3rd International Conference Advanced Mechanics: Structure, Materials, Tribology

Determination of parameters of nonlinear soil strain

Determination of parameters of nonlinear soil strain

Pavel Loginov[1, a)], Nodirbek Akbarov[1,] and Saidjon Khamidov[2]

[1]*Institute of Mechanics and Seismic Stability of Structures named after M.T. Urazbaev, Uzbekistan Academy of Sciences, Tashkent, Uzbekistan*
[2]*NRU "Tashkent Institute of Irrigation and Agricultural Mechanization Engineers", Tashkent, Uzbekistan*

[a)] Corresponding author: lopavi88@gmail.com

Abstract. Under loads up to 0.1-0.3 MPa, soils exhibit elastic properties. With increasing load, viscous, plastic, and nonlinear properties of soils appear. Nonlinear properties of soils arise due to the micro-shattering of their structure under compression. As a result, the physical and mechanical characteristics of soils (density, strain modulus, Poisson ratio, etc.) change. In this article, from the results of experiments on loam compression obtained by other authors, changes in the soil strain modulus are determined. The results of experiments on compression of clay samples are presented. From the results of their processing, the values of the strain modulus of soil (loam) are determined. A numerical solution to the nonlinear equation of state (law of strain) of soils is obtained for strain values known from the experiment, and the strain modulus of clay is determined. A comparison of the values of the strain modulus obtained from the experimental results and numerical calculations showed a good agreement.

INTRODUCTION

Numerous publications are devoted to the study of clay deformation. In [1], Grigoryan conducted research on the stress-strain state of soils based on experiments. Rykov and Skobeev [2] measured stresses in soils under short-term loads. The authors of this article conducted a large number of experiments with various types of soils, including clays. However, numerical analysis was not performed due to technical restrictions. In this regard, no study of soil deformation modulus was conducted. In [3], Balandin et al. conducted tests on clay with low moisture content to find the parameters of the Grigoryan model of soil. The research was conducted using the PG-20 setup. These experiments made it possible to determine the compressive strength of clay at different strain rates and to obtain diagrams of experimental relationships between stresses and strains. Data analysis showed that the strain rate does not have a significant effect on the deformation pattern. In [3], numerical results were obtained that were coherent with the experiment when considering the dry friction coefficient. In [4], Eremeyev et al. conducted experiments on clay with low moisture content under uniaxial loading. Eremeyev et al. realized the Split Hopkinson Pressure Bar method. The strength of clay was determined using the Grigoryan model, and the parameters of this model were determined using the Kolsky method. Based on numerical modeling, the results were compared with experiments and their consistency was shown for a dry friction coefficient equal to 0.5. In [5], Konstantinov et al. presented the results of experiments and numerical simulations of dynamic deformation of dry clay at strain rates of ~103 s-1. Clay properties were determined using the Split Hopkinson Pressure Bar method. Based on the results of the experiments, the dependencies of axial stresses on axial strains were plotted and, based on the data obtained, a parametric identification of the clay deformation model was conducted in the form of the Grigoryan constitutive relation. Good agreement was obtained between the numerical and experimental results.

Balandin et al. [6] presented a comprehensive experimental and theoretical approach to studying the problem of high-speed deformation of soft soils. This approach combines the Hopkinson-Kolsky method and the method of shock experiments on plane waves. This approach makes it possible to study high-speed deformation. In [7], Luo et al. conducted tests on the dynamic compression of soil on the Hopkinson bar. The soil was a mix of dry clay and dry stone sand. The effects of different clay/sand ratios and water content on the compressive behavior were investigated. Compressibility was determined as a function of axial stress. The results obtained for this mix were compared with pure clay and sand samples. Bian et al [8] showed the importance of considering the deformation

modulus to quantify the subsidence of soft clays. Tang et al. [9] studied the relationship between pressure and deformation of foundations built of gray clay. The influence of these factors on the deformation modulus was revealed. Tang et al. applied their results to two engineering problems and the data obtained matched the actual measured values, indicating its validity for practical application.

In [10], Pedroso et al. conducted an experimental study of a clay earth foundation with a plate loaded on it to evaluate the deformation modulus after the compaction of layers. Under load, an increase in soil moduli was recorded. Schuster et al. [11] studied the behavior of opaline clay fractions during 42 triaxial tests. The moisture content of samples, compaction, and drainage were considered. The samples exhibited brittle behavior characterized by cataclastic flow. The strength and Young's modulus of samples were close to the Reuss isostress limit. Fouad et al. [12] conducted a study of the characteristics of road pavement materials. They studied the optimal clay content at which high elastic characteristics and high resistance to plastic deformation under transport loads were maintained. The deformation modulus was assessed during triaxial testing. Wang et al. [13] showed that in the presence of 20% clay soils, the bearing capacity was reduced by 43%, and the deformation modulus was reduced by 31%. Li et al. quantitatively assessed the influence of the clay fraction and fabric on the static elastic properties of soft clayey rocks [14]. It was shown that with an increase in the clay fraction in soft clays, the deformation moduli decrease since some of the non-clay minerals are replaced by clay-water composites. Kinslev et al. [15] showed that for a reliable prediction of the occurrence of soil deformations over time, a detailed characterization of primary and secondary deformations is necessary. To better characterize time-dependent behavior, a new index, the primary time strain index, was defined

