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THE STRESS-STRAIN STATE INVESTIGATION OF UNDERGROUND STRUCTURES ON THE BASIS OF SOIL MODELS WITH ADJUSTED INPUT PARAMETERS

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The article evaluates the possibility of using Hardening Soil Model and Coulomb-Mohr soil models with corrected input parameters by investigating the stress-strain state (SSS) of underground structures.

Keywords: underground structure, finite element method (FEM), Coulomb-Mohr model, Hardening Soil model, stress-strain station (SSS).

Introduction. The modeling of underground structures has to take into account a number of features fully: the difficult and nonlinear nature of the load, which remains until the occurrence of areas with different histories of use in the soil, as well as the nonlinear proper generation and deformation. Correct numerical modeling of such nonlinear deformation of underground structures is possible only for the use of modern soil models.

The selection and use of such models nowadays is a problem because of their low prevalence and excellent tradition of soil mechanics in the countries of the former Soviet Union, a large number of input parameters, the definition of which is not verified by regulatory documents, and the availability of quality reference literature, as most are written in foreign languages.

At present, various mathematical models of soil can be used in numerical modeling: Coulomb-Mohr Model, Hardening Soil Model and its derivatives (Hardening Soil Small-strain), Soft Soil and its derivatives, Cam-Clay, etc. They are characterized by varying degrees of complexity and range of use.

In the practice of design, the simple Coulomb-Mohr elastic-plastic soil model, which is based on the Hooke's law and Coulomb strength conditions, is very often used for geotechnical calculations. This model requires the determination of all four calculated soil parameters: total modulus E, Poisson coefficient ν, clutch c, and internal friction angle φ. The advantages of simple models are the small number of input parameters and the simplicity of the equations. However, the simulation results, when used, may be fairly approximate and inconsistent with the actual data.

The Hardening Soil elastic-plastic model is an advanced nonlinear soil model that is versatile and suitable for modeling a wide range of soil soils. This model describes soil behavior more accurately. It separates the shear and bulk components of the deformations, since the dependences of the deformations on the stresses during the triaxial compression method test (in fact, the deviatoric load is modeled in the instrument) and the compression clutch (the isotropic load is modeled in the instrument). The "strain-strain deviator" curve in the model is described by a hyperbolic function. Unloading-reloading deformations occur on a separate trajectory. Three modules of deformation are used for realization of the above in the model: the modulus of deformation on the secular at 50% strength E_{50}, - the modulus of deformation at unloading and reloading E_{ur}, the odometric module E_{oed}. The problems that may arise when these and other input parameters of the Hardening Soil Model are determined and the solutions are described in [1].

Another advantage of the Hardening Soil Model is that it describes the dependence of the deformation modules on the stress level:

$$E = E^{ref}\left(\frac{c\cos\varphi - \sigma_3\sin\varphi}{c\cos\varphi + p^{ref}\sin\varphi}\right)^m . \quad (1)$$

The purpose of this article is to evaluate the possibility of using the Hardening Soil Model with insufficient input parameters using empirical formulas, and the possibility of more accurate modeling using the Coulomb-Mohr Model using the techniques proposed in the article.

In several sources attempts have been made to link the deformation modules of the Hardening Soil Model [2], and the Plaxis software complex uses the following dependencies, which are in the range of the indicated sources:

$$E_{ur} = 3E_{50}, \quad (2)$$

$$E_{oed} = E_{50}. \quad (3)$$

Another deformation parameter - the exponent m will be equal to 0.5, for the reasons given in [1], as the minimum of those that are appropriate to use in the Hardening Soil Model.

It is proposed, using these values and dependences for deformation parameters, to investigate the SSS of underground structures and to compare with the results obtained using the Hardening Soil model with the input parameters, which were determined in the laboratory and reported in [3]. From the same source we will use strength parameters. Their definition is clearly regulated and no difficult to use.

Experiment 1. The SSS of the soil mass under the effect of a 10 m wide stamp (plate) was investigated in the Plaxis. The considerable width was chosen considering the fact that the Eoed parameter, which is responsible for the volumetric component of deformations, will be subject of adjustment, since such zones appear below the plates, it will be possible to give a more accurate estimate of the possibility of using the calculated odometric module. The soil characteristics for the Hardening Soil Model are from publication [3].

The dimensions of the soil model in the first case were taken from the considerations given in [4] – the lower boundary at a depth of 12 m, and the side faces at a distance of 12 m from the edge of the plate. In the second case the dimensions are taken twice as large – 24 m respectively.

The results of the research showed that the accuracy of the simulation using the calculation modules depends on the initial relationship between the deformation characteristics of the soil. The greatest differences are predicted to arise when the true ratios differ substantially from those adopted empirically by formulas (2-3). So the difference between the deformation values for the loam (E50 = 40 MPa, Eoed = 30 MPa, Eur = 160 MPa, m = 0.7) is about 15%, and for the loam (E50 = 170 MPa, Eoed = 85 MPa, Eur = 850 MPa, m = 1) 35%. It should be noted that even such a difference can be considered satisfactory due to characteristics of the soil. Thus, the comparison of sediment values got in the software complex and calculated by the layer summation method showed a significant difference - the results of settlements using Hardening Soil Model are 1.5-2 times bigger than those calculated by the layer summation method. This can be explained by the fact that the original deformation modules (with reference index) were determined at a reference pressure pref = 100 kPa, which actually measures up to some depth yref. According to formula (1), the values of the modulus of deformation at a smaller depth are smaller, and in the layer-by-layer method, the output module belongs to the "bottom surface" and increases with depth. It should be mentioned that the formulas in the Hardening Soil Model well describe the soil hardening itself, so it is recommended to choose the lowest reference pressure for this engineering-geological element (GEE) [1].

