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«Қазақстан Республикасы Ұлттық ғылым академиясының Хабарлары. Геология және техникалық ғылымдар сериясы» ғылыми журналы 2016 жылдан бастап халықаралық реферативтік және ғылымиметриялық Scopus дерекқорында индекстеледі және тұрақты библиометриялық көрсеткіштерді көрсетіп келеді.

Сонымен қатар журнал Web of Science платформасының (Clarivate Analytics, 2018) халықаралық реферативтік және наукометриялық дерекқоры Emerging Sources Citation Index (ESCI) тізіміне енгізілген.

ESCI дерекқорында индекстелуі журналдың халықаралық ғылыми рецензиялау талаптары мен редакциялық этика стандарттарына сәйкестігін растайды, сондай-ақ Clarivate Analytics компаниясы тарапынан басылымды Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) және Arts & Humanities Citation Index (AHCI) дерекқорларына енгізу қарастырылуда.

Scopus және Web of Science дерекқорларында индекстелуі жарияланымдардың халықаралық деңгейде жоғары сұранысқа ие болуын қамтамасыз етеді, олардың дәйексөз алу көрсеткіштерінің артуына ықпал етеді және редакциялық алқаның геология мен техникалық ғылымдар саласындағы өзекті, бірегей және ғылыми тұрғыдан маңызды зерттеулерді жариялауға ұмтылысын айқындайды.

Научный журнал «News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences» с 2016 года индексируется в международной реферативной и наукометрической базе данных Scopus и демонстрирует стабильные библиометрические показатели.

Журнал также включён в международную реферативную и наукометрическую базу данных Emerging Sources Citation Index (ESCI) платформы Web of Science (Clarivate Analytics, 2018).

Индексирование в ESCI подтверждает соответствие журнала международным стандартам научного рецензирования и редакционной этики, а также рассматривается компанией Clarivate Analytics в рамках дальнейшего включения издания в Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) и Arts & Humanities Citation Index (AHCI).

Индексирование в Scopus и Web of Science обеспечивает высокую международную востребованность публикаций, способствует росту цитируемости и подтверждает стремление редакционной коллегии публиковать актуальные, оригинальные и научно значимые исследования в области геологии и технических наук.

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CONTENTS

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[1]Mukhtar Auezov South Kazakhstan University, Shymkent, Kazakhstan;
[2]Almaty University of Power Engineering and Telecommunications named after Gumarbek Daukeev, Almaty, Kazakhstan.
[*]E-mail: artykbaev_d@mail.ru

DYNAMIC PROPERTIES AND DEFORMATION BEHAVIOR OF SANDY SOILS UNDER MULTIDIRECTIONAL SEISMIC LOADING

Nakbayev Nurken — PhD student, Mukhtar Auezov South Kazakhstan University, Shymkent, Kazakhstan,
E-mail: turkestanproject@gmail.com, https://orcid.org/0009-0003-3608-7208;
Faiz Nursultan — PhD, Associate Professor, Mukhtar Auezov South Kazakhstan University, Shymkent, Kazakhstan,
E-mail: nursultan_90faiz@mail.ru, https://orcid.org/0000-0002-7491-4281;
Kuttybay Musa — PhD, Senior Lecturer, Mukhtar Auezov South Kazakhstan University, Shymkent, Kazakhstan,
E-mail: m-kuttybay@mail.ru, https://orcid.org/ 0009-0004-3980-9445;
Artykbaev Darkhan — PhD, Associate Professor, Mukhtar Auezov South Kazakhstan University, Shymkent, Kazakhstan,
E-mail: artykbaev_d@mail.ru, https://orcid.org/0000-0003-4794-8707;
Nauryz Bauyrzhan — PhD, Senior Teacher, Almaty University of Power Engineering and Telecommunications named after Gumarbek Daukeev, Almaty, Kazakhstan,
E-mail: nauryzb@list.ru, https://orcid.org/0009-0002-9971-6732.

Abstract. *Relevance.* Sandy soils are widely distributed in the southern and southeastern regions of the Republic of Kazakhstan and serve as foundation soils for buildings and structures located in seismically active areas. During earthquakes, soil foundations experience multidirectional seismic loading, resulting in a complex stress–strain state that cannot be adequately described using conventional unidirectional approaches. Therefore, investigating the dynamic behavior of sandy soils under multidirectional seismic loading is an important task in modern geotechnical engineering. *Objective.* This study evaluates the influence of multidirectional seismic loading on the dynamic characteristics and deformation behavior of sandy soils through experimental investigations and numerical modeling to improve the reliability of seismic resistance assessment for foundations and substructures. *Methods.* Experimental investigations included resonant column tests, cyclic shear tests, and shaking-table simulations. Numerical analysis was performed using the finite element method in PLAXIS 2D/3D with nonlinear elastoplastic soil models. The analysis focused on changes in the dynamic shear modulus, damping ratio, and residual deformations under different loading directions. *Results.* The normalized dynamic shear modulus decreased more rapidly under multidirectional than unidirectional loading. Multicomponent seismic loading accelerated the accumulation of residual deformations and increased the damping ratio because of more complex stress paths. Quantitative analysis showed a 15–20% reduction in soil stiffness and a 1.5–2-fold increase in residual deformations. The discrepancy between the experimental and numerical results did not exceed 10–12%, confirming the reliability of the proposed numerical model. *Conclusions.* The results demonstrate the importance of considering the spatial nature of seismic loading in geotechnical analysis. The proposed approach improves prediction of dynamic response of sandy soils during earthquakes and enhances the seismic design of foundations and engineering structures in seismically active regions of Kazakhstan.

