету қабілетіне эксперименттік баға берілген. Зертханалық соққылы сынақтар жүк массасын белгіленген биіктіктен түсіру арқылы жүргізіліп, үдеулердің динамикалық жауабы жоғары сезімтал пьезоэлектрлік акселерометр және спектралдық талдау жүйесі көмегімен тіркелді. Материалдардың демпфирлеу тиімділігін бағалау үшін үдеу амплитудаларының шектік және орташа мәндері талданды. Нәтижелер табиғи топырақтың демпфирлеу қасиеттері ең төмен екенін көрсетті. Грунтосиликат дірілді бәсеңдету тиімділігін арттырып, табиғи топырақпен салыстырғанда діріл амплитудаларын шамамен 60%-ға төмендетеді. Ең жоғары демпфирлеу тиімділігі зола уносында анықталды: ол табиғи топырақпен салыстырғанда дірілді шамамен 80%, ал грунтосиликатпен салыстырғанда 50%-ға азайтады. Сонымен қатар, зола уносы қайталама сынақтар барысында ең тұрақты динамикалық жауап көрсетті. Алынған нәтижелер зола уносына негізделген техногендік материалдардың жоғары демпфирлеу қасиеттеріне ие екенін және скважиналық экран-барьерлер үшін тиімді толтырғыш болып табылатынын дәлелдейді. Мұндай материалдарды қолдану виброзащита мен геотехникалық сейсмооқшаулау жүйелерінің тиімділігін айтарлықтай арттырумен қатар, өндірістік қалдықтарды экологиялық тұрғыдан ұтымды пайдалануға мүмкіндік береді.

Түйін сөздер: геотехникалық сейсмооқшаулау, скважиналық экран-барьерлер, зола уносы, демпфирлеу қасиеттері, динамикалық жүктеме, дірілдік жауап.

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Исследование эффективности скважинных экранов-барьеров из отхода ГМК

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Аннотация
Геотехнические системы сейсмоизоляции на основе скважинных экранов-барьеров являются перспективным подходом к снижению сейсмических и вибрационных воздействий на основания и строительные конструкции. Эффективность таких систем в значительной степени зависит от демпфирующих свойств заполнителя экранов. В статье представлена экспериментальная оценка способности к виброгашению природного грунта, грунтосиликата и золы уноса при импульсном динамическом нагружении. Лабораторные ударные испытания проводились путём сбрасывания груза с фиксированной высоты, при этом отклик ускорений регистрировался с использованием высокочувствительного пьезоэлектрического акселерометра и системы спектрального анализа. Для оценки демпфирующей эффективности материалов были проанализированы пиковые и средние значения амплитуд ускорений. Результаты показывают, что природный грунт обладает наименее выраженными демпфирующими свойствами. Грунтосиликат демонстрирует заметное улучшение виброгасящих характеристик, снижая амплитуды вибраций примерно на 60% по сравнению с природным грунтом. Наиболее высокая демпфирующая эффективность выявлена у золы уноса, которая обеспечивает среднее снижение вибраций примерно на 80% относительно природного грунта и на 50% по сравнению с грунтосиликатом. Кроме того, зола уноса характеризуется наиболее стабильным динамическим откликом в серии повторных испытаний. Полученные результаты подтверждают, что техногенные материалы на основе золы уноса обладают высокими демпфирующими характеристиками и являются эффективным заполнителем для скважинных экранов-барьеров. Их применение позволяет существенно повысить эффективность виброзащиты и геотехнической сейсмоизоляции, одновременно обеспечивая экологически устойчивое использование промышленных отходов.

Ключевые слова: геотехническая сейсмоизоляция, скважинные экран-барьеры, зола уноса, демпфирующие свойства, динамическое нагружение, вибрационный отклик

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1. Introduction

Contemporary international practice demonstrates that geotechnical methods for reducing seismic impacts represent a key component of protecting buildings and infrastructure in seismically active regions [1]. In countries with high seismicity, including Japan, the United States, China, and EU member states, a wide range of engineering solutions is applied to mitigate ground motion amplitudes and reduce structural vulnerability. These solutions include trench barriers, vertical and inclined barrier systems, vibration-damping barriers, and borehole screen barriers, whose effectiveness has been confirmed by both experimental investigations and numerical modeling. The primary function of such systems is to modify seismic wave propagation paths, dissipate seismic energy, and adjust the frequency response of soil deposits [2].