In [16], Lekstutytė et al. showed the influence of several factors on the soil deformation moduli, such as the intensity of the applied load in drained or undrained conditions, characteristics of the stress-strain state, etc. Ma et al. [17] indicated that with prolonged exposure to cyclic traffic loads, the accumulated deformation of red clay soil increases, the strength decreases, and problems, such as non-uniform settlement, arise. The influence of cyclic stress coefficients and compactness on the development of the dynamic modulus of elasticity of saturated red clay was analyzed. The purpose of the study is achieved by conducting a series of dynamic triaxial tests. The model derived by Ma et al. implements the prediction of the dynamic modulus of elasticity of red clay at an arbitrary time of cyclic vibrations. This provides a theoretical basis for correctly assessing the dynamic stability of soil under cyclic loading. Li et al. [18] proposed a tangent modulus method of undisturbed soil that is applicable to clays. Results obtained by Li et al. show that the proposed method for determining the tangential modulus of soil is theoretically feasible, and the accuracy of calculating the tangential modulus is significantly higher than that of the traditional compressive modulus.

In [19], Wang et al. considered spatial variability using the Monte Carlo method for analyzing the influence of spatial variability on time-dependent clay deformation. The authors of that article found that the uncertainty of creep deformation would accumulate over time until it becomes constant. Hov et al. [20] considered the characteristics and properties of clays using the example of Stockholm clays. As a result of the analysis, it was revealed that a common feature of clays is the low value of undrained shear strength and, as a consequence, low values of yield strength and odometer moduli. A great dependence of deformation moduli on moisture content is shown, which emphasizes the importance of selecting soil samples for experiments. In [21], Wang et al. showed that clays exhibit different long-term behavior at different cyclic stress ratios. The authors of [21] developed an improved plasticity model. A new unified interpolation function for the plasticity modulus and a new damage coefficient were given. Wang et al. compared results obtained with those available in the scientific literature and showed the adequacy of their approach, which considered the behavior of soils. Wang et al. [22] examined the evolution of the elastic modulus depending on stress using the example of the Nanjing metro. Laboratory experiments were conducted on soft clay samples taken from the Yangtze River floodplain to determine the parameters of a rainforced soil model with small strain stiffness and inverse analysis using the finite element method. The reference tangent module, the reference secant module, the reference load and unload module, and the reference initial module were determined. Studies by Wang et al. showed the importance of these parameters during the construction and operation of structures in soil.

In [23], Tang et al. showed the importance of studying the changes in the mechanical properties of clay from the Zhanjiang Formation. Soil characteristics were studied during thixotropy using triaxial consolidation and drainage tests. The results of the study [23] served as a guideline for calculating the strength and deformation thixotropy of clays. In [24], Maltseva et al. considered the stress-strain state of foundations of buildings and structures made of weak viscoelastic soils, the characteristics of which were determined experimentally. Maltseva et al. proposed a calculation method that more accurately predicts the deformation of foundations made of water-saturated viscoelastic soils than the solution for elastic and elastoplastic soils, in which pore pressure is not taken into consideration. The method of Maltseva et al. is new because it allows us to consider the residual pore pressure and viscoelasticity of soils simultaneously. In [25], Sabri et al. studies the properties of soils reinforced with fiberglass.

The results were compared with theory. A comparison of the reinforced and reference soil samples showed a 25% increase in deformation modulus after the reinforcement process at a pressure of 25 kPa. In [26], Ma et al. showed a model for calculating the settlement of a soft clay foundation using Hooke's law and the Duncan-Chang model. The authors of [26] presented a method for determining the deformation modulus of soil before and after damage under load. Jia et al. [27] showed that increasing the elastic modulus of the foundation soil would reduce the vertical deformation of the wall but increase the horizontal deformation. Hu et al. [28] investigated unsaturated compacted silty clays using triaxial tests. Experiments showed that the elastic modulus increased monotonically with strain rate at low confining pressures, but at high confining pressures, it first decreased and then increased. In [29], Guo et al. studied the deformation behavior of soft clay under long-term cyclic loading. Based on the experimental results, two equations were derived to predict the long-term elastic modulus.

Tiennot et al. [30] showed that clays influence stone properties at very low moisture content, whereas less swelling clays have an effect only when high moisture content is reached. In [31], Sun studied the deformation of saturated marine clay soils and showed the importance of conducting experiments. The mechanical characteristics of soils and their definition in various soil structures are important, for example, when calculating loads on the sides of a quarry [32]. The mechanical characteristics of soils are determined by various methods, for example, a quasi-static nature of the deformation process is observed by solving the wave problem [33]. In [34], Sultanov et al. established that the deformation moduli of clayey and loess soils under static and dynamic deformation vary depending on the strain rate, the state of the structure and the level of compressive load. Based on an analysis of the stress-strain state of soils in various sections, obtained by numerical calculations, in [35], Sultanov et al. obtained a condition under which the influence of wave processes on the mechanical characteristics of soils was excluded. This condition (formula) establishes a relationship between the wavelength, the velocity of wave propagation in soil, the thickness of the soil sample in the setup, and the duration of dynamic load. In [36], based on an analysis of the results of a numerical solution to the wave problem, Loginov et al. determined conditions for quasi-static deformation of soil under dynamic loading in the experiment. By comparing the experimental results with numerical calculations and the method of successive approximation, refined values of the mechanical characteristics of soils were determined based on the elastoviscoplastic model of soil deformation [36].