Keywords: sandy soils, dynamic shear modulus, damping ratio, residual deformations, multidirectional seismic loading, seismic resistance, PLAXIS, dynamic testing

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[1]М.Әуезов атындағы Оңтүстік Қазақстан университеті, Шымкент, Қазақстан;

[2]Ғ. Даукеев атындағы Алматы энергетика және байланыс университеті, Алматы, Қазақстан.

[*]E-mail: artykbaev_d@mail.ru

ӘРТҮРЛІ БАҒЫТТАҒЫ СЕЙСМИКАЛЫҚ ӘСЕРЛЕР КЕЗІНДЕГІ ҚҰМДЫ ГРУНТТАРДЫҢ ДИНАМИКАЛЫҚ ҚАСИЕТТЕРІ МЕН ДЕФОРМАЦИЯЛАНУ ЕРЕКШЕЛІКТЕРІ

Нақбаев Нұркен — PhD докторант, М. Әуезов атындағы Оңтүстік Қазақстан университеті, Шымкент, Қазақстан,
E-mail: turkestanproject@gmail.com, https://orcid.org/0009-0003-3608-7208;

Фаиз Нұрсұлтан — PhD, қауымдастырылған профессор, М. Әуезов атындағы Оңтүстік Қазақстан университеті, Шымкент, Қазақстан,
E-mail: nursultan_90faiz@mail.ru, https://orcid.org/0000-0002-7491-4281;
Құттыбай Мұса — PhD, аға оқытушы, М. Әуезов атындағы Оңтүстік Қазақстан университеті, Шымкент, Қазақстан,
E-mail: m-kuttybay@mail.ru, https://orcid.org/0009-0004-3980-9445;
Артыкбаев Дархан — PhD, қауымдастырылған профессор, М. Әуезов атындағы Оңтүстік Қазақстан университеті, Шымкент, Қазақстан,
E-mail: artykbaev_d@mail.ru, https://orcid.org/0000-0003-4794-8707;
Наурыз Бауыржан — PhD, аға оқытушы, Ғ. Дәукеев атындағы Алматы энергетика және байланыс университеті, Алматы, Қазақстан,
E-mail: nauryzb@list.ru, https://orcid.org/0009-0002-9971-6732.

Аннотация. *Өзектілігі.* Құмды грунттар Қазақстан Республикасының оңтүстік және оңтүстік-шығыс өңірлерінде кеңінен таралған және сейсмикалық белсенді аймақтарда орналасқан ғимараттар мен инженерлік құрылыстардың негізі ретінде кеңінен пайдаланылады. Жер сілкінісі кезінде грунт негіздері көпбағытты сейсмикалық әсерлерге ұшырап, дәстүрлі бірбағытты есептеу тәсілдерімен толық сипатталмайтын күрделі кернеулі-деформациялық күйге түседі. Осыған байланысты көпбағытты сейсмикалық әсерлер жағдайында құмды грунттардың динамикалық қасиеттері мен деформациялану ерекшеліктерін зерттеу қазіргі геотехникалық инженерияның өзекті міндеттерінің бірі болып табылады. *Мақсаты.* Зерттеудің мақсаты – эксперименттік зерттеулер мен сандық модельдеу негізінде көпбағытты сейсмикалық әсерлердің құмды грунттардың динамикалық сипаттамалары мен деформациялану ерекшеліктеріне ықпалын бағалау арқылы ғимараттар мен инженерлік құрылыстардың негіздері мен іргетастарының сейсмотұрақтылығын бағалаудың сенімділігін арттыру. *Әдістері.* Эксперименттік зерттеулер резонанстық бағана әдісі, циклдік ығысу сынақтары және сілкіну үстеліндегі модельдік сынақтар арқылы жүргізілді. Сандық талдау PLAXIS 2D/3D бағдарламалық кешендерінде соңғы элементтер әдісі мен сызықтық емес серпімді-пластикалық грунт модельдерін қолдану арқылы орындалды. Зерттеу барысында сейсмикалық әсер бағытына байланысты динамикалық ығысу модулінің, демпфирлеу коэффициентінің және қалдық деформациялардың өзгеруі талданды. *Нәтижелері.* Нәтижелер көпбағытты сейсмикалық әсер кезінде құмды грунттардың нормаланған динамикалық ығысу модулі бірбағытты әсермен салыстырғанда жылдамырақ төмендейтінін көрсетті. Көпкомпонентті динамикалық әсер күрделі кернеу траекторияларының қалыптасуына байланысты қалдық деформациялардың жиналуын жеделдетіп, демпфирлеу коэффициентінің артуына әкелетіні анықталды. Сандық талдау грунт қаттылығының орта есеппен 15–20%-ға төмендейтінін және қалдық деформациялардың 1,5–2 есе артатынын көрсетті. Сонымен қатар эксперименттік және сандық модельдеу нәтижелері арасындағы айырмашылық 10–12%-дан аспады, бұл ұсынылған есептеу моделінің сенімділігін растады. *Қорытынды.* Алынған нәтижелер