International experience indicates that barrier systems can significantly reduce seismic loads acting on industrial and critical infrastructure. In Japan, barrier trenches and screens are used to protect nuclear and thermal power plants; in the United States, they are applied to facilities of national importance; and in Europe, they are implemented within large-scale research initiatives such as the SYNER-G project aimed at systemic seismic vulnerability assessment. The continuous development of geotechnical seismic protection methods is supported by extensive research focused on improving damping materials and structural configurations [3,4].

Recent analytical and experimental studies confirm the effectiveness of such approaches. For example, Wang et al. (2024) demonstrated that large shallow tunnels constructed in weak soils experience substantially higher seismic demands than deep underground structures, necessitating specialized isolation measures. Numerical analyses comparing grouting reinforcement, buffer damping layers, and combined systems showed that integrated configurations can reduce seismic effects by more than 95%, while single buffer layers or grouting provide considerably lower mitigation. These findings highlight the critical role of material properties and barrier geometry in seismic energy dissipation [5–7].

Previous studies have emphasized the importance of selecting appropriate damping materials for enhancing the efficiency of geotechnical seismic isolation. Investigations by Li et al. (2019) revealed that the shear modulus of isolation layers plays a governing role in reducing seismic wave transmission, while Poisson’s ratio significantly influences transverse isolation performance. These conclusions are directly relevant to the present study, in which borehole screen barriers filled with technogenic materials are considered as damping layers capable of reducing seismic energy transfer due to their low shear stiffness [8–10].

Modern seismic design philosophies increasingly favor deformation-based and performance-oriented approaches rather than traditional force-based methods. Such concepts allow for a more realistic assessment of soil–structure interaction, especially in weak or saturated soils. Borehole screen barriers, forming energy-dissipating zones within the ground, are consistent with these principles, as their effectiveness depends on the deformational and damping characteristics of the infill material. The use of fly ash from thermal power plants and mining and metallurgical waste provides an opportunity to create energy-absorbing, ductile, and environmentally sustainable geotechnical systems [11–14].

Recent experimental and numerical studies further demonstrate that the efficiency of geotechnical seismic isolation is closely linked to actual deformation mechanisms in soils and foundations under strong earthquakes. Large-scale vibration tests and fully coupled nonlinear dynamic models have shown that damping and isolating elements can effectively control kinematic soil response and reduce damage concentration in foundation systems. In this context, borehole screen barriers composed of technogenic materials are of particular interest, as they form localized zones of enhanced energy dissipation [15–18].

Despite extensive international research on geotechnical seismic isolation, the application of mining and metallurgical waste and thermal power plant fly ash as infill materials for barrier systems remains insufficiently explored. These materials possess pozzolanic activity, structural-forming potential, and high energy dissipation capacity, making them promising candidates for damping applications. Their use simultaneously addresses seismic safety enhancement and environmentally responsible waste utilization [19–21].

Therefore, the present study provides a comprehensive assessment of the effectiveness of borehole screen barriers constructed using mining and metallurgical waste, focusing on their dynamic and damping properties and identifying optimal material compositions for seismic regions.

2. Materials and Methods

2.1 Experimental Program and Sample Preparation

The experimental program comprised a series of laboratory dynamic tests conducted on fly ash specimens prepared in accordance with standard compaction procedures for dispersed soils. All tests were performed at the Research Laboratory of Architecture and Civil Engineering of the Institute of Architecture and Construction named after T.K. Bassenov, Satbayev University. The laboratory is accredited by the National Accreditation Center and complies with ISO/IEC 17025:2019, ensuring the reliability and traceability of the obtained results.

Fly ash samples were first conditioned to an air-dry state and cleared of coarse inclusions. The material was gently disaggregated to preserve particle integrity and subsequently sieved through a 5 mm mesh to obtain a uniform grain-size composition suitable for standard compaction testing. Initial physical properties, including natural moisture content and bulk density, were determined in accordance with national standards. Moisture content was measured by oven drying at 105 °C to constant mass, while density was obtained using gravimetric methods.

Sample compaction was carried out using the standard Proctor-type compaction procedure to determine the optimum moisture content and maximum dry density (fig.1). Compaction was performed in layers to ensure uniform density throughout the specimen volume. Prepared samples were then conditioned until moisture and density stabilization was achieved, preventing internal gradients that could affect the dynamic response. This approach ensured structural homogeneity, which is critical for reliable assessment of dynamic behavior.