In [37], Khamidov et al. established that the maximum values of stress, strain, and particle velocity in viscous media vary according to a nonlinear law. In the initial region of the medium and near it, the stress first reaches a maximum, and then the strains and particle velocities reach maximum values [37]. In the construction and operation of buildings and the design of road pavements [38], the consideration of the possibility of seismic impact and the account for the properties of soils are also important.

METHODS

Due to the metric scale effect, laboratory tests may not reflect the deformation of soil masses in field tests. However, they can help save huge amounts of money. By studying changes in soil deformation moduli, we obtain results that reflect the situation as a whole well.

Soil properties can be described by mathematical equations between the stress and strain tensors and time. These equations are obtained from experiments. The experiment conducted considered the processes that occurred in soil under deformation. Experimental laws take into account the fact that soils are complex in composition. The experimental results show the non-homogeneity of samples. The point is that all properties inherent in soils are considered in the experimental law of compression, i.e. dependence $\sigma(\varepsilon)$ reflects this.

In studying the process of nonlinear deformation of soils based on a generalized model of a standard linear body, it is necessary to determine the deformation moduli and coefficient of internal friction (bulk viscosity) of soil.

There are two ways. First, we should formulate a mathematical statement to find a module through its components. Here, we face many difficulties. When solving them, some simplifications are made.

The second way is to find modules through experimental diagrams. Here, all the properties for various components are reflected in the curve, shown in the graph. This way is more accurate than the first. In this regard, we choose the second way.

From graph $\sigma(\varepsilon)$ we can express E_f (actual strain modulus) or E (secant strain modulus). To do this, we use dependence $\sigma(\varepsilon)$.

To find E_f, $\sigma(\varepsilon)$ is divided into small sections with the same step $\Delta\varepsilon$. Then $\Delta\sigma$ are determined, which correspond to $\Delta\varepsilon$ and $E_f = \Delta\sigma/\Delta\varepsilon$. The value of E is found as $E = \sigma/\varepsilon$, where σ and ε are the stress and strain values.

To describe the process of soil compression, we propose a mathematical model in the form of a physically nonlinear law of deformation of the standard linear body:

$$\frac{d\sigma}{E_D(\varepsilon)\text{dt}} + \mu(\varepsilon)\frac{\sigma}{E_S(\varepsilon)} = \frac{d\varepsilon}{\text{dt}} + \mu(\varepsilon)\varepsilon \tag{1}$$

Let us approximate it in difference form

$$\frac{\sigma_{i+1}-\sigma_i}{E_D(\varepsilon_i)\Delta t} + \mu\frac{0.5(\sigma_{i+1}+\sigma_i)}{E_S(\varepsilon_i)} = \frac{\varepsilon_{i+1}-\varepsilon_i}{\Delta t} + 0.5\mu(\varepsilon_{i+1}+\varepsilon_i) \tag{2}$$

$E_S(\varepsilon_i)$, ε_i are set from experimental data and viscosity modulus μ is selected and accepted. $E_D(\varepsilon_i) = 2E_S(\varepsilon_i)$.

The task is to correctly find the values of these soil characteristics using experiments. The following are the results of the numerical solution.

RESULTS

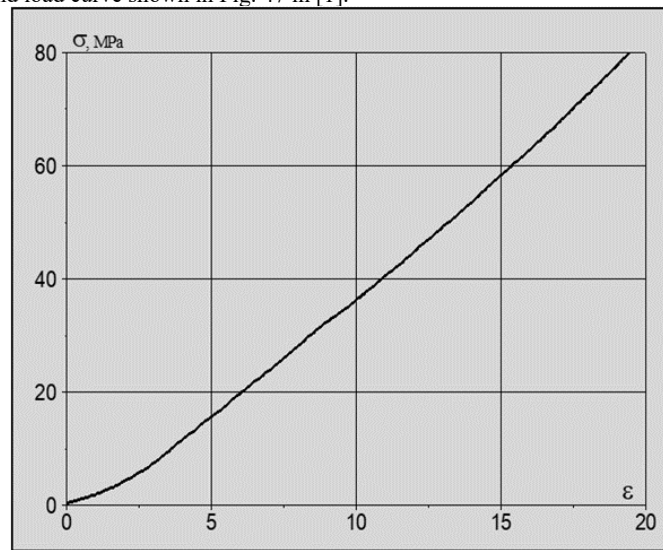Consider the second load curve shown in Fig. 47 in [1].

FIGURE 1. Second curve in Fig. 47 from [1], the stress-strain dependence
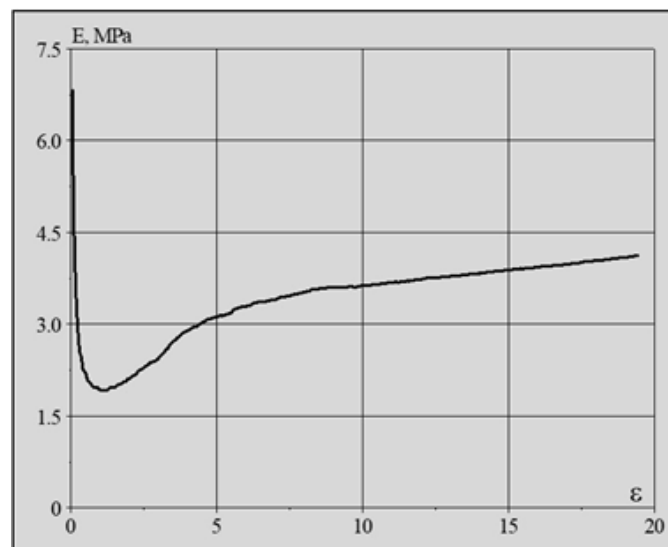

