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Stress distribution in ash and slag mixtures

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Abstract. In the design of roads, a number of engineering tasks that requires determining the stress state of the road structure are solved: estimating the stability of the embankment, calculating the load resistance, predicting deformations, determining the loads affecting on the culverts and communication lines in the body of the roadbed, etc. The solution of these tasks in the design of ash and slag mixture embankments cannot be performed due to the insufficient knowledge of the stress state formation mechanisms in similar solids. The article reviews and compares theoretical solutions for predicting stresses in a continuous and granular environment arising in the body under the flat plate effect on its surface. The tests were carried out on a solid with a compaction coefficient (0.95), with five values of humidity (from 22 to 38 % by weight). The results of experimental studies on the change in pressure arising in the ASM at different depths, when exposed to the vertical load from the stamp, are presented. The value of the shear resistance to increase by 21 % with an increase in moisture content from 22 % to 28 %, and with further growth returned to almost the original values without any visible effect on the stress distribution. Conclusions about the insignificant effect of humidity on the stress distribution in the ASM were drawn (at least under the chosen experimental conditions). Estimates of mathematical models for stress prediction in relation to the bulk body from the ash and slag mixture are given. To determine the distribution environment coefficient in the Fröhlich model, a correlation dependence between the CBR and the modulus of elasticity was derived. This correlation allowed us to link the theoretical solutions of Gonzalez and earlier experiments on the evaluation of the modulus of elasticity of embankments from ASM at different humidity with the stresses distribution.

1. Introduction

When designing roads, a number of engineering tasks are solved that requires determining the stress state of the road structure: estimating the stability of the embankment, calculating the load stability, predicting deformations, determining the loads acting on the culverts and communication lines in the embankment body, etc. In Russia and abroad, the use of man-made soils, industrial wastes and coal ash from the dumps of thermal power plants for the construction of embankments, in particular, planning embankments, etc. is becoming increasingly important. However, the verification of the stability of such structures cannot be performed with adequate accuracy due to the insufficient knowledge of the formation mechanisms of the stress state in such solids.

The studies in the field of stress state prediction have been carried out by a number of researchers, but mainly they relate to natural soils or abstract granular materials. Therefore, the solution of these tasks is complicated due to the insufficient knowledge of the mechanical characteristics of ash and slag mixture and the formation mechanism of the stress state in similar solids with a special structure, significantly different from natural soils.

In contrast to the first classical solutions for predicting the stressed soil state under the influence of an external load (Boussinesq, Flaman, Mitchell, Das, etc.) [1–3], modern concepts of the stressed

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state formation take into account the difference in the structure of different soil types and the body state influence on stress distribution (structure influence is confirmed Beringer′s, Santamarine′s, Tadanaga′s Clarke′s experiments) [4–7]. Depending on the soil type, solutions of continuum mechanics or mechanics of granular materials are usually applied. In both cases, taking into account the different soil behavior, either distributive environment capacity coefficients are introduced into the solution, which is a numerical stress distribution characteristic, or the difference in mechanical parameters is taken into account.

In the continuous environment mechanics, the solutions involving distribution Fröhlich′s environment capacity coefficients are mainly used for stress prediction [8, 9]. Also, within structural mechanics framework, engineering approximations and theories based on certain angle presence of the environment distributive capacity (Piskunov, Timoshenko, Matveev, Klein) are sometimes used [10–14]. These theories are mostly developed to describe the quasi-flat environment behavior (soils with a finely dispersed structure), which, fine-grained ash and slag mixture can be attributed to (according to the granulometric composition analysis) [15, 16].

I.I. Kandaurov developed mechanics of granular materials (MGM) in contrast to the continuous environment mechanics, where individual particles are the object of investigation, the interaction between which is predicted on the basis of probability theory methods [17]. Unlike the basic formulas for continuous environment mechanics, the MGM initially took into account the difference in particles interaction by the environment coefficient distribution (Kandaurov). A priori, we believe that the granular environment mechanics laws can also be applied to the ash and slag mixture, since the shape and features of the contact pressure transfer between the ash and slag mixture particles are similar to the fine sands that are the description object of the MGM [17–19].