Figure 1. Standard Proctor-type compaction apparatus [Own material]

2.2 Measurement of Dynamic Properties

Dynamic response measurements were performed using a piezoelectric accelerometer (BC-111 (fug.2), IEPE type) with a sensitivity of 10 mV/g and a frequency range of 0.5–15,000 Hz, enabling accurate registration of both low- and high-frequency vibration components. The sensor was mounted on the specimen surface using threaded fixtures, magnetic bases, or mounting wax to ensure stable contact during impact loading.

Figure 2. Piezoelectric accelerometer BC-111 [Own material]

Acceleration signals were recorded and processed using a ZET 017-U8 spectrum analyzer connected to a personal computer running ZETLAB software. The system provided high-resolution data acquisition (24-bit ADC) and enabled time-domain recording, spectral analysis, and signal filtering. Anti-aliasing filters and adjustable gain settings ensured signal fidelity across a wide dynamic range.

Dynamic excitation was applied by freely dropping a 470 g mass from heights of 10 cm and 20 cm onto the compacted specimen surface, generating impulse vibrations representative of short-duration seismic loading. Acceleration time histories were recorded for 1 s following each impact. For each material configuration, at least six repeated tests were conducted to reduce random variability and ensure statistical reliability.

The impulse vibration intensity was quantified using the peak acceleration value (a_{max}), which served as the primary parameter for comparative analysis of dynamic response and damping performance.

3. Results

The dynamic properties of materials used in borehole screen barriers govern their ability to attenuate seismic wave amplitudes and dissipate vibration energy within the soil mass. Among technogenic materials considered for damping applications, thermal power plant fly ash demonstrates high potential due to its porous structure, particle morphology, and grain-size distribution, which promote viscous–frictional energy dissipation.

To evaluate material performance under seismic-type loading, short-duration impulse tests were conducted to simulate transient seismic excitations. Time histories of acceleration were recorded for natural soil (loam), ground–silicate mixtures, and fly ash specimens using a high-sensitivity BC-111 accelerometer coupled with a ZET 017-U8 spectrum analyzer. The measurements provided reliable information on peak accelerations and vibration decay characteristics.

Analysis of the acceleration time histories allowed identification of key dynamic response parameters, including peak acceleration amplitude, attenuation rate, waveform shape, and spectral characteristics. These parameters are fundamental for quantifying the damping capacity of geomaterials and assessing their effectiveness when used as infill in vertical borehole screen barriers. Comparative analysis of the oscillograms revealed distinct response patterns associated with differences in material structure, density, and mechanical properties.