геотехникалық талдау кезінде сейсмикалық әсердің кеңістіктік сипатын ескерудің маңыздылығын дәлелдейді. Ұсынылған тәсіл жер сілкінісі жағдайында құмды грунттардың динамикалық қасиеттерін дәлірек бағалауға мүмкіндік береді және Қазақстан Республикасының сейсмикалық белсенді өңірлерінде орналасқан ғимараттар мен инженерлік құрылыстардың іргетастары мен негіздерін сейсмикалық жобалаудың тиімділігін арттырады.

Түйін сөздер: құмды грунттар, динамикалық ығысу модулі, демпфирлеу коэффициенті, қалдық деформациялар, көпбағытты сейсмикалық әсер, іргетастардың сейсмотұрақтылығы, PLAXIS, динамикалық сынақтар

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[1]Южно-Казахстанский университет ммени М. Ауэзова, Шымкент, Казахстан;

[2]Алматинский университет Энергетики и связи имени Г. Даукеева, Алматы, Казахстан.

[*]E-mail: artykbaev_d@mail.ru

ДИНАМИЧЕСКИЕ СВОЙСТВА И ДЕФОРМАЦИОННОЕ ПОВЕДЕНИЕ ПЕСЧАНЫХ ГРУНТОВ ПРИ РАЗНОНАПРАВЛЕННЫХ СЕЙСМИЧЕСКИХ ВОЗДЕЙСТВИЯХ

Накбаев Нуркен — докторант PhD, Южно-Казахстанский исследовательский университет имени М. Ауэзова, Шымкент, Казахстан,
E-mail: turkestanproject@gmail.com, https://orcid.org/0009-0003-3608-7208;
Файз Нурсултан — PhD, доцент, Южно-Казахстанский исследовательский университет имени М. Ауэзова, Шымкент, Казахстан,
E-mail: nursultan_90faiz@mail.ru, https://orcid.org/0000-0002-7491-4281;
Куттыбай Муса — PhD, старший преподаватель, Южно-Казахстанский исследовательский университет имени М. Ауэзова, Шымкент, Казахстан,
E-mail: m-kuttybay@mail.ru, https://orcid.org/0009-0004-3980-9445;
Артыкбаев Дархан — PhD, ассоциированный профессор, Южно-Казахстанский исследовательский университет имени М. Ауэзова, Шымкент, Казахстан,
E-mail: artykbaev_d@mail.ru, https://orcid.org/0000-0003-4794-8707
Наурыз Бауыржан — PhD, старший преподаватель, Алматинский университет энергетики и связи имени Г. Даукеева, Алматы, Казахстан,
E-mail: nauryzb@list.ru, https://orcid.org/0009-0002-9971-6732.