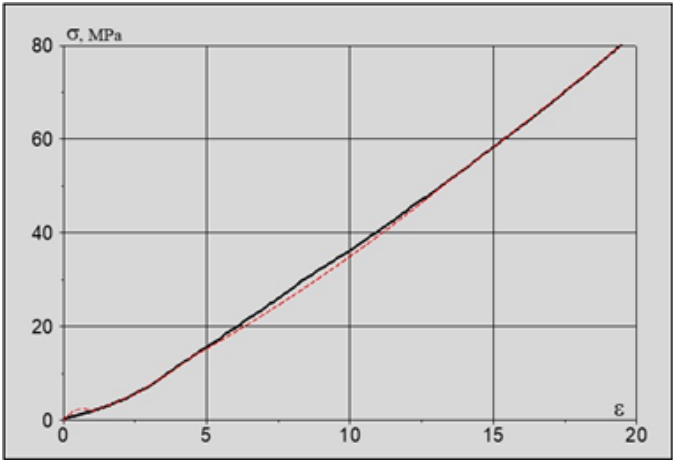**FIGURE 2.** Change in the deformation modulus of clay under loading

FIGURE 3. Stress-strain dependence. The program uses 7 points for calculation
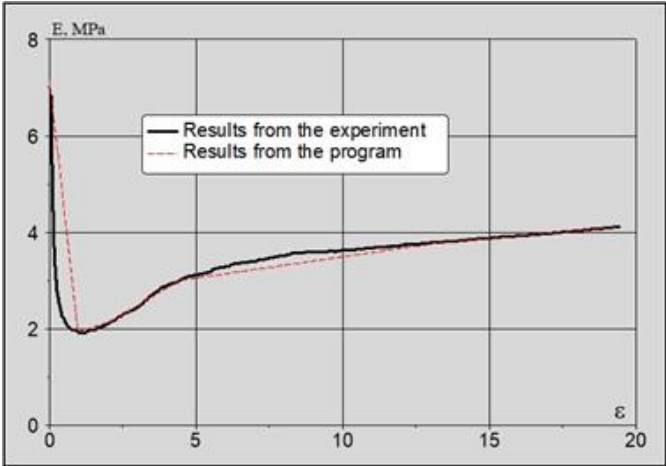

FIGURE 4. Change in the deformation modulus of clay under loading. The program
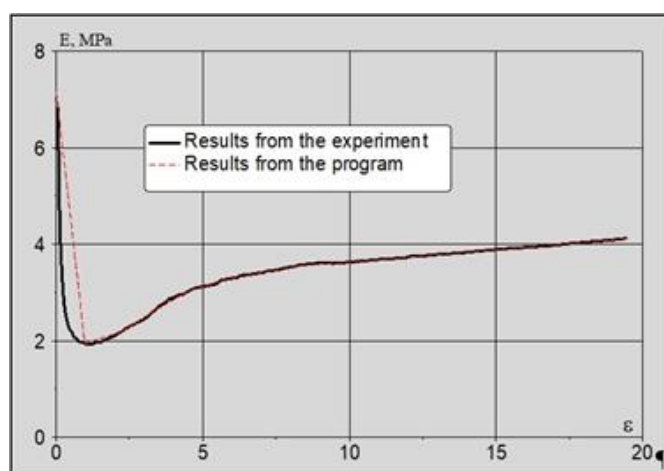
uses 7 points for calculation

FIGURE 5. Change in the deformation modulus of clay under loading. The program uses 17 points for calculation

ANALYSIS

As seen from the above graphs, with an increase in the number of points from 7 to 17, almost complete agreement between the experimental curves and the curves obtained from the program is observed. From experiments, it can be noted that soil compression using dynamic loading setup UDN-150 or a similar device is a difficult process. Note that by stress σ we mean pressure P. This must be remembered, as σ=-P. In the graphs, the minus in front of σ is omitted for simplicity. Using graphs of soil loading (experimental) and the graphs we obtained, it is possible to determine the values of the mechanical characteristics of soils.

DISCUSSION AND CONCLUSIONS

The results analysis indicates that the curves effectively describe the process of soil compression. Graphs for clays are presented based on a mathematical model in the form of a physically nonlinear deformation law of a standard nonlinear body. The numerical analysis method of the mathematical model (2) demonstrates its reliability compared to the experimentally obtained results.

ACKNOWLEDGMENTS

REFERENCES

1. S.S. Grigoryan, *Research on soil mechanics. Dissertation for the degree of Doctor of Physics and Mathematics. Sci*. (Moscow, M.V. Lomonosov Moscow State University, 1965).
2. G.V. Rykov, A.M. Skobeev, *Stress Measurement in Soils under Short-Term Loads* (Moscow: Nauka, 1978)
3. V. V. Balandin, V. V. Balandin, A. M. Bragov, L. A. Igumnov, A. Y. Konstantinov, and V. L. Kotov, "Identification and Verification of the Soil Medium S. S. Grigoryan's Model for Dry Clay," in *Adv. Struct. Mater* (Springer Science + Business Media, USA, 2023), pp. 13–46. https://doi.org/10.1007/978-3-031-43210-1_2
4. V. A. Eremeyev, V. V. Balandin, V. V. Balandin, A. M. Bragov, A. Y. Konstantinov, and L. A. Igumnov, Contin. Mech. Thermodyn. **35**, 457 (2023). https://doi.org/10.1007/s00161-023-01189-w
5. A. Konstantinov, A. Bragov, L. Igumnov, V. Eremeyev, V. V. Balandin, and V. V. Balandin, J. Appl. Comput. Mech. **8**(3), 981 (2022). https://doi.org/10.22055/JACM.2022.39321.3387