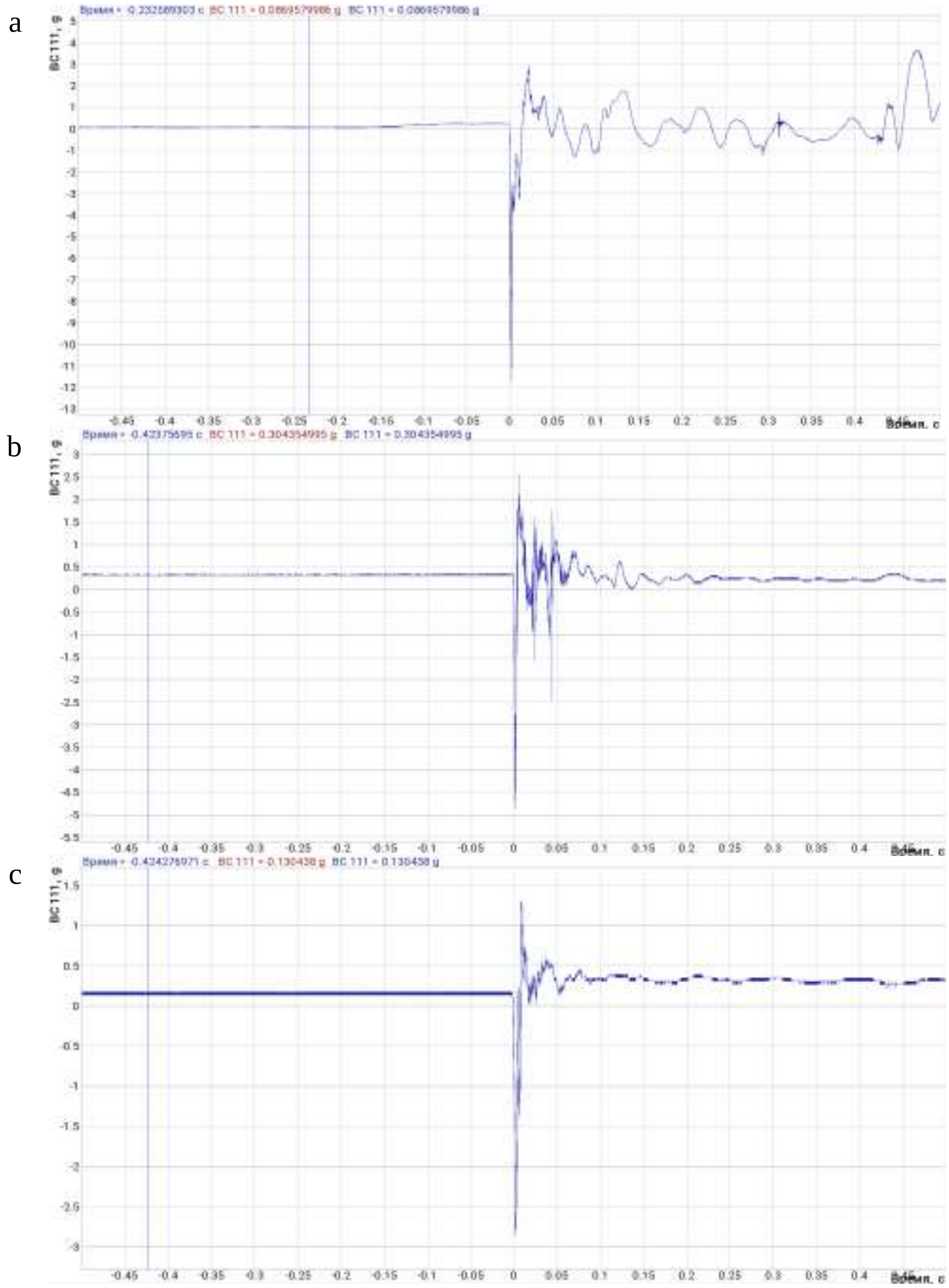

Figure 3. Acceleration time histories recorded by the BC-111 accelerometer for six repeated tests on fly ash specimens at a drop height of 10 cm: a) natural soil, b) ground–silicate specimens, c) fly ash specimens [Own material]

Figure 3a present acceleration time histories recorded during six repeated tests on natural loam specimens subjected to an impact load generated by a falling mass from a height of 10 cm. All records exhibit a pronounced initial impulse followed by a decaying oscillatory response. Peak acceleration values are consistent with those reported in Table 1, confirming stable experimental conditions and correct instrumentation setup. The waveforms show similar qualitative behavior across tests, with energy concentrated in the initial response phase and gradual attenuation toward zero. Minor variations in peak amplitude and decay rate are attributed to natural variability in soil properties and local contact conditions during impact. These results characterize the typical dynamic response of uncompacted loam and provide a baseline for comparison with technogenic materials.

Figure 3b illustrates the acceleration time histories obtained for ground–silicate specimens under identical loading conditions. Compared to natural soil, the initial acceleration peaks are generally lower, reflecting the higher viscosity and energy-absorbing capacity of the silicate binder. The subsequent oscillatory response exhibits a shorter duration and faster attenuation, indicating enhanced internal friction and energy dissipation within the material matrix. Despite some variability between individual tests, the overall response pattern remains consistent, demonstrating stable damping behavior.

The acceleration records for fly ash specimens (fig.3c) show the most pronounced damping effect among all tested materials. The initial impact peak is significantly reduced, and vibrations decay rapidly within a short time interval. This behavior is attributed to the high porosity of fly ash, its microcellular structure, and extensive internal surface area, which facilitate efficient dissipation of impact energy through interparticle friction, pore compression, and microplastic deformation. Variability between repeated tests is minimal, indicating homogeneous specimen properties and stable mechanical response.

Overall, the results demonstrate that fly ash exhibits the highest damping capacity, followed by ground–silicate mixtures, while natural soil shows the weakest energy dissipation performance. These findings are consistent with the average acceleration amplitudes summarized in Table 1 and confirm the effectiveness of fly ash as a technogenic material for borehole screen barriers. The ability of fly ash to rapidly attenuate impulse vibrations highlights its potential for reducing seismic wave amplitudes and mitigating resonance effects in soil foundations.

Table 1 summarizes the experimental vibration amplitude data recorded during impact loading from a drop height of 10 cm on three materials: natural soil, ground–silicate, and fly ash. The reported values correspond to the peak negative acceleration amplitudes of the impulse response measured by the accelerometer immediately after impact.