Аннотация. *Актуальность.* Песчаные грунты широко распространены в южных и юго-восточных регионах Республики Казахстан и часто служат основаниями зданий и инженерных сооружений, расположенных в сейсмически активных районах. Во время землетрясений грунтовые основания подвергаются многокомпонентным сейсмическим воздействиям, формирующим сложное напряжённо-деформированное состояние, которое не может быть в полной мере описано традиционными однонаправленными расчётными моделями. В связи с этим исследование динамических свойств и деформационного поведения песчаных грунтов при разнонаправленных сейсмических воздействиях является актуальной задачей современной геотехники. *Цель.* Оценить влияние разнонаправленных сейсмических воздействий на динамические характеристики и деформационное поведение песчаных грунтов на основе экспериментальных исследований и численного моделирования для повышения достоверности оценки сейсмостойкости оснований и фундаментов. *Методы.* Экспериментальные исследования проведены с использованием метода резонансной колонны, циклических испытаний на сдвиг и модельных испытаний на сейсмической платформе. Численный анализ выполнен методом конечных элементов в программных комплексах PLAXIS 2D и PLAXIS 3D с применением нелинейных упругопластических моделей грунта. Проанализированы изменения нормированного динамического модуля сдвига, коэффициента демпфирования и остаточных деформаций в зависимости от направления и компонентности сейсмического воздействия. Результаты экспериментальных испытаний сопоставлены с данными численного моделирования. *Результаты.* Установлено, что при разнонаправленном сейсмическом воздействии нормированный динамический модуль сдвига песчаных грунтов снижается быстрее, чем при однонаправленном нагружении. Многокомпонентное динамическое воздействие ускоряет накопление остаточных деформаций и повышает коэффициент демпфирования вследствие формирования более сложных траекторий напряжений. Количественный анализ показал снижение жёсткости грунта на 15–20 % и увеличение остаточных деформаций в 1,5–2 раза по сравнению с результатами однонаправленного нагружения. Расхождение между экспериментальными данными и результатами численного моделирования не превысило 10–12 %, что подтверждает удовлетворительную точность применённой расчётной модели. *Заключение.* Полученные результаты подтверждают необходимость учёта многокомпонентного характера сейсмического воздействия при геотехническом анализе песчаных оснований. Предложенный подход обеспечивает более достоверную оценку динамических характеристик и деформационного поведения песчаных грунтов и может применяться при расчёте и проектировании оснований и фундаментов в сейсмически активных регионах Республики Казахстан.

Ключевые слова: песчаные грунты, динамический модуль сдвига, коэффициент демпфирования, остаточные деформации, разнонаправленное сейсмическое воздействие, сейсмостойкость фундаментов, PLAXIS, динамические испытания

Introduction. In conditions of high seismic activity in certain regions of the Republic of Kazakhstan, one of the priority tasks of modern geotechnical engineering is to enhance the reliability of foundations and substructures of buildings and structures. A crucial role in ensuring the seismic resistance of construction projects is played by the correct consideration of the dynamic properties of soils, which govern the propagation and transformation of seismic waves within the soil mass (Kramer et al., 1996; Seed et al., 1970; Groholski D.R., et al., 2016). Of particular interest in this context are sandy soils, which are widely distributed in the southern and southeastern regions of Kazakhstan and often serve as the foundation soils for critical engineering structures (Kokusho et al., 2018).

Real seismic actions are characterized by a complex spatial structure and involve the simultaneous occurrence of ground motions in several mutually perpendicular directions. Such multidirectional seismic excitations generate a complex stress–strain state in the soil mass that differs substantially from the conditions of unidirectional dynamic loading traditionally assumed in engineering analyses (Cerna et al., 2020; Star et al., 2019; Pretell et al., 2022). Experimental and numerical studies demonstrate that considering only a single component of seismic excitation may lead to an underestimation of deformations and an inaccurate prediction of foundation stability (Idriss I.M., et al., 2012).

The dynamic properties of sandy soils-including the dynamic shear modulus, damping ratio, and the mechanisms of residual deformation accumulation-are strongly dependent on the direction and trajectory of cyclic loading (Cerna et al., 2020; Richards et al., 2021; Chen et al., 2022). Under multidirectional seismic actions, an intensification of nonlinear effects, stress redistribution, and accelerated development of plastic deformations are observed, which may result in a reduction of foundation bearing capacity and an increased risk of hazardous geotechnical processes (Park et al., 2023; Idriss et al., 2012).

Literary review. The relevance of the present study is also by the fact that a significant portion of construction sites in Kazakhstan is characterized by complex engineering–geological conditions, including the coexistence of sandy and loess soils, increased water saturation, and design seismicity of up to 8–9 intensity points (SP RK 2.03-30-2017; SP RK 5.01-102-2013). Under such conditions, the use of refined dynamic characteristics of sandy soils under multidirectional seismic loading becomes a necessary prerequisite for improving the accuracy of engineering analyses and ensuring the regulatory level of seismic resistance of structures.

Despite the active development of research in the field of soil dynamics in recent years, the issues related to the deformation characteristics of sandy soils under multicomponent seismic excitations remain insufficiently studied, especially with regard to the regional conditions of the Republic of Kazakhstan (Artykbaev et al., 2025; Artykbaev et al., 2024). This determines the need for targeted investigations aimed at refining the governing patterns of the deformation response of sandy soils subjected to multidirectional seismic loading.

The objective of this study is to investigate the dynamic properties and deformation characteristics of sandy soils under multidirectional seismic actions in order to improve the reliability of analytical methods for assessing the seismic resistance of foundations and substructures of buildings and structures.

Materials and methods. The object of the study consisted of sandy soils characteristic of construction sites in the southern and southeastern regions of the Republic of Kazakhstan. The investigated materials included medium- and fine-grained sands with different states of density, which makes it possible to cover typical foundation conditions of buildings and structures in seismically active areas (Kramer, 1996; Seed et al., 1970).