6. V. V. Balandin, A. M. Bragov, L. A. Igumnov, A. Y. Konstantinov, V. L. Kotov, and A. K. Lomunov, Mech. Solids **50**, 286 (2015). https://doi.org/10.3103/S002565441503005X

7. H. Luo, Z. Hu, T. Xu, L. Guo, and H. Lu, High-Strain Rate Compressive Behavior of a "Natural Soil" Under Uniaxial Strain State. in *Conf. Proc. Soc. Exp. Mech. Ser.* (John Wiley & Sons, Inc., Switzerland, 2018), pp. 87–92. https://doi.org/10.1007/978-3-319-62956-8_15

8. X. Bian, L.-L. Zeng, X.-Z. Li, and J.-T. Hong, Eng. Geol. **295**, 106450 (2021). https://doi.org/10.1016/j.enggeo.2021.106450

9. B. Tang, Y. Song, and X. Yin, Sustainability **14**, 13323 (2022). https://doi.org/10.3390/su142013323

10. G. O. M. Pedroso, G. Ramos, and J. Lins da Silva, Stud. Constr. Mater. **16**, e00880 (2022). https://doi.org/10.1016/j.cscm.2022.e00880

11. V. Schuster, E. Rybacki, A. Bonnelye, J. Herrmann, A. M. Schleicher, and G. Dresen, Mech. Rock Eng. **54**, 4009 (2021). https://doi.org/10.1007/s00603-021-02474-3

12. A. Fouad, R. Hassan, and A. Mahmood, Transp. Geotech. **31**, 100679 (2021). https://doi.org/10.1016/j.trgeo.2021.100679

13. X.-Z. Wang, X. Wang, Z.-C. Jin, C.-Q. Zhu, R. Wang, and Q. Ocean Eng. **134**, 77 (2017). https://doi.org/10.1016/j.oceaneng.2017.02.019

14. B. Li and R. C. K. Wong, Geophysics **82**, MR27 (2017). https://doi.org/10.1190/geo2015-0575.1

15. E. M. Kinslev, O. Hededal, I. Rocchi, and V. Zania, Soils Found. **63**, 101375 (2023). https://doi.org/10.1016/j.sandf.2023.101375

16. Lekstutytė, D. Urbaitis, G. Žaržojus, Š. Skuodis, and S. Gadeikis, Baltica **36**, 190 (2023). https://doi.org/10.5200/baltica.2023.2.8

17. H. Ma, Y. Zhuang, L. Chen, M. Lv, and S. Xu, Sustainability **15**, 26 (2022). https://doi.org/10.3390/su15010026

18. Y. Li, L. Yao, G. Chen, W. Zhao, and X. Liu, Buildings **13**, 892 (2023). https://doi.org/10.3390/buildings13040892

19. F. Wang, H. Huang, Z. Yin, and Q. Huang, Eur. J. Environ. Civ. Eng. **26**, 6096 (2022). https://doi.org/10.1080/19648189.2021.1933604

20. S. Hov and D. Gaharia, AIMS Geosci. **9**, 258 (2023). https://doi.org/10.3934/geosci.2023015

21. J. Wang, G. Xotta, N. De Marchi, and V. Salomoni, Materials (Basel). **15**, 7609 (2022). https://doi.org/10.3390/ma15217609

22. T. Wang, T. Deng, Y. Deng, X. Yu, P. Zou, and Z. Deng, Int. J., Civ. Eng. **21**, 541 (2023). https://doi.org/10.1007/s40999-022-00755-8

23. B. Tang, T. Liu, and B. Zhou, "Duncan–Chang E-υ Model Considering the Thixotropy of Clay in the Zhanjiang Formation," Sustainability **14**, 12258 (2022). https://doi.org/10.3390/su141912258

24. T. V. Maltseva, E.R. Trefilina, and T. V. Saltanova, Mag. Civ. Eng., **95**, 119 (2020). https://doi.org/10.18720/MCE.95.11

25. M.M.S. Sabri, N.I. Vatin, A.B. Ponomarev, R.R. Nurmukhametov, and I.I. Kostyukov, Materials (Basel). **15**(14), 4744 (2022). https://doi.org/10.3390/ma15144744

26. B. Ma, Z. Li, K. Cai, Z. Hu, M. Zhao, C. He, B. Chen, and X. Huang, Geofluids **2021**, 1–7 (2021). https://doi.org/10.1155/2021/8837889

27. X. Jia, J. Xu, and Y. Sun, Discret. Dyn. Nat. Soc. **2018**, 1–9 (2018). https://doi.org/10.1155/2018/6946492

28. T. Hu, D. Liu, and J. Chang, Case Stud. Constr. Mater. **12**, e00332 (2020). https://doi.org/10.1016/j.cscm.2020.e00332

29. L. Guo, J. Wang, Y. Cai, H. Liu, Y. Gao, and H. Sun, Soil Dyn. Earthq. Eng. **50**, 28–37 (2013). https://doi.org/10.1016/j.soildyn.2013.01.029

