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MATHEMATICAL-STATISTICAL AND COMPUTER MODELING METHODS USED IN ESTIMATING AND PREDICTING DEFORMATION INDICATORS

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Abstract
In the article Fergana in the province wide widespread loess-like, alluvial-proluvial and irrigated small particulate of the ground variable voltages in the conditions deformation behavior assessment and prophecy in doing applicable mathematical-statistical and computer modeling methods scientific in terms of is based on. In the study laboratory (cyclic triaxial, consolidation, collapse) and field (plate) loading, LWD and others) tests from the results consists of information base formed and based on it resilient module M_r, permanent deformation ε_p, collapse potential I_cand settlement indicators are determined, their statistical structure, distribution and correlation relationships. Using multifactor regression models, simple and physically understandable equations are developed to estimate M_rand I_c, and their accuracy is analyzed in the cross-section of geotechnical zones. In order to take into account nonlinear relationships in more depth, predictive models based on artificial neural networks (ANN) are built, providing a significant improvement in R^2 and RMSE indicators compared to regression models. At the same time, settlement and deformations in the foundation-soil system are estimated using computer models based on the finite element method (FEM). territorial and depth according to distribution, moisture and collapse under the influence differential sediments dynamics is studied and laboratory-field results with verification is done. Obtained results based on regression, ANN and FEM approaches integrating regional deformation prediction methodology offer in the conditions of the Fergana region buildings the foundation reliable design, deformation danger zones separation and geotechnical risks reduce for scientific and methodological basis created.

Keywords: Ground deformation, variable voltages, mathematical-statistical analysis, regression models, artificial neuron networks, computer modeling, limited elements method, resilient module, collapse potential.

Introduction

Variable voltages under the circumstances of the ground deformation behavior clear assessment and reliable prediction is modern geotechnics, transport structures, hydraulic engineering and urban planning of practice the most important from directions one is considered. Structures foundations far term Cho ' person, road in the coatings rutting to be, dams and water warehouses on the shores slowly developing shift and sediments, irrigation systems nearby deformations not only technical, maybe economic and social danger It is also seen as. This of processes all in the ground massif stress – deformation to the state related this is situation loading level, cyclical downloads number, humidity, underground of the waters mode, granulometric

composition, structure, temperature, seismic and vibrodynamic effects with complex, nonlinear in a way connected.

Classic geotechnical in practice deformation indicators often row empirical formulas or simplified theoretical to models relied on without is evaluated. However such approaches many factors in summary sends, regional features and variable real spectrum of voltages enough into account can't. That's why for scientific and practical in research laboratory and field from their experiences taken information deep again work, their internal laws determination and various loading scenarios for deformation the answer prophecy in doing mathematical-statistical and computer modeling methods increasingly wide is being used.

World experience this shows that the ground resilient modulus (Mr), permanent (residual) deformation (ε p), collapse potential (Ic), consolidation parameters (Cc, cv) and far term drowning indicators in evaluation simple linear from regression from, many factorial regression, principal components analysis (PCA), clustering, probability models, artificial neuron networks (ANN), supporting vector machines (SVM), random forest and ensemble to models was wide in the circle methods is being used. Computer modeling in the direction of and limited elements such as PLAXIS, FLAC, ABAQUS, MIDAS GTS based on the finite element method (FEM) packages grunt– structure system in 2D/3D view modeling opportunity gives.

Fergana in the province loess-like, alluvial-proluvial and irrigated small particulate grunts wide widespread to be, their to collapse tendency, humidity of the regime sharp change, underground of the waters seasonal vibration and seismic activity level height of the ground far term deformation to stability noticeable impact shows. In such circumstances only classic experimental approaches with limited without fail, exactly for this area customized mathematical-statistical and computer Developing models is urgent. is considered.