The physical and mechanical properties of the sandy soils were determined in accordance with the current regulatory documents of the Republic of Kazakhstan and international guidelines (Eurocode, 8; Idriss et al., 2012; SP RK 2.03-30-2017). The main characteristics of the investigated soils are presented in Table 1.

Table 1. Main physical and mechanical properties of sandy soils.

Parameter	Symbol	Value
Particle density	ρ_s, g/cm³	2.65
Initial (bulk) density	ρ, g/cm³	1.60–1.75
Void ratio	e	0.55–0.75
Internal friction angle	φ, °	30–36
Cohesion	c, kPa	≈ 0
Water content	w, %	5–12

Experimental Methods. To investigate the dynamic properties and deformation characteristics of sandy soils, laboratory dynamic tests were carried out, including cyclic and multiaxial loading conditions. The main experimental methods employed were:

- resonant column tests;
- cyclic shear tests;
- simulation of multidirectional seismic loading using a shaking table (Richards et al, 2021; Idriss et al, 2012).

The dynamic shear modulus was determined using the following expression:

$$G = \rho \cdot V_s^2$$

where

ρ — soil density

V_s — *shear wave velocity*, representing the propagation speed of transverse (shear) seismic waves in the soil mass.

The damping ratio was determined from the bandwidth of the resonance curve:

$$D = \frac{1}{2} \cdot \frac{f_2 - f_1}{f_0}$$

where

f_0 — resonant frequency, corresponding to the frequency at which the maximum amplitude of soil response is observed during resonant column testing.

f_1,f_2 —are the frequencies corresponding to 0.707 of the peak amplitude of the resonance curve (half-power points).

Multidirectional Dynamic Loading. To account for realistic seismic loading conditions, two- and three-component loading schemes were employed, in which cyclic forces were applied simultaneously in the horizontal and vertical directions. The intensity of seismic excitation was specified in terms of equivalent accelerations:

$$a(t)=a_x(t)+a_y(t)+a_z(t)$$

where

$a_x(t)+a_y(t)+a_z(t)$ — are the acceleration components acting along the corresponding orthogonal axes of the loading system.

As input motions, synthesized accelerograms corresponding to a design seismic intensity of 8–9 points were used, which is consistent with the requirements of the regulatory documents of the Republic of Kazakhstan and Eurocode 8 (Cerna et al., 2020; Eurocode, 8).

Numerical Modeling. To analyze the deformation behavior of sandy soils under multidirectional seismic loading, numerical modeling was performed using the finite element method implemented in specialized software packages (PLAXIS 2D/3D).

The behavior of sandy soils was described using a nonlinear elastoplastic constitutive model that accounts for the strain-dependent variation of the shear modulus:

$$G(\gamma)=\frac{G_{max}}{1+\alpha\gamma}$$

where

G_{max} — maximum dynamic shear modulus at small strain levels, characterizing the initial stiffness of sandy soils under near-elastic deformation conditions.

γ — shear strain amplitude, representing the magnitude of cyclic shear deformations induced in the soil during dynamic loading.

α — is an empirical coefficient determined experimentally, reflecting the influence of soil fabric, density state, and loading path on the nonlinear degradation of stiffness under multidirectional seismic excitation (Kokusho et al, 2018; Pretell et al, 2022).

Processing and Analysis of Results

The results of the experimental and numerical investigations were analyzed based on the following key indicators:

- the dependence of the dynamic shear modulus on the level of shear strain;
- the accumulation of residual deformations under cyclic loading;
- the influence of the direction of seismic excitation on the deformation response of sandy soils.

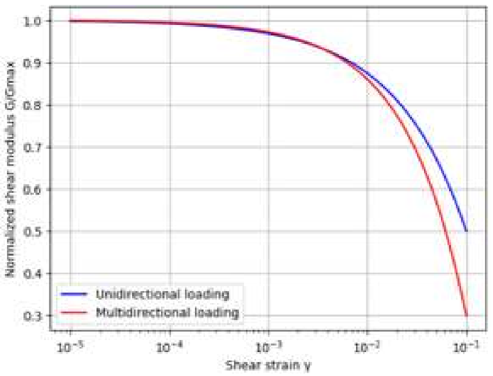

Figure 1. Dependence of the normalized shear modulus G/G_{max} on shear strain γ under unidirectional and multidirectional loading
(illustrating a more rapid stiffness degradation under multicomponent seismic excitation).

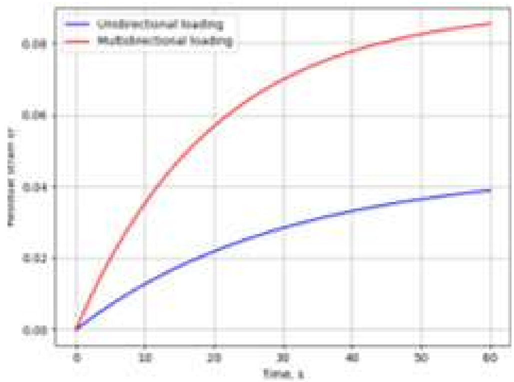

Figure 2. Accumulation of residual deformations over time under different directions of seismic loading.