30. M. Tiennot, J.-D. Mertz, and A. Bourgès, Rock Mech. Rock Eng. **52**(6), 1599–1611 (2019). https://doi.org/10.1007/s00603-018-1672-1

31. L. Sun, Adv. Mater. Sci. Eng. **2022**, 1–11 (2022). https://doi.org/10.1155/2022/9630795

32. K.S. Sultanov, E.K. Khalikulov and P. V. Loginov, Gorn. Zhurnal **8**, 36-38 (2013). https://doi.org/

33. K.S. Sultanov, P. V. Loginov, S.I. Ismoilova and Z.R. Salikhova, Mag. Civ. Eng. **85**, 71-91 (2019). https://doi.org/10.18720/MCE.85.7

34. K. Sultanov, P. Loginov, S. Ismoilova and Z. Salikhova, "Variable moduli of soil strain," in *FORM-2019* 97, edited by A. Volkov *et al*. (EDP Sciences, Tashkent, Uzbekistan, 2019), 04013. https://doi.org/10.1051/e3sconf/20199704013

35. K. Sultanov, P. Loginov, S. Ismoilova and Z. Salikhova, "Wave processes in determining mechanical characteristics of soils," in *FORM-2019* 97, edited by A. Volkov *et al*. (EDP Sciences, Tashkent, Uzbekistan, 2019), 04009. https://doi.org/10.1051/e3sconf/20199704009

36. P. V. Loginov, Z.R. Salikhova and K.S. Sultanov, Mech. Solids **54**, 915–928 (2019). https://doi.org/10.3103/S0025654419060074

37. S.S. Khamidov, P.V. Loginov and N.A. Akbarov, "Propagation of longitudinal waves in a linear viscoelastic medium," in *EMMFT-2023* 458, edited by V. Pukhkal *et al.* (EDP Sciences, Voronezh, Russia, 2023), 08013. https://doi.org/10.1051/e3sconf/202345808013

38. A. Aleksandrov, G. Dolgih, and N. Aleksandrova, J. Phys. Conf. Ser. **1614**(1), 012095 (2020). https://doi.org/10.1088/1742-6596/1614/1/012095

AIP Publishing

LICENSE TO PUBLISH AGREEMENT FOR CONFERENCE PROCEEDINGS

This License to Publish must be signed and returned to the Proceedings Editor before the manuscript can be published. If you have questions about how to submit the form, please contact the AIP Publishing Conference Proceedings office (confproc@aip.org). For questions regarding the copyright terms and conditions of this License, please contact AIP Publishing's Office of Rights and Permissions, 1305 Walt Whitman Road, Suite 300, Melville, NY 11747-4300 USA; Phone 516-576-2268; Email: rights@aip.org.

Article Title ("Work"): Determination of parameters of nonlinear soil strain
_____

(Please indicate the final title of the Work. Any substantive changes made to the title after acceptance of the Work may require the completion of a new agreement.)

All Author(s):   Pavel Loginov, Nodirbek Akbarov, Saidjon Khamidov
_____

(Please list **all** the authors' names in order as they will appear in the Work. All listed authors must be fully deserving of authorship and no such authors should be omitted. For large groups of authors, attach a separate list to this form.)

Title of Conference: International Conference Advanced Mechanics: Structure, Materials, Tribology

Name(s) of Editor(s)   Prof. Dr. Valentin L. Popov

All Copyright Owner(s), if not Author(s):

_____

(Please list **all** copyright owner(s) by name. In the case of a Work Made for Hire, the employer(s) or commissioning party(ies) are the copyright owner(s). For large groups of copyright owners, attach a separate list to this form.)

Copyright Ownership and Grant of Rights

For the purposes of this License, the "Work" consists of all content within the article itself and made available as part of the article, including but not limited to the abstract, tables, figures, graphs, images, and multimedia files, as well as any subsequent errata. "Supplementary Material" consists of material that is associated with the article but linked to or accessed separately (available electronically only), including but not limited to data sets and any additional files.

This Agreement is an Exclusive License to Publish not a Transfer of Copyright. Copyright to the Work remains with the Author(s) or, in the case of a Work Made for Hire, with the Author(s)' employer(s). AIP Publishing LLC shall own and have the right to register in its name the copyright in the proceedings issue or any other collective work in which the Work is included. Any rights granted under this License are contingent upon acceptance of the Work for publication by AIP Publishing. If for any reason and at its own discretion AIP Publishing decides not to publish the Work, this License is considered void.

Each Copyright Owner hereby grants to AIP Publishing LLC the following irrevocable rights for the full term of United States and foreign copyrights (including any extensions):

1. The exclusive right and license to publish, reproduce, distribute, transmit, display, store, translate, edit, adapt, and create derivative works from the Work (in whole or in part) throughout the world in all formats and media whether now known or later developed, and the nonexclusive right and license to do the same with the Supplementary Material.
2. The right for AIP Publishing to freely transfer and/or sublicense any or all of the exclusive rights listed in #1 above. Sublicensing includes the right to authorize requests for reuse of the Work by third parties.
3. The right for AIP Publishing to take whatever steps it considers necessary to protect and enforce, at its own expense, the exclusive rights granted herein against third parties.

Author Rights and Permitted Uses

Subject to the rights herein granted to AIP Publishing, each Copyright Owner retains ownership of copyright and all other proprietary rights such as patent rights in the Work.