The highest acceleration amplitudes were observed for natural soil, with values ranging from −8.348 to −14.261, indicating a low energy dissipation capacity and weak damping performance. Ground–silicate specimens exhibited intermediate behavior, with amplitudes varying between −2.347 and −7.739. The relatively wide scatter reflects the viscous–structural nature of the silicate binder and its sensitivity to local deformation conditions.

The lowest acceleration amplitudes were recorded for fly ash specimens, ranging from −1.173 to −3.173. These results confirm the superior damping capacity of fly ash, which effectively reduces the intensity of impulse-induced vibrations due to its porous structure and enhanced internal energy dissipation mechanisms.

Overall, the comparison demonstrates that technogenic materials—particularly fly ash—exhibit significantly higher damping efficiency than natural soil, highlighting their potential for application in vibration protection systems and geotechnical seismic isolation.

Table 1. Experimental peak acceleration amplitudes at a drop height of 10 cm

Material	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6
Natural soil	−11.739	−13.348	−11.608	−14.261	−8.348	−8.478
Ground–silicate	−2.965	−4.869	−7.739	−4.043	−2.347	−5.695
Fly ash	−2.869	−2.869	−2.173	−3.173	−1.173	−1.608

The data presented in Table 1 clearly indicate a pronounced reduction in peak acceleration amplitudes when technogenic materials are used instead of natural soil. In particular, fly ash consistently exhibits the lowest acceleration levels across all repeated tests, demonstrating both reduced peak values and improved stability of the dynamic response. Ground–silicate shows intermediate behavior with noticeable variability, reflecting its viscous–structural nature. These results confirm that material composition and internal structure play a decisive role in vibration attenuation and support the suitability of technogenic materials—especially fly ash—for use as damping infill in borehole screen barriers under seismic loading.

4. Discussion

This section discusses the experimental results obtained from impact loading tests and focuses on the comparative damping performance of the investigated materials. By analyzing both the peak vibration amplitudes and their averaged values, the dynamic response characteristics of natural soil, ground–silicate, and fly ash are evaluated in terms of energy dissipation efficiency. The discussion emphasizes the influence of material structure and rheological properties on vibration attenuation and highlights the potential of technogenic materials, particularly fly ash, for application in borehole screen barriers and geotechnical seismic isolation systems.

The figure 4 presents comparative experimental vibration amplitude data for three materials—natural soil (loam), ground–silicate, and fly ash—under identical loading conditions with a drop height of 10 cm. Natural soil exhibits the highest absolute acceleration amplitudes, reaching −14.261, indicating limited energy dissipation capacity and a low damping potential. Ground–silicate shows lower amplitudes overall but with noticeable variability, particularly in Test 3 (−7.739), which can be attributed to its viscous–structural behavior. The lowest and most stable negative amplitudes are observed for fly ash, ranging from −1.173 to −3.173. This response demonstrates the high ability of fly ash to attenuate impulse-induced vibrations and effectively dissipate transmitted energy. Overall, the results confirm that technogenic materials—especially fly ash—exhibit significantly enhanced damping properties compared to natural soil.