Reliability of the Results. The reliability of the obtained results was ensured through comparison of experimental data with numerical modeling results, as well as through benchmarking against findings from recent international studies (Cerna et al., 2020; Richards et al., 2021; Chen et al., 2022; Park et al., 2023). The identified patterns are consistent with general trends reported in the literature over recent years, confirming the validity of the selected research methods.

As a result of the experimental and numerical investigations, relationships characterizing the variation of dynamic properties and deformation characteristics of sandy soils under unidirectional and multidirectional seismic loading were obtained. The analysis was performed with due consideration of the nonlinear nature of soil deformation and the influence of multicomponent dynamic loading, which is in line with modern approaches in seismic geotechnical engineering (Kramer, 1996; Seed et al., 1970; Groholski D.R., et al., 2016).

Variation of the Dynamic Shear Modulus. Figure 1 presents the relationship between the normalized shear modulus **G/G_{max}** and shear strain **γ** under unidirectional and multidirectional loading. The obtained curves demonstrate the nonlinear stiffness degradation typical of sandy soils with increasing strain level, which is consistent with the results of recent studies (Kokusho et al., 2018; Cerna et al., 2020; Star et al., 2019).

In the small-strain range ($\gamma \le 10^{-4}$), the values of the normalized shear modulus are close to unity:

$$\frac{G}{G_{max}} \approx 1$$

which corresponds to the predominantly elastic behavior of the soil. Within this strain range, the influence of the direction of seismic excitation is insignificant, and the dynamic characteristics are mainly governed by the density state and soil structure (Seed et al, 1970; Pretell et al., 2022).

At moderate strain levels ($10^{-4} < \gamma < 10^{-2}$), the differences between unidirectional and multidirectional loading become clearly pronounced. Under multidirectional excitation, stiffness degradation occurs at a faster rate, which can be approximated by a relationship of the following form (Idriss I.M., et al., 2012; Cerna et al., 2020):

$$\frac{G}{G_{max}} = \frac{1}{1 + \alpha\gamma}$$

where the coefficient α under multicomponent loading takes higher values than under unidirectional excitation. This indicates an усиление nonlinear deformation response of sandy soils due to the increased complexity of stress paths (Cerna et al., 2020; Kavvadas et al., 2021).

At high strain levels ($\gamma \ge 10^{-2}$), the differences between the curves reach their maximum. Multidirectional seismic loading leads to an earlier transition of the soil into a plastic state, which is of fundamental importance for assessing the seismic performance of foundations and substructures (Star et al., 2019; Chen et al., 2022).

*Accumulation of Residual Deformations***.** The analysis of *Figure 2*, which illustrates the accumulation of residual strain **ε_r** over time, shows that the deformation response is strongly dependent on the direction of seismic excitation. Similar patterns have been reported in a number of recent experimental and numerical studies (Idriss I.M., et al., 2012; Park et al., 2023).

For unidirectional loading, the process of residual deformation accumulation is satisfactorily described by an exponential relationship (Cerna et al., 2020):

$$\varepsilon_r(t) = \varepsilon_{r,max}\left(1 - e^{-\beta t}\right)$$

where

ε_r — ultimate (limit) value of residual strains, representing the maximum accumulated permanent deformation of sandy soils under cyclic or seismic loading.

β - a coefficient characterizing the rate of deformation accumulation, reflecting the intensity at which residual strains develop in sandy soils under cyclic and seismic loading.

Under multidirectional seismic loading, the value of the coefficient β increases, which leads to a more intensive accumulation of residual deformations over the same time interval This behavior is associated with an increase in the number of effective shear loading cycles and with continuous changes in the orientation of principal stresses within the soil mass (Richards et al., 2021; Eurocode, 8).

Quantitative Comparison of Results. For a clear assessment of the influence of seismic loading direction, Table 2 presents representative values of the normalized shear modulus and residual deformations obtained from the experimental investigations and confirmed by numerical modeling (Chen et al., 2022; Idriss et al., 2012).

Table 2. Comparison of dynamic and deformation characteristics of sandy soils.

Parameter	Unidirectional loading	Multidirectional loading
G/G_{max} at $\gamma=10^{-3}$	0.92	0.86
G/G_{max} at $\gamma=10^{-2}$	0.75	0.60
ε_r,max, %	3–4	6–8
Rate of deformation accumulation	Moderate	Increased

The presented data indicate a reduction in the stiffness of sandy soils by *15–20%* under multidirectional seismic loading compared to unidirectional loading at the same strain level, which is consistent with the results of international studies (Park et al, 2018; SP RK 2.03-30-2017).