The use of the distribution environment coefficients allows application of the same solutions for different soils by changing this coefficient value. The distribution environment coefficients, as a rule, should be determined from stress-strain experiments, but such studies are complex and expensive. Therefore, a number of researchers (Alexandrov, Gonzalez, Muller, Matveev, and others) attempted to relate the stress distribution mechanism to soil parameters determined in the laboratory [9, 11, 20].

So Gonzalez linked Frohlich′s parameter and the main parameter used for the road structures design in Western countries – the California bearing ratio (CBR). Empirical relationships connecting these quantities are presented in the form of formulas:

$$n = 2 \cdot \left(\frac{CBR}{6} \right)^{0.337}, \quad n = 2 \cdot \left(\frac{CBR}{6} \right)^{0.1912}, \tag{1, 2}$$

where n is the stress distribution coefficient introduced by Fröhlich;

CBR is the California bearing capacity rate, %.

Analyzing Kandaurov′s work and developing them, Muller found a relationship between the coefficient of lateral pressure ζ and the coefficient of the distributive environment capacity v_p :

$$\xi = \frac{1}{8 \cdot \nu_p}. \tag{3}$$

In soil mechanics, lateral pressure coefficient determination, as a rule, requires complex tests. At the same time, there are dependencies deduced for the lateral pressure coefficient calculating through the internal friction angle φ. We also know our own solutions for determining the distribution environment coefficient. A number of mathematical models are presented in Table 1 [21–25].

The presented formulas make it possible to determine the environment distributional capacity coefficient based on the material parameters, but there is no data on the applicability of any solution for the entire variety of man-made soils (for example, for the ash and slag mixture) in the sources. It is not known which of the formulas for a solid or granular environment gives greater accuracy when estimating the stress state in the ash and slag mixture body. For this reason, the article conducts experimental verification of existing solutions.

Table 1. Formulas associated with the internal friction angle.

Authors	Determining coefficient formula	
	lateral pressure	Environment distribution capacity
J. Biarez and co-authors	$\xi = \frac{1-\sin\varphi}{1+\sin\varphi}$	$\nu_p = \frac{1+\sin\varphi}{8(1-\sin\varphi)}$
M.D. Bolton	$\xi = \frac{1-\sin(\varphi-11.5)}{1+\sin(\varphi-11.5)}$	$\nu_p = \frac{1+\sin(\varphi-11.5)}{8-8\sin(\varphi-11.5)}$
Brooker-Ireland	$\xi = 0.95-\sin\varphi$	$\nu_p = \frac{1}{7.6-8\sin\varphi}$
R.Ya. Popilsky and co-authors	$\xi = \mathrm{tg}^2\left[\frac{\pi}{4}-\frac{\varphi}{2}\right]$	$\nu_p = \left(8\,\mathrm{tg}^2\left[\frac{\pi}{4}-\frac{\varphi}{2}\right]\right)^{-1}$
Mayne-Kulhawy	$\xi = 1-0.998\sin\varphi$	$\nu_p = \left(8(1-0.998\sin\varphi\right)^{-1}$
G.I. Pokrovsky	$\xi = 1-0.74\,\mathrm{tg}\varphi$	$\nu_p = \left(8(1-0.74\sin\varphi)\right)^{-1}$
Badanin and co-authors	–	$\nu_p = \mathrm{ctg}(\varphi+45°)$

2. Methods

To evaluate the most adequately describing the stress ash and slag mixture body state mathematical models, experimental studies were performed using original strain gauges located at different body depths. Body pressure along the flat plate axis is measured by vertical load. The prediction of the stresses values at the sensor position depth was carried out according to the coupling formulas presented above, based on the ash and slag mixture parameters, given in the paper [26].

An analogue of pressure sensors (pressure cells) constructed on the basis of liquid level sensors Piezus APZ 2422 (Figure 1) was used to determine the stresses (pressure measurements).