Each Copyright Owner retains the following nonexclusive rights to use the Work, without obtaining permission from AIP Publishing, in keeping with professional publication ethics and provided clear credit is given to its first publication in an AIP Publishing proceeding. Any reuse must include a full credit line acknowledging AIP Publishing's publication and a link to the Version of Record (VOR) on AIP Publishing's site.

Each Copyright Owner may:

1. Reprint portions of the Work (excerpts, figures, tables) in future works created by the Author, in keeping with professional publication ethics.
2. Post the Accepted Manuscript (AM) to their personal web page or their employer's web page immediately after acceptance by AIP Publishing.
3. Deposit the AM in an institutional or funder-designated repository immediately after acceptance by AIP Publishing.

4. Use the AM for posting within scientific collaboration networks (SCNs). For a detailed description of our policy on posting to SCNs, please see our Web Posting Guidelines (https://publishing.aip.org/authors/web-posting-guidelines).
5. Reprint the Version of Record (VOR) in print collections written by the Author, or in the Author's thesis or dissertation. It is understood and agreed that the thesis or dissertation may be made available electronically on the university's site or in its repository and that copies may be offered for sale on demand.
6. Reproduce copies of the VOR for courses taught by the Author or offered at the institution where the Author is employed, provided no fee is charged for access to the Work.
7. Use the VOR for internal training and noncommercial business purposes by the Author's employer.
8. Use the VOR in oral presentations made by the Author, such as at conferences, meetings, seminars, etc., provided those receiving copies are informed that they may not further copy or distribute the Work.
9. Distribute the VOR to colleagues for noncommercial scholarly use, provided those receiving copies are informed that they may not further copy or distribute the Work.
10. Post the VOR to their personal web page or their employer's web page 12 months after publication by AIP Publishing.
11. Deposit the VOR in an institutional or funder-designated repository 12 months after publication by AIP Publishing.
12. Update a prior posting with the VOR on a noncommercial server such as arXiv, 12 months after publication by AIP Publishing.

Author Warranties

Each Author and Copyright Owner represents and warrants to AIP Publishing the following:

1. The Work is the original independent creation of each Author and does not infringe any copyright or violate any other right of any third party.
2. The Work has not been previously published and is not being considered for publication elsewhere in any form, except as a preprint on a noncommercial server such as arXiv, or in a thesis or dissertation.
3. Written permission has been obtained for any material used from other sources and copies of the permission grants have been supplied to AIP Publishing to be included in the manuscript file.
4. All third-party material for which permission has been obtained has been properly credited within the manuscript.
5. In the event that the Author is subject to university open access policies or other institutional restrictions that conflict with any of the rights or provisions of this License, such Author has obtained the necessary waiver from his or her university or institution.

This License must be signed by the Author(s) and, in the case of a Work Made for Hire, also by the Copyright Owners. One Author/Copyright Owner may sign on behalf of all the contributors/owners only if they all have authorized the signing, approved of the License, and agreed to be bound by it. The signing Author and, in the case of a Work Made for Hire, the signing Copyright Owner warrants that he/she/it has full authority to enter into this License and to make the grants this License contains.

1. The Author must please sign here (except if an Author is a U.S. Government employee, then please sign under #3 below):

Pavel Loginov	29.09.2025
Author(s) Signature	Print Name	Date

2. The Copyright Owner (if different from the Author) must please sign here:

_____
Name of Copyright Owner   Authorized Signature and Title   Date

3. If an Author is a U.S. Government employee, such Author must please sign below.
The signing Author certifies that the Work was written as part of his/her official duties and is therefore not eligible for copyright protection in the United States.

_____
Name of U.S. Government Institution (e.g., Naval Research Laboratory, NIST)

_____
Author Signature   Print Name   Date

PLEASE NOTE: NATIONAL LABORATORIES THAT ARE SPONSORED BY U.S. GOVERNMENT AGENCIES BUT ARE INDEPENDENTLY RUN ARE NOT CONSIDERED GOVERNMENT INSTITUTIONS. (For example, Argonne, Brookhaven, Lawrence Livermore, Sandia, and others.) Authors at these types of institutions should sign under #1 or #2 above.

If the Work was authored under a U.S. Government contract, and the U.S. Government wishes to retain for itself and others acting on its behalf, a paid-up, nonexclusive, irrevocable, worldwide license in the Work to reproduce, prepare derivative works from, distribute copies to the public, perform publicly, and display publicly, by or on behalf of the Government, please check the box below and add the relevant Contract numbers.

☐ Contract #(s) _____   [1.16.1]

LICENSE TERMS DEFINED

Accepted Manuscript (AM): The final version of an author's manuscript that has been accepted for publication and incorporates all the editorial changes made to the manuscript after submission and peer review. The AM does not yet reflect any of the publisher's enhancements to the work such as copyediting, pagination, and other standard formatting.

arXiv: An electronic archive and distribution server for research article preprints in the fields of physics, mathematics, computer science, quantitative biology, quantitative finance, and statistics, which is owned and operated by Cornell University, http://arxiv.org/.