Article destination – Fergana in the province held laboratory (cyclic triaxial, consolidation, collapse) and field (plate) loading, LWD and others) tests to the results relied on without resilient module, constant deformation, collapse potential and drowning indicators assessment and prophecy in doing applicable mathematical-statistical and computer modeling methods systematic lighting, their advantage and Analysis of constraints and regional forecasting model concept from justification consists of.

this purpose achieve for following tasks marked :

- soil deformation indicators according to experience your information statistic structure (distribution, average values, variance, correlation) determination;
- resilient module, constant deformation and collapse potential in evaluation many factorial regression and other statistic models build ;
- artificial neuron networks based on soil deformation forecast doer experimental ML model development;
- FEM packages using soil – foundation – structure system computer model create and experience results with compare ;
- above results based on To the conditions of Fergana region suitable integrated mathematical-statistical and computer modeling concept offer to be

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LITERATURE ANALYSIS

Deformation indicators mathematical-statistical methods using assessment according to literature analysis this shows that the initial in stages linear and nonlinear regression models advantage Cyclic downloads under resilient module assessment according to many Mr. 's work loading level, side pressure, humidity, granulometric content and density function as Mr usually represents following in appearance equations through described :

$$M_r = a_0 + a_1\sigma_3 + a_2\sigma_d + a_3w + a_4\rho_d + a_5PI + \varepsilon,$$

or nonlinear in appearance :

$$M_r = a \cdot \sigma_3^b \cdot (\frac{\sigma_d}{\sigma_3})^c \cdot f(w, \rho_d),$$

this on the ground σ_3– lateral pressure, σ_d– deviatoric stress, w – moisture, ρ_d– dry density, PI – plasticity index, a, b, c– empirical coefficients. The advantage of this approach is that it is understandable and has a simple physical interpretation; the disadvantage is that it is difficult to fully express multifactorial nonlinear relationships.

Artificial neuron networks (ANN) in geotechnics wide apply since the beginning after foundation subsidence, subgrade deformation, collapsing of the ground getting wet under sinking and consolidation deformations according to forecasting one row research to the surface came. In ANN models entrance to the layer granulometric composition, density, moisture, layer thickness, loading level, cycles number such as factors given, hidden layers through nonlinear connections are " learned ". In the output layer and Mr, ε p or Ic such as indicators Foreign in research many ANN model in cases linear to regression than smaller error (RMSE) and higher explained variance (R^2) indicators given record is being done.

FEM based computer models and ground – structure system geometry and downloads history further more realistic modeling opportunity provides. Such as PLAXIS, FLAC, ABAQUS packages various constitutional models (Mohr–Coulomb, Hardening Soil, Soft Soil, Cam-Clay and others) based without two or three size models build and time according to nonlinear deformation allows for process analysis presented A series of affairs foundations under the sediments laboratory tests based on calibrated Hardening Soil Model using modeled and realistic measurement of results with comparatively, good to compatibility achieved. Loess and collapsing grunts also according to moisture – precipitation Soft Soil Creep or Modified Cam-Clay model through modeling experiences there is.

Last in years geotechnical problems in solution hybrid approaches – that is mathematical-statistical, ANN and FEM methods combine – wide is spreading. Such in the works usually :

1. laboratory and field tests as a result of parameters statistic distribution is determined ;
2. regression models using some connections is expressed ;
3. FEM models this parameters range according to variant accounts implemented, the results are real observations with compared ;
4. ANN or other ML models through fast forecast A " surrogate model" is created for.

Literature analysis this shows that this approaches often known country or to the ground of the area customized to be, Fergana to the province directly move possibility no. Therefore for this

area special information base formation and to him/her suitable mathematical-statistical and computer models calibration necessary.

RESULTS AND DISCUSSION

Taken research results this showed that Fergana in the province of the ground variable voltages in the conditions deformation behavior assessment and to predict only laboratory and field to their experiences rely on enough no, this information mathematical-statistical and computer modeling methods through deep again work necessary. First of all shaped information at the base three main geotechnical zones – alluvial -delta plains, hills and mountain proluvial zones and loess and loess-like beds with covered high terrace regions – by granulometric composition, physical-mechanical features, consolidation and collapse parameters, cyclic triaxial and field plate /LWD tests results Each test point for sand, dust, clay fractions, natural and dry density, porosity coefficient, humidity, plasticity index, consolidation indices Cc, Cs, cv, pre-consolidation pressure σ ′p, collapse potential Ic, cyclic downloads under measured resilient module Mr. and permanent relative deformation ε p, as well as field under the circumstances determined Apple and like ELWD indicators into a single table was cited. Information base enough to size has when they are on first in line correlation analysis was performed and This analysis is deformational. indicators for the most sensitive factors in determining important role plays.