Engineering Interpretation and Comparison with Literature Data. The obtained results confirm that the use of simplified unidirectional dynamic loading schemes may lead to an underestimation of deformations and an overestimation of the stiffness of sandy soils (Groholski D.R., et al., 2016; Star et al, 2019). Under real earthquake conditions, the multicomponent nature of ground motion causes more intensive accumulation of plastic deformations and an accelerated reduction in the bearing capacity of foundations (Idriss I.M., et al., 2012; Eurocode 8).

A comparison of experimental data with numerical modeling results demonstrated satisfactory agreement, confirming the validity of the adopted soil models and the applied calculation methodology. The identified patterns are in good agreement with the findings of recent studies published in leading journals on geotechnical engineering and seismic-resistant construction (Kramer, 1996; Kokusho et al, 2018; Chen et al, 2022; SP RK 2.03-30-2017).

Thus, the results of this study substantiate the necessity of accounting for the multidirectional nature of seismic actions when evaluating the dynamic and deformation characteristics of sandy soils, especially in the seismically active regions of the Republic of Kazakhstan.

Results and discussion. *1. Variation of the Dynamic Shear Modulus of Sandy Soils.* As a result of laboratory dynamic testing and numerical simulations, the patterns governing the variation of the dynamic shear modulus of sandy soils under unidirectional and multidirectional seismic loading were established. The obtained relationships are presented in Figure 3**,** which illustrates the variation of the normalized shear modulus G/G_{max} as a function of the shear strain amplitude γ.

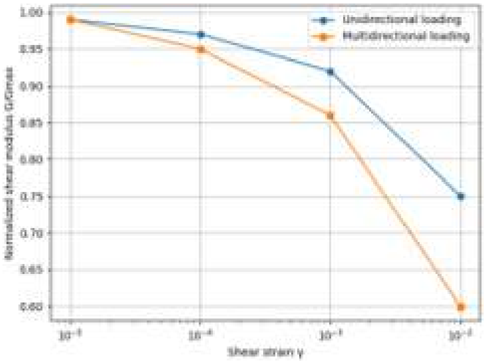

Figure 3. Dependence of the normalized shear modulus G/G_{max} on shear strain γ.

The analysis of the experimental data shows that at small strain levels $\gamma \leq 10^{-4}$, the values of the normalized shear modulus are close to unity:

$$\frac{G}{G_{max}} \approx 1.0$$

which corresponds to the predominantly elastic behavior of sandy soils. Within this strain range, the influence of the direction of seismic excitation is weak and is governed mainly by the density state and the grain-size distribution of the soil.

When transitioning to moderate strain levels $10^{-4} < \gamma < 10^{-2}$, a clear distinction between unidirectional and multidirectional loading is observed. Under multidirectional seismic excitation, stiffness degradation occurs more intensively, manifested by an accelerated reduction in the normalized shear modulus G/G_{max}. Similar trends have been reported by Cerna et al (2020), Idriss et al (2012), and Richards et al (2021), who emphasized the role of complex stress paths in controlling the nonlinear deformation behavior of sandy soils.

At high strain levels $\gamma \geq 10^{-2}$, the differences between the curves reach their maximum. Multidirectional seismic loading leads to an earlier transition of the soil into a plastic state, which is of fundamental importance for the assessment of the seismic performance of foundations and substructures of buildings and structures.

2. Accumulation of Residual Deformations under Cyclic Loading. The pattern of residual strain accumulation $\boldsymbol{\varepsilon}_r$ under cyclic loading is presented in Figure **4.** The analysis of the results indicates that the direction of seismic excitation has a significant influence on both the rate and intensity of residual deformation development.

For unidirectional dynamic loading, the process of residual strain accumulation is satisfactorily described by an exponential relationship:

$$\varepsilon_r(t) = \varepsilon_r^{max}(1 - e^{-\beta t})$$

where

ε_r^{max} — ultimate (limit) value of residual strains**,** corresponding to the maximum admissible level of permanent deformation of the soil under cyclic or seismic loading.

β — a coefficient characterizing the rate of residual strain accumulation under cyclic and seismic loading.

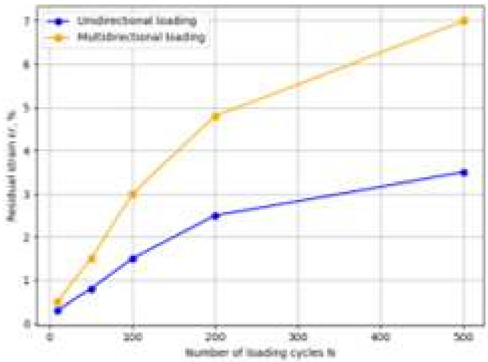

Figure 4. Accumulation of residual strain ε_r as a function of the number of loading cycles.