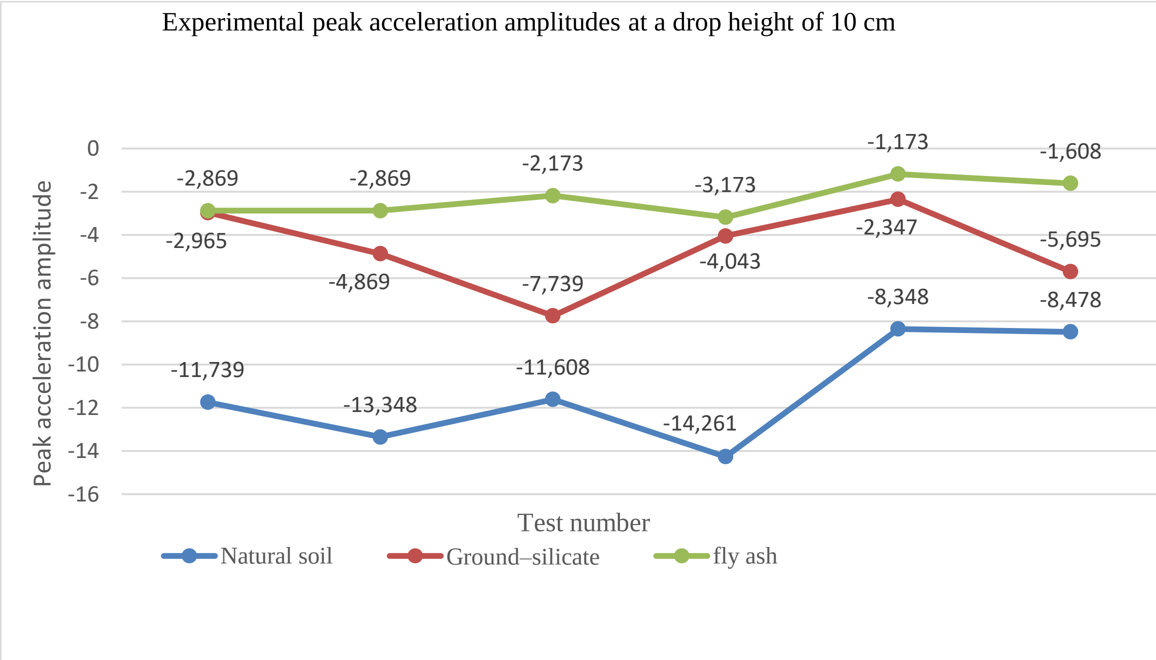

Figure 4. Recording and visualization of experimental results on the computer [Own material]

Average Vibration Amplitude Calculation. The average vibration amplitude was determined as the arithmetic mean of the values obtained from a series of experiments. For each material, the amplitudes recorded in six repeated tests were summed and divided by the total number of measurements. This approach smooths random fluctuations in individual values and provides a representative indicator of the typical dynamic response of the material under impact loading.

The average value was calculated using the standard expression:

$$\underset{x}{\rightarrow} = \frac{1}{n}\sum_{i=1}^{n} x_i, \quad (1)$$

where $\bar{x}$ is the mean amplitude, n=6 is the number of experiments, and x_i denotes the amplitude measured in each test. This data processing method enables a reliable comparison of different soil models in terms of their dynamic properties.

Table 2 presents the average vibration amplitudes for the three investigated materials: natural soil, ground–silicate, and fly ash. The values were obtained from six repeated experiments, ensuring statistical reliability. The highest absolute mean amplitude corresponds to natural soil (−11.297), indicating a low energy dissipation capacity and weak damping behavior. Ground–silicate exhibits a substantially lower average amplitude (−4.610), reflecting improved energy absorption due to its viscous–structural characteristics. The lowest mean amplitude was recorded for fly ash (−2.311), confirming its superior ability to attenuate vibration and dissipate dynamic energy.

Table 2. Average vibration amplitude for each material

No.	Material	Average amplitude
1	Natural soil	−11.297
2	Ground–silicate	−4.610
3	Fly ash	−2.311

Overall, the comparative analysis demonstrates that technogenic mixtures—particularly fly ash—significantly outperform natural soil in terms of damping efficiency, highlighting their suitability for use in borehole screen barriers and other vibration mitigation systems.

5. Conclusions

This study experimentally evaluated the damping performance of natural soil, ground–silicate, and fly ash under impulse dynamic loading with a drop height of 10 cm, focusing on their potential application in borehole screen barrier systems.

The results show that natural soil exhibits the weakest damping behavior, with peak acceleration amplitudes ranging from −8.348 to −14.261 and an average value of −11.297. These values indicate a low ability to dissipate vibration energy and confirm the limited damping potential of untreated soil under impact-type excitation.

Ground–silicate demonstrates improved damping performance compared to natural soil. Its peak acceleration amplitudes vary from −2.347 to −7.739, with an average amplitude of −4.610. On average, ground–silicate reduces vibration amplitudes by approximately 59% relative to natural soil. However, noticeable variability between repeated tests reflects the influence of its viscous–structural properties on dynamic response stability.

Fly ash exhibits the highest damping efficiency among all investigated materials. Peak acceleration amplitudes range from −1.173 to −3.173, while the average amplitude is −2.311. Compared to natural soil, fly ash reduces the average vibration amplitude by approximately 80%, and by about 50% compared to ground–silicate. In addition, fly ash shows the most stable response across repeated experiments, indicating consistent and reliable energy dissipation.

Overall, the experimental findings clearly demonstrate that fly ash is the most effective material for attenuating impulse-induced vibrations, followed by ground–silicate, while natural soil shows the poorest damping performance. These results confirm the high potential of fly ash-based technogenic materials for use as damping infill in borehole screen barriers and geotechnical seismic isolation systems. The application of fly ash not only enhances vibration mitigation efficiency but also provides an environmentally sustainable solution through the utilization of industrial waste.

Conflict of interest. The correspondent author declares that there is no conflict of interest.

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