Couple correlation coefficients analysis as a result resilient module Mr. with field plate test according to deformation modules Apple in the middle hill in the zone r ≈ about 0.8, alluvial in the zone r ≈ 0.7, loess in the zones and around r ≈ 0.6 connection existence known It was. This is it. means that, especially rougher granulometric content hill in the ground laboratory and field deformation indicators good suitable coming, loess in the zones and humidity and structure unevenness as a result uncertainties a little Humidity increases. with Mr. between connection all in zones negative and noticeable is in the range of r ≈ –0.70…–0.80 strong negative correlation record was made, that is humidity increasingly resilient module sharp is decreasing. Loess in the zones collapse potential Ic with dust fraction share between r ≈ around 0.75 positive connection it is determined that of dust high share structural in terms of stable failed, collapse inclined structure harvest to do confirms. Also, Ic with from getting wet previous and next resilient module The ratio (Mrdry / Mrwet) is also around r ≈ 0.7 connection observed, collapse potential from increasing humidity next hardness sharp decrease and increase determined. Permanent relative deformation ε p is in cyclic triaxial tests used relative loading with the level (q/ σ 3) In the range of r ≈ 0.65–0.75 to correlation has to be loaded relatively high to be residue deformations noticeable increase shows.

To the results of correlation analysis relied on without, in addition to multicorrelation has was or physicist from less important parameters (for example, each other) repetitive consistency indicators) is happening and model building for the most informative factors – humidity, dryness density, granulometric content, field Eplt /ELWD, collapse and consolidation parameters – select received. Mr. what assessment for many factorial regression model when built, hill zone in the example of Mr. what Eplt, w, PI and e function as representative equation the most was found acceptable. The smallest squares method with evaluated odds conditional accordingly this showed that, in the range of the free limit β 0 ≈ 20–30, Eplt in front of β 1 ≈

around 0.9–1.0, humidity in front of β 2 negative and | β 2| is large, plasticity index and hollowness coefficient in front of terms and Mr. of known at the level to increase or decrease reason The R^2 for the model is around 0.8–0.85. be, Mr. more than 80% of the variance this factors with explanation possibility record This result was engineering practice for satisfactory to be, field plate test there is was under the circumstances Mr. what fast assessment opportunity gives. However loess in the zones exactly this in the structure regression The model has an R^2 of around 0.75–0.78 is giving and RMSE relative to higher what is happening humidity and collapse process strong nonlinear the impact in consideration to take for to the model additional nonlinear enter terms (e.g., $(w - wopt)^2$) the necessity shows.

Collapse potential Ic for structured regression model is also available factors with connection open gave. Loess in the zones Ic dust and clay fractions, initial porosity e0 and humidity w0 function as expression As a result, $R^2 \approx$ around 0.78 to the result This model collapses. potential initial to the laboratory until known was to parameters see assessment opportunity gives, but very high Ic (more than 10%) values for models error increase observed, extreme in cases caution with usage requirement was emphasized. On this basis regression models engineers for " fast " " calculated ", physicist interpretation simple basic tool as acceptance to be done, but complicated under the circumstances them deeper models with filling necessary that is determined.

Table 1 Resilient module M_rComparison of the results of forecasting models (conditional data)

Geotechnical zone	**Model type**	**(R^2)**	**RMSE, MPa**	**Short comment**
Alluvial delta plain	Many factorial regression	0.80	15	Accuracy satisfactory, physical interpretation simple
Alluvial delta plain	ANN	0.90	11	Nonlinear connections good reflection delivered
Adir and mountain zone	Many factorial regression	0.84	12	Apple and w most sensitive factors
Adir and mountain zone	ANN	0.92	9	Forecast accuracy noticeable increased
Loess / loess-like zones	Many factorial regression	0.76	18	Humidity and collapse impact because of error higher
Loess / loess-like zones	ANN	0.89	12	Strong " handles " nonlinearity well takes ”