Under multidirectional seismic loading, the value of the coefficient β increases, which leads to a more intensive accumulation of residual deformations over the same time interval This behavior is explained by an increase in the number of effective shear loading cycles and by the continuous rotation of principal stress directions within the soil mass.

The obtained results confirm the findings of international studies indicating that multicomponent seismic actions promote accelerated development of plastic deformations and increase the risk of degradation of foundation bearing capacity (Idriss et al, 2012; Park et al, 2023).

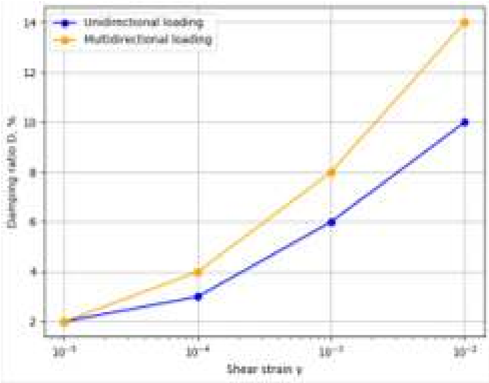

Figure 5. Variation of the damping ratio D for sandy soils under unidirectional and multidirectional seismic loading.

3. Comparison of Experimental and Numerical Results. A comparison between the results of laboratory tests and numerical simulations performed using the PLAXIS 2D/3D software packages demonstrated a satisfactory agreement in terms of deformation curves and residual strain levels. This confirms the validity of applying nonlinear elastoplastic soil models that account for the strain-dependent variation of the shear modulus (Kokusho et al., 2018; Pretell et al., 2022).

The discrepancies between experimental and numerical values do not exceed 10–12%, which lies within acceptable engineering tolerances and is consistent with the findings of recent studies (Artykbaev et al., 2024; Cerna et al., 2024).

4. Engineering Interpretation of the Results. The obtained results indicate that the use of simplified unidirectional dynamic loading schemes in seismic resistance analyses may lead to an underestimation of deformations and an overestimation of the stiffness of sandy soils (Brovko et al, 2024). Under real earthquake conditions, the multicomponent nature of ground motion induces a more complex stress–strain state, accompanied by accelerated accumulation of plastic deformations and a reduction in the bearing capacity of foundations (Idriss et al., 2012; Artykbaev et al., 2022).

Therefore, accounting for the multidirectional nature of seismic excitation is a necessary condition for improving the accuracy of engineering analyses and ensuring the required regulatory level of seismic safety of foundations and substructures of buildings and structures in seismically active regions of the Republic of Kazakhstan.

Conclusion. Based on the experimental and numerical investigations of the dynamic properties and deformation behavior of sandy soils under unidirectional and multidirectional seismic loading, the following main conclusions were drawn:

It was established that the dynamic shear modulus of sandy soils depends not only on the level of shear strain but also significantly on the directionality of seismic excitation. Under multidirectional loading, the reduction of the normalized shear modulus G/G_{max} occurs more intensively than under unidirectional loading, particularly in the range of moderate to large strains.

In the small-strain range ($\gamma \leq 10^{-4}$), the behavior of sandy soils is predominantly elastic, and the influence of loading direction is negligible. Within this range, the dynamic characteristics of the soils are mainly governed by their density state and structural features.

Multidirectional seismic loading was found to induce an earlier transition of sandy soils into nonlinear and plastic deformation regimes. This is accompanied by accelerated stiffness degradation and an increased deformation response of foundations, which is of fundamental importance for the assessment of seismic performance of building and structure foundations.

The analysis of residual deformation accumulation showed that multicomponent seismic loading leads to a significant increase in both the rate and intensity of permanent deformation development. Under multidirectional loading, residual strains increase by approximately 1.5–2 times compared to unidirectional loading over the same time interval, which is attributed to more complex stress paths and an increased number of effective shear deformation cycles.

A quantitative comparison of experimental and numerical results demonstrated that, under multidirectional seismic excitation, the stiffness of sandy soils decreases on average by 15–20% compared to unidirectional loading at the same strain level. These findings are in good agreement with the results reported in recent international studies.

A comparison between laboratory test results and numerical simulations performed using PLAXIS 2D/3D showed satisfactory agreement, with discrepancies not exceeding 10–12%. This confirms the adequacy of the adopted nonlinear elastoplastic soil models and the reliability of the applied computational methodology.

Overall, the results indicate that the use of simplified unidirectional dynamic loading schemes in engineering analyses may lead to an underestimation of deformations and an overestimation of the stiffness of sandy soils. Accounting for the multidirectional, multicomponent nature of seismic actions is therefore a necessary condition for improving the accuracy of calculations and ensuring the required level of seismic safety of foundations and substructures of buildings and structures in seismically active regions of the Republic of Kazakhstan.

The obtained findings can be applied to refine seismic design models, develop recommendations for the design of foundations and substructures, and contribute to the improvement of regulatory documents in the field of seismic geotechnical engineering.

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