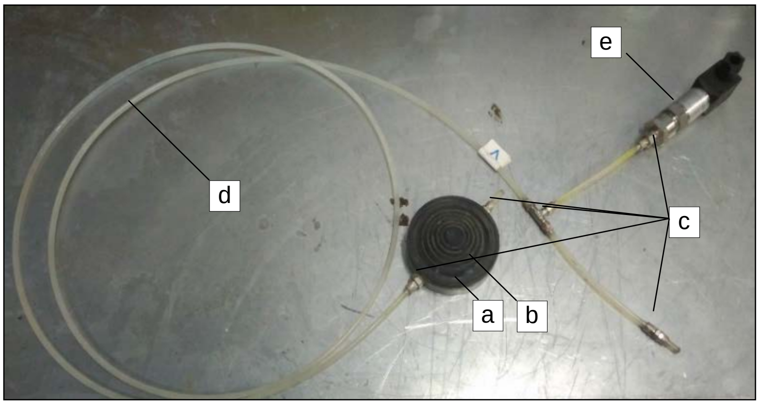

Figure 1. Soil pressure sensor (pressure cell) based on a Piezus APZ 2422 level sensor: a – metal chamber; b – rubber membrane; c – fittings made of nickel-plated brass; d – polyamide tubes; e – liquid level sensor Piezus APZ 2422.

Each pressure sensor is a closed system, filled with multigrade oil hydraulic thickened consisting of the following elements: an all-metal chamber with diameter of 82 mm, height of 18 mm; membrane Rm-L-Nd82 mm made of oil-resistant rubber (used to transfer pressures in ultra-sensitive environment separators); fittings with union nut for hydraulic systems of nickel-plated brass; tubes with an inner diameter of 3 mm and a wall thickness of 1 mm made of polyamide PA 12 Rilsan for transferring pressures up to 40 Bar; level sensor Piezus APZ 2422 with a measuring limit of 6 bar. The connection between the membrane and the chamber is carried out using a mixture for cold cure NILOS TL-T70 TOPGUM.

To obtain readings from the sensors (output signal 4–20 mA), the TRM-1-SHCH11.U.I. measuring instrument-regulator with built-in 12 V power supply, necessary for level sensors, was used. Before installation in the body, the sensors were calibrated in a universal test machine IR 5081-5.

To carry out the experiment, the laboratory tray was filled with the ash and slag mixture in layers, moistened to optimum moisture and compacted to a seal factor of 0.95. The lower layer had thickness of 15 cm. The subsequent layers were stacked according to the same algorithm, but with thickness of 7–8 cm. After preparing each layer, a laser level was set on it, which was directed along the marks to the design sensor position. The sensor positioning is shown in Figure 2.

Figure 2. Sensor positioning in the ash and slag mixture body.

The height sensor position was monitored using a level. In the center of the sensor, a rack was installed and a height mark was taken relative to the reference point. After that, a manual backfill was carried out with the tamping of the ash and slag mixture around the sensor. Three pressure sensors were laid in depth. The pressure was created by means of a hydraulic press stamp with diameter of 33 cm. The force produced by the plate was measured by an electronic dynamometer. Stamping to the installation site (along the sensor axis) was carried out using the laser level, which was used for sensor stacking (Figure 3).