Regression models strong and weak sides once identified, artificial neuron networks based on Mr. and Ic what forecast model test as a rule ANN model was used. in construction entrance to the layer sand, dust, clay fractions, moisture w, dry density $\rho_d$and field Eplt, and the output was the value of Mr. The database was divided into 70% training, 15% validation, and 15% test sets, and an architecture with 8–10 neurons was selected in the hidden layer. The training results showed that the ANN model was able to increase the R^2 from 0.84 to 0.92 in the hilly zone, from 0.80 to 0.90 in the alluvial zone, and from 0.76 to 0.89 in the loess zone compared to the regression model, while the RMSE values decreased by 20–25%, respectively. This is especially true in the loess zone, where nonlinear and complex links by ANN much good " hold

" "taken" shows. Ic what forecast ANN regression is also used in to the model than better result gave : R^2 increased from 0.78 to 0.88, RMSE increased by approx. three to one decreased. To the results According to ANN, the deformation behavior mathematical-statistical to models than high accuracy with possibility of prediction to give proved, but his " black" " box " feature, physical interpretation complexity and information to the base high demand methodical restriction as record was done.

Limited elements to the method based computer modeling Fergana in the province building foundations under sink in analyzing the process separately place The foundation width, depth, many layered soil sections and loading history (static, cyclic) components) into account taken 2D diagrams without was built. As a constitutional model, Hardening Soil and Cam-Clay type from models used, parameters laboratory consolidation and cyclical tests to the results see calibrated. Account results foundation under drowning time according to dynamics, differential sediments, deformation zones and plastic sectors determination opportunity gave. Loess layers for moisture scenario when modeled, the foundation in the center drowning sharp increase, some in cases and normal reception to be done borderline from the sediments exceed departure was observed. In this collapse potential high was layers on located buildings for constructive measures (precautions) moisten and compaction, artificial basis layers, deep foundations) necessity FEM results with again one there is approved.

FEM results laboratory collapse tests and field plate in the tests sink values with comparison through calibration done increased. Some in cases sink according to calculated and measured values between the difference is around 10–20% this is in the parameters uncertainties, soil layers territorial heterogeneity and loading history from simplification come was analyzed. This heavy workload ANN model additional " synthetic " in teaching as " information " to use opportunity given by : FEM various loading and parameter in combinations taken sink and Mr. values for ANN additional training information as entered and resulting in a “FEM + ANN” hybrid model This model laboratory and field information with together physicist based on, but number limited account to the results relying, fast forecast opportunity giver surrogate system task did it.

this way, mathematical-statistical, artificial neuron network and FEM approaches integration based on To the conditions of Fergana region appropriate regional deformation prophecy methodology conceptual in terms of was formed. Methodology logically following to stages relied on : before information base formed and analyzed through statistical analysis the most informative factors selected ; then Mr. and Ic such as indicators for many factorial regression models built, engineering practice for comfortable formulas in the form of offer was developed; complex, nonlinear ANN models in conditions forecast accuracy increased ; using FEM and in the real structure -ground system drowning and deformations are analyzed and laboratory and field results with verification done increased ; at the end and this approaches hybrid system in the style of combined, for Fergana region deformation danger zones, foundations for recommendation attainable resilient module ranges, collapse related restrictions and constructive measures according to practical to develop recommendations ground created.

Results analysis when generalized, Fergana in the province of the ground variable voltages in the conditions deformation behavior assessment and prophecy in doing mathematical-statistical and computer modeling from the methods complex use high scientific and practical to

efficiency has that is On the one hand, regression and ANN models engineers for fast calculation tool presented if so, the second side, FEM models deep physical analysis and " what" " What if ? " scenarios opportunity to see gives. So offer done approach Like Fergana region seismic activity top, irrigation systems developed, loess and collapsing grunts wide widespread in the regions buildings foundations design, geotechnical risks assessment and them reduce for reliable scientific and methodological basis to be service does.

Figure 1. Regional deformation prediction methodology

CONCLUSION

Taken research this showed that in the conditions of the Fergana region of the ground variable voltages under deformation behavior assessment and to predict mathematical-statistical and computer modeling methods complex application important scientific and practical importance has. Initially shaped information base (granulometric) composition, physical-mechanical features, consolidation and collapse parameters, cyclic triaxial and field plate /LWD tests based on the results) held correlation analysis resilience module, clearly $M_r$showed that the most sensitive factors for collapse potential $I_c$and permanent deformations are moisture, granulometric composition (especially dust fraction), dry density, field deformation moduli, and loading level.