Commercial and noncommercial scholarly use: *Noncommercial* scholarly uses are those that further the research process for authors and researchers on an individual basis for their own personal purposes. They are author-to-author interactions meant for the exchange of ideas. *Commercial* uses fall outside the author-to-author exchange and include but are not limited to the copying or distribution of an article, either in hard copy form or electronically, for resale or licensing to a third party; posting of the AM or VOR of an article by a site or service where an access fee is charged or which is supported by commercial paid advertising or sponsorship; use by a for-profit entity for any type of promotional purpose. Commercial uses require the permission of AIP Publishing.

Embargo period: The period of time during which free access to the full text of an article is delayed.

Employer's web page: A web page on an employer's site that highlights the accomplishments and research interests of the company's employees, which usually includes their publications. (See also: Personal web page and Scholarly Collaboration Network).

Exclusive License to Publish: An exclusive license to publish is a written agreement in which the copyright owner gives the publisher exclusivity over certain inherent rights associated with the copyright in the work. Those rights include the right to reproduce the work, to distribute copies of the work, to perform and display the work publicly, and to authorize others to do the same. The publisher does not hold the copyright to the work, which continues to reside with the author. The terms of the AIP Publishing License to Publish encourage authors to make full use of their work and help them to comply with requirements imposed by employers, institutions, and funders.

Full Credit Line: AIP Publishing's preferred format for a credit line is as follows (you will need to insert the specific citation information in place of the capital letters): "Reproduced from [FULL CITATION], with the permission of AIP Publishing." A FULL CITATION would appear as: Journal abbreviation, volume number, article ID number *or* page number (year). For example: Appl. Phys. Lett. 107, 021102 (2015).

Institutional repository: A university or research institution's digital collection of articles that have been authored by its staff and which are usually made publicly accessible. As authors are encouraged and sometimes required to include their published articles in their institution's repository, the majority of publishers allow for deposit of the Accepted Manuscript for this purpose. AIP Publishing also allows for the VOR to be deposited 12 months after publication of the Work.

Journal editorial office: The contact point for authors concerning matters related to the publication of their manuscripts. Contact information for the journal editorial offices may be found on the journal websites under the "About" tab.

Linking to the Version of Record (VOR): To create a link to your article in an AIP Publishing journal or proceedings, you need to know the CrossRef digital object identifier (doi). You can find the doi on the article's abstract page. For instructions on linking, please refer to our Web Posting Guidelines at https://publishing.aip.org/authors/web-posting-guidelines.

National Laboratories: National laboratories are sponsored and funded by the U.S. Government but have independent nonprofit affiliations and employ private sector resources. These institutions are classified as Federally Funded Research and Development Centers (FFRDCs). Authors working at FFRCs are not considered U.S. Government employees for the purposes of copyright. The Master Government List of FFRDCs may be found at http://www.nsf.gov/statistics/ffrdclist/.

Personal web page: A web page that is hosted by the author or the author's institution and is dedicated to the author's personal research interests and publication history. An author's profile page on a social media site or scholarly collaboration network site is *not* considered a personal web page. (See also: Scholarly Collaboration Network; Employer's web page).

Peer X-Press: A web-based manuscript submission system by which authors submit their manuscripts to AIP Publishing for publication, communicate with the editorial offices, and track the status of their submissions. The Peer X-Press system provides a fully electronic means of completing the License to Publish. A hard copy of the Agreement will be supplied by the editorial office if the author is unable to complete the electronic version of the form. (Conference Proceedings authors will continue to submit their manuscripts and forms directly to the Conference Editors.)

Preprint: A version of an author's manuscript intended for publication but that has not been peer reviewed and does not reflect any editorial input or publisher enhancements.

Professional Publication Ethics: AIP Publishing provides information on what it expects from authors in its "Statement of ethics and responsibilities of authors submitting to AIP Publishing journals" (http://publishing.aip.org/authors/ethics). AIP Publishing is also a member of the Committee on Publication Ethics (COPE) (http://publicationethics.org/), which provides numerous resources and guidelines for authors, editors, and publishers with regard to ethical standards and accepted practices in scientific publishing.

Scholarly Collaboration Network (SCN): Professional networking sites that facilitate collaboration among researchers as well as the sharing of data, results, and publications. SCNs include sites such as Academia.edu, ResearchGate, and Mendeley, among others.

Supplementary Material: Related material that has been judged by peer review as being relevant to the understanding of the article but that may be too lengthy or of too limited interest for inclusion in the article itself. Supplementary Material may include data tables or sets, appendixes, movie or audio clips, or other multimedia files.

U.S. Government employees: Authors working at Government organizations who author works as part of their official duties and who are not able to license rights to the Work, since no copyright exists. Government works are in the public domain within the United States.

Version of Record (VOR): The final published version of the article as it appears in the printed journal/proceedings or on the Scitation website. It incorporates all editorial input, is formatted in the publisher's standard style, and is usually viewed in PDF form.

Waiver: A request made to a university or institution to exempt an article from its open-access policy requirements. For example, a conflict will exist with any policy that requires the author to grant a nonexclusive license to the university or institution that enables it to license the Work to others. In all such cases, the Author must obtain a waiver, which shall be included in the manuscript file.

Work: The "Work" is considered all the material that comprises the article, including but not limited to the abstract, tables, figures, images, multimedia files that are directly embedded within the text, and the text itself. The Work does not include the Supplementary Material (see Supplementary Material above).

Work Made for Hire: Under copyright law, a work prepared by an employee within the scope of employment, or a work that has been specially ordered or commissioned for which the parties have agreed in writing to consider as a Work Made for Hire. The hiring party or employer is considered the author and owner of the copyright, not the person who creates the work.