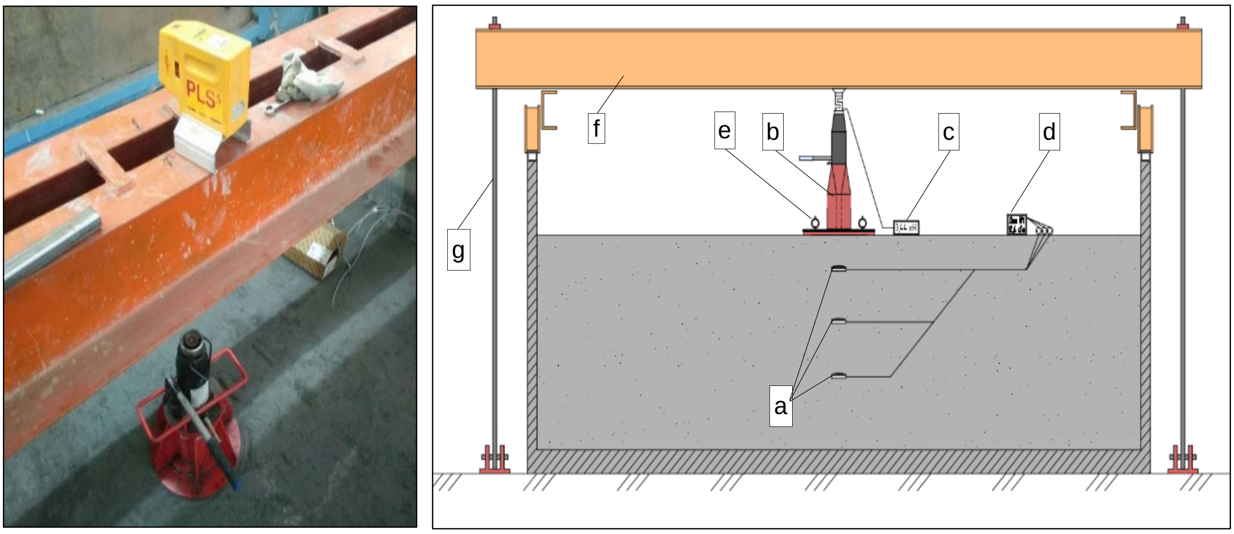

Figure 3. Placement of measuring equipment and a test stamp:
on the left – stamp positioning; on the right – equipment layout.
a – pressure sensors; b – press stamp; c – force gauge; d – measuring instrument-regulator;
e – displacement indicators; f – resistant system; g – anchor rod.

The rigid plate was successively loaded to a pressure of 50, 100, 150 and 200 kPa. The choice of the maximum pressure of 200 kPa is assigned to the known maximum voltage transmitted to the subgrade surface. After reaching the required pressure, a cascade plate discharge was carried out to 100, 50 and 1 kPa. Further, the stamp was re-loaded and unloaded, similarly to the first cycle. During the tests at each stage, movements along the displacement indicators mounted on the opposite edges of the stamp and the forces created by loading the die were measured.

After the test cycle, the body was hydrated, the calculated humidification step was 3 % for mom in the first three points and 5 % for the last two. Water was distributed through a watering gun with the function of watering can. The amount of water supplied to the ash and slag mixture body was monitored by the electronic digital water meter. Additional moisture control was carried out by sampling in layers along the body depth.

A number of test cycles were performed at a moisture content of 22 %, 25 %, 28 %, 33 % and 38 % by mass (corresponding to relative humidity values of 0.58, 0.68, 0.74, 0.87, 1.00).

In addition to the stressed state study, after each test cycle, the modulus of elasticity at different ash and slag mixture humidity was calculated. The need to determine the elasticity modulus is due to the fact that this indicator is the main parameter for the roadbed and road clothes bearing capacity calculating in the Russian Federation. In addition, according to research by Heukelom and C.R. Foster, W. Heukelom and A.J.G. Klomp Green and Hall, Witczak and Powell et. al Putri et. al, the elasticity modulus and CBR have a direct functional connection. This mathematical connection was established by us for fine-grained ash and slag mixture for the first time [27, 30].

To compare to the experimental data, theoretical solutions for determining the main maximum stresses along the circular plate axis are chosen: Kandaurov, Harr, Olson, Timoshenko, Piskunov and Matveev (Table 2).

Table 2. theoretical solutions for main maximum stresses determining along round plate axis.