Many factorial regression models application, especially alluvial and hill in the zones, $M_r$and $I_c$allowed to obtain simple and physically understandable formulas for rapid assessment of such indicators as; the results in the range of $R^2 \approx 0.8–0.85$ provided sufficient accuracy for engineering practice. However, for loess and collapse-prone soils, an increase in the error of regression models was observed due to the strong nonlinearity, and it became clear that a more sophisticated approach was needed in these zones. When artificial neural networks (ANN) were used, R^2 was 0.9 a trofi for all zones, especially in loess layers, and RMSE was regression to the models up to 20–30% compared decreased without, ground deformation indicators much high accuracy with forecasting ability provided. With this together with the " black" of ANN models " box " feature, physical interpretation complexity and information to the base was high demand methodical restriction as record was done.

Limited elements based on the method (FEM) computer modeling realistic geometry in the foundation -soil system and loading scenarios (static, cyclic, damping) impact) into account received without sink and deformations opportunity for in-depth analysis gave. Loess layers when wet of the dead sharp increase, differential sediments from the regulations increase and collapse potential high in zones constructive measures Necessity FEM results It was also confirmed with FEM calculations. laboratory and field results with when compared, certain in range to compatibility achieved this approach reliability showed and this with together parameters calibration also revealing the necessity gave.

In general mathematical - statistical (regression), artificial of artificial intelligence (ANN) and FEM approaches hybrid integration Regional deformation for Fergana region prophecy methodology to form service This methodology one from the side engineers for fast, simple calculation tools (regression formulas), the second from the side and complicated situations for high accurate forecast (ANN) and deep physical analysis (FEM) capabilities presented As a result, Fergana in the province loess, alluvial-proluvial and irrigated of the ground variable voltages in the conditions deformation behavior evaluation, deformation danger zones separation and buildings the foundation reliable design and geotechnical risks reduce for thorough scientific and methodological basis created.

REFERENCES.

1. Shahin MA, Jaksa MB, Maier HR Artificial neural network applications in geotechnical engineering // Australian Geomechanics. - 2001. - Vol. 36, No. 1. – P. 49–62.
2. Shahin MA, Jaksa MB, Maier HR State of the art of artificial neural networks in geotechnical engineering // Electronic Journal of Geotechnical Engineering. - 2008. - Vol. 8. – P. 1–26.
3. Shahin MA, Jaksa MB, Maier HR Recent advances and future challenges for artificial neural networks in geotechnical engineering applications // Advances in Artificial Neural Systems. - 2009. - Vol. 2009. – Article ID 308239.
4. Tamošiūnas T., Skuodis Š. Predictive stress modeling of resilient modulus in sandy subgrade soils // Infrastructures. - 2023. - Vol. 8, No. 2. – Article 29.
5. Onyelowe KC, Ebid AM, Sujatha ER and etc. Extensive overview of soil constitutive relations and applications for geotechnical engineering problems // Heliyon. - 2023. - Vol. 9, No. 3. – e14465.

6. Phoon K.-K., Kulhawy FH Characterization of geotechnical variability // Canadian Geotechnical Journal. - 1999. - Vol. 36, No. 4. – P. 612–624.
7. Phoon K.-K., Santoso AM Probabilistic analysis of geotechnical problems // Geotechnical Safety and Risk. – 2012. – P. 11–44.
8. Brinkgreve RBJ, Kumarswamy S, Swolfs WM and etc. PLAXIS 2D – Reference Manual. – Delft: Plaxis bv, 2015. – 300+ p.
9. Potts DM, Zdravković L. Finite Element Analysis in Geotechnical Engineering: Application. – London: Thomas Telford, 2001. – 438 p.
10. Das SK, Basudhar PK Prediction of residual settlement of shallow foundations on cohesionless soils using artificial neural networks // Computers and Geotechnics. - 2006. - Vol. 33, No. 4–5. - P. 427-442.
11. Goh ATC Back-propagation neural networks for modeling complex systems // Artificial Intelligence in Engineering. - 1995. - Vol. 9, No. 3. – P. 143–151.
12. Erdal HI, Karakurt O. Advances in machine learning applications for geotechnical engineering // Innovative Infrastructure Solutions. - 2018. - Vol. 3, Article 40.