Authors	*Determining formula*
I.I. Kandaurov	$\sigma_z = p\left[1-\exp\left(\frac{-R^2}{2z^2\nu}\right)\right]$
M. Harr	$\sigma_z = p\left[1-\exp\left(\frac{-4R^2\nu_p}{z^2}\right)\right]$
R. Olson	$\sigma_z = p\left[1-\frac{a^n}{\left(1+a^2\right)^{n/2}}\right], \quad \sigma_z = p\cdot\left[1-\left(\frac{z^n}{R^2+z^2}\right)^{\frac{n}{2}}\right]$
V.G. Piskunov, N.N. Ivanov	$\sigma_z = B\cdot\exp\left(-\gamma z\right)$
G.K. Klein	$\sigma_z = p\cdot\left(1+\frac{2\cdot z}{D_o}\cdot\mathrm{tg}\ f(\varphi)\right)^{-2}$
S.A. Matveyev (modified)	$\sigma_z = p\cdot\left[\exp\left(\nu\left\{1-\gamma z\right\}\right)\right]^{(1-\nu)}$
where p is pressure value on circular punch sole, MPa; z is point depth along stamp axis where the stress is determined, m; R is plate radius, m; λ is Kandaurov′s environment distribution capacity coefficient λ is Hara′s environment distribution coefficient; γ is attenuation coefficient; n is Frohlich′s environment distribution coefficient; D_o is plate diameter, m; $f(\varphi)$ is internal friction angle function, numerically equal to natural slope angle, deg.	

To compare the experimental and theoretical data, Gonzalez′s formulas were used to determine Frohlich′s distribution environment coefficient, which is part of Olson′s formula. The transition to CBR was carried out through the previously obtained empirical formula:

$$CBR = 0.57\cdot E^{0,922}, \tag{4}$$

where CBR is the California bearing capacity rate, %;

E is elasticity modulus, MPa.

An analysis using the mechanics of granular materials formulas (Kandaurov, Harr) was carried out using Muller′s formula to determine Hara′s distribution environment coefficient through the lateral pressure coefficient. The lateral pressure coefficient was determined through the internal friction angle according to the dependences developed by Biares, Bolton, Jaky, and others (Table 1) [21–25].

Comparison of the experimental data and the values predicted on Piskunov′s approximation basis was carried out by using the same dependences for lateral pressure coefficient determining (the attenuation coefficient is related to the lateral pressure coefficient) as for mechanics of granular materials solutions (Table 2).

Comparison with *Klein's* formula was conditional, since there is no data on the friction angle function form in his formula. For this reason, the comparison was carried out only to evaluate the possibility of stress shape and values describing when selecting this function value.

3. Results and Discussion

According to the provisions given earlier, and formulas (4), CBR variation patterns and elasticity modulus from humidity have similar values. Consequently, in stress state prediction using Olson′s formula with Fröhlich′s environment distribution capacity coefficient, found on Gonzalez′s theory basis, elasticity modulus has a significant effect. Elasticity modulus dependence on humidity is shown in Figure 4 [26].

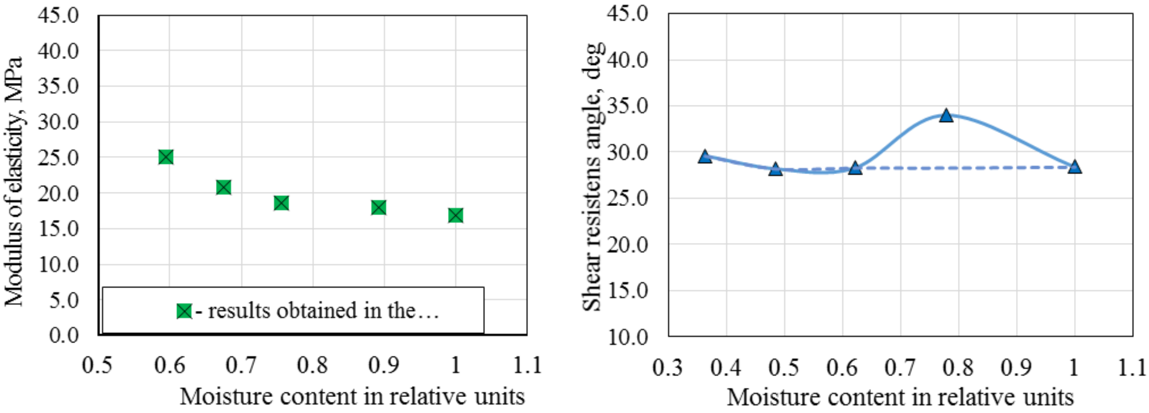

Figure 4. Ash and slag mixture parameters changing with humidity change.

You can notice a significant decrease in elasticity modulus when the body is moistened, which should seriously affect the stress distribution according to *Gonzalez's* theory. However, almost identical stress distributions were noted for almost all ash and slag mixture moisture content values in an experimental study (Figure 5).

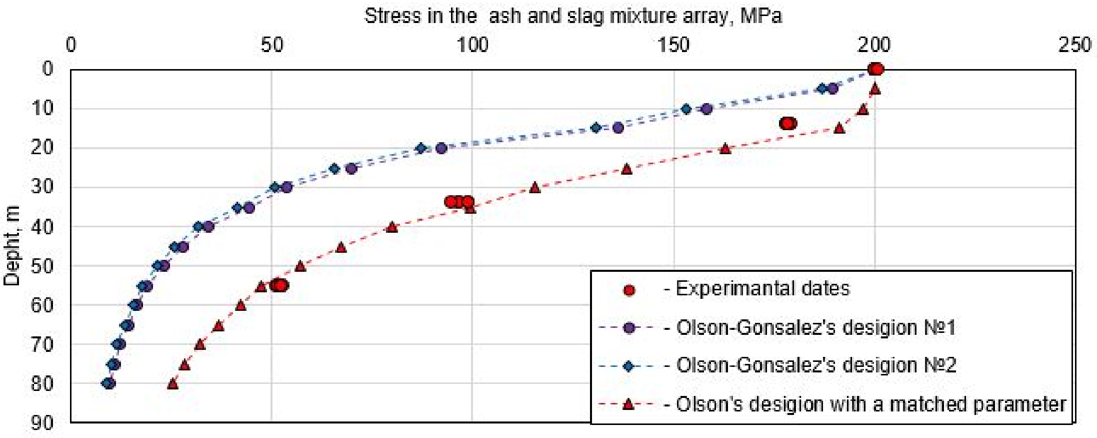

Figure 5. Stress distribution comparison according to Olson's formula and experimental data.

An attempt to describe the stress distribution using Olson's solution, formulas (1) and (2), showed the unsuitability (the approximation error amounted to 26.2 % and 27.8 %, respectively). In the rest, Olson's formula, when selecting the parameter (n = 6.5), describes the experimental data with an average approximation error (3.7 %). At the same time, when predicting a stress state according to mechanics of granular materials theory and Klein's formula, the stress distribution mainly depends on internal friction angle. Internal friction angle for the ash and slag mixture investigation basically depends on compaction degree and much less on the moisture material content.

Although in Figure 4 there is a significant increase in resistance angle to shear (internal friction angle), it is not a true physical friction angle. Apparently, its increase at the optimum humidity is caused by an increase in water films retention forces (capillary connectivity effect), which even more increased the shear resistance with increasing vertical load and particles approaching.

In the range of humidity values chosen for the experiment, internal friction angle (if the effect of the retaining water films was not taken into account) varied by only 1 %. That practically does not affect stress values arising in the body.

Among the dependencies presented above (see Table 2), there are those in which relationship forms between the parameters have already been proposed (Matveev), or are unclear (Piskunov), or are not completely defined (Klein). However, it is also relevant to evaluate stress distribution form in them and to compare it with the experimental data. Engineering methods comparison with experimental data is presented in Figure 6.

The analysis showed with the greatest approximation, by choosing the damping parameter, Piskunov's solution gave an error of approximation of 5.8 %. Function value choice for proposed by Klein dependence, namely $f(x)$, gave the approximation error of 3.7 % with the best approximation, as was Olson′s solution in Fröhlich′s modification. Matveev's solution (modified), when calculated with lateral pressure coefficient substitution from the experimental data [26], gives an error of 4.9 % approximation.

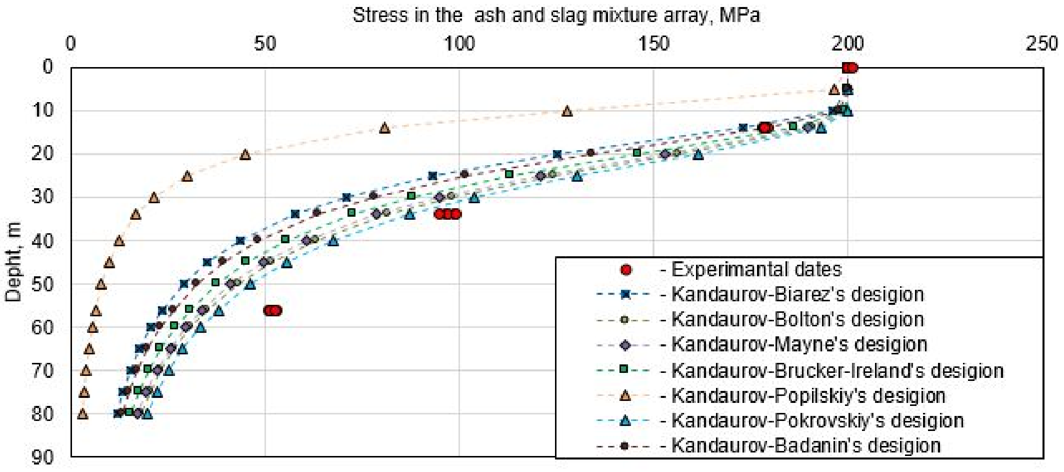

Figure 6. Stress distribution comparison by engineering solutions and experimental data

Experimental data comparison was carried out the same with mechanics of granular materials solutions. Comparison with Kandaurov's decision, in which environment distribution capacity coefficient determination was carried out through internal friction angle based on the dependencies of Table 1, is shown in Figure 7.

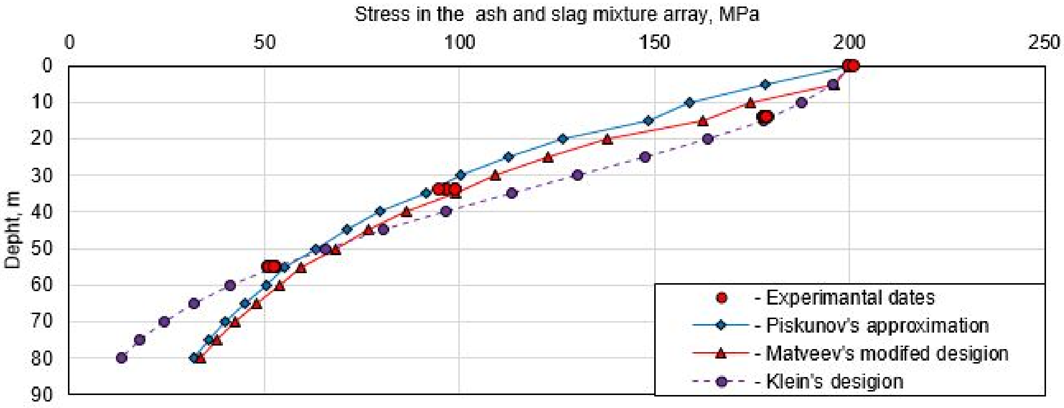

Figure 7. Stress distribution in the ash and slag mixture body by MGM solutions and experimental data.

The greatest approximation in comparison with the experimental data was given by the formula for determining Pokrovsky′s distribution ability coefficient, the approximation error for it was 9.2 %. Popilsky's dependence has the lowest accuracy, the approximation error for which was 45.1 %. All other dependencies are between the error values of 11 % to 20 %.

Kandaurov′s solution greatest accuracy, achieved when selecting environment distribution capacity parameter (0.15) is 5.3 %. Although Kandaurov's solution can describe the stress distribution in the ash and slag mixture, it has less accuracy than Olson's solution. Moreover, when using the Muller′s formula for the transition to Hara′s distribution environment coefficient, distribution values turn out to be identical to the Kandaurov′s solution.

4. Conclusion

The following learning points emerged from the findings of the study.

1. Stress distribution in the body from the investigated ash and slag mixture (at the boundary experiment values) is almost independent of this technogenic soil humidity.

2. The formulas proposed by Gonzalez to determine Frohlich′s distribution environment coefficient proved to be unsuitable for predicting stress distribution in fine-grained ash and slag mixture body.

3. It is established that the solution, expressed for a continuous environment (Olson) by selecting Frohlich′s parameter, gives the most accurate results for stress state prediction in the ash and slag mixture body among all the investigated dependencies (3.7 % approximation error). However, due to the limited data, it is not possible to identify the relationship between the ash and slag mixture parameters and the value of the Fröhlich′s parameter (at this stage of the study).

4. Engineering approximations of the experimental data (Piskunov, Matveev) gave satisfactory results, but even when substituting the lateral pressure coefficient obtained from laboratory tests, their accuracy was less than Olson's solution.

5. The formula proposed by Klein (as well as the Olson′s solution) gives a high approximation accuracy, but, unlike continuous environment mechanics solution, it allows us to predict only the maximum values of the principal stresses under circular plate axis.

6. Mechanics of granular materials solutions (using Jaky′s, Bolton′s, Brucker-Ireland′s, Mayne-Kulhawy′s, Popilsky′s and Pokrovsky′s dependencies) showed a lower accuracy of forecasts than the continuous environment mechanics solutions with parameter selection. However, when choosing a parameter, experimental values approximation by Kandurov's solution gives quite acceptable results with an average error of 5.3 %.

In future, it is planned to conduct a series of similar studies with different solid densities of ash and slag mixture. It will help to predict the stress state in the layers of solids and embankments made of the man-made soils more exact.

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Распределение напряжений в массиве из золошлаковой смеси

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Ключевые слова: строительство; золошлаковая смесь; распределение напряжений; математическое моделирование.

Аннотация. При проектировании автомобильных дорог решается ряд инженерных задач, требующих определения напряженного состояния дорожной конструкции: оценка устойчивости насыпи, расчет сдвигоустойчивости, прогнозирование деформаций, определение нагрузок, действующих на водопропускные сооружения и коммуникации в теле земляного полотна и т. д. Решение этих задач при проектировании насыпей земляного полотна из золошлаковой смеси (ЗШС) не могут выполняться в связи со слабой изученностью механизмов формирования напряженного состояния в подобных массивах. В статье проводится обзор и оценка теоретических решений для прогнозирования напряжений в сплошной и зернистой среде, возникающих в массиве из ЗШС от воздействия на его поверхность нагрузки в виде плоского штампа. Испытания проводили на массиве с коэффициентом уплотнения (0,95), при пяти значениях влажности (от 22 до 38 % по массе). Представлены результаты экспериментальных исследований по изменению давлений, возникающих в ЗШС на разной глубине, при воздействии вертикальной нагрузки от штампа. Величина сопротивления сдвигу возрастала на 21 % при увеличении влажности от 22 % до 28 %, и при дальнейшем росте возвращалась практически до исходных значений без видимого влияния на распределение напряжений. Поэтому сделан выводы о незначительном влиянии влажности на распределение напряжений в ЗШС (по крайней мере при выбранных условиях эксперимента). Даны оценки существующих математических моделей для прогнозирования напряжений применительно к насыпному уплотнённому массиву из ЗШС. Для определения параметров распределительной среды в модели Фрелиха, была выведена корреляционная зависимость между CBR и модулем упругости, которая позволила связать теоретические решения Гонзалеза и более ранние опыты по оценке модуля упругости ЗШС при разной влажности с распределением напряжений.

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