In addition, soil hardening (actually "scattering" of stresses with depth) in the layer-by-layer method is based on the theory of linearly deformed medium. The change of pressure with depth here does not depend on the characteristics of the soil, but only on the size of the platform that exerts pressure on the base:

$$\sigma=\frac{2\cdot p}{\pi}(\mathrm{arctg}(\frac{\eta}{\zeta\cdot\sqrt{1+\zeta^2+\eta^2}})+\frac{\zeta\cdot\eta\cdot(1+\eta^2+2\zeta^2)}{(\eta^2+\zeta^2)\cdot(1+\zeta^2)\cdot\sqrt{1+\zeta^2+\eta^2}}), \quad (4)$$

where η – the ratio of the sides of the site, ζ – the relative depth to the width of the site, p – the average pressure under the sole of the foundation.

In Hardening Soil, soil hardening is described by its characteristics, including density and depth.

The usage of the Coulomb-Mohr Model gives approximate values of precipitation to the calculated by layer-by-layer summation. However, only if the recommendations for the selection of boundaries of the calculation area are fulfilled. As the depth of the model increases, the SSS values at the base and plate increase in proportion to the depth. This problem and one of the possible ways to solve it are described in [5].

The described method has demonstrated its effectiveness once again. However, because of the features and differences discussed above, the Hardening Soil Model and the theory of linear deformed medium on which the methodology is based there is no need to speak about the convergence of results.

The Article [3] describes another approach to modeling soil hardening with depth. The model is broken down into layers, the modulus of deformation for each is calculated using formula (1). In this formulation, a fairly good convergence of the deformation values with those obtained using the Hardening Soil Model is achieved. However, the stresses in the soil array and plate are not so well matched, but closer than usual using the Coulomb-Mohr Model.

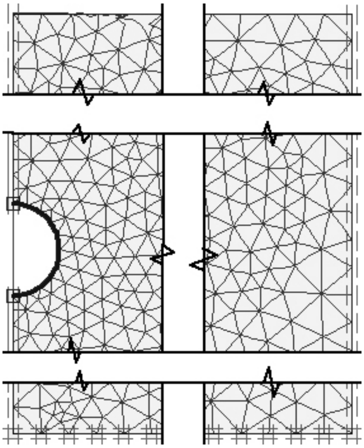


Fig. 1. The scheme of numerical experiment 2

Experiment 2. The SSS of the underground tunnel was investigated (Fig. 1). The depth of the tunnel was varied to investigate the effect of the thickness of the soil mass above the tunnel rim on the SSS. The lower boundary of the model also varied for the same reasons. The lateral face was simulated at a sufficient distance to minimize its impact on the SSS.

The direct dependence between the load on the soil mass above the underground structure and the depth of its deposition is preserved and does not depend on the soil models used. Such a change in constant loads does not correspond to the true state of affairs at great depths. This problem is considered in article [6].

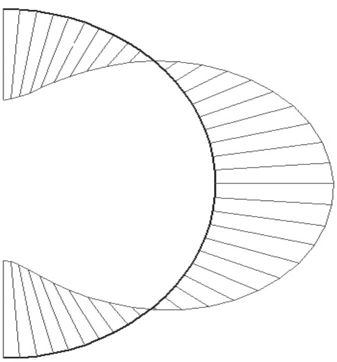


Fig. 2. The nature of the plot of the moments in the tunnel frame

As the thickness of the array under the tunnel increases, the value of raising the lower part of the tunnel frame increases. When using the Coulomb-Mohr Model, no direct correlation is observed without adjusting the parameters.

When using the Hardening Soil Model, the absolute values of the bottom of the tunnel are lower, because the model uses a deformation module during unloading-reloading, and the process of the excavation of soil from the tunnel space is accompanied by some unloading of the soil mass below it. In addition, the dependence of this module on the level of stresses in the soil array reduces the influence of the values of the thickness of the array under the underground structure on the value of deformations.

The use of the Hardening Soil Model with the corrected parameters again confirms the conclusions drawn in the previous experiment and depends on the initial relationships between the deformation characteristics of the soil while maintaining the benefits of the model.

The possibility of using Coulomb-Mohr to involve techniques of increasing the modulus of deformation with depth allows to reduce the effect of the thickness of the array under the tunnel on the values of deformations, which still remain inflated compared to the values obtained using the model Hardening Soil.

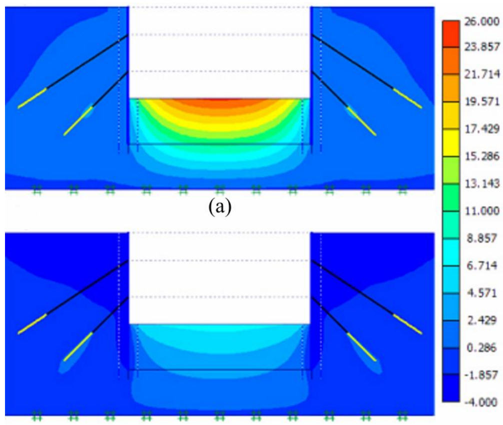
In addition, the values of the moments in the frame, when calculating using the Coulomb-Mohr Model, are almost doubled compared to Hardening Soil. The nature of the charts remains unchanged. It somewhat reduces the value of modeling efforts to strengthen the soil with depth.

Experiment 3. The value of the modulus of deformation during unloading-reloading clearly illustrates an example of the calculation of a pit.

During the excavation of the soil, the bottom of the pit is washed out, due to the removal of its own stresses from the soil massif. However, in the absence of the unloading-reloading module, excavation modeling using the Coulomb-Mohr Model results are in an overestimation of the deformation values.

The validity of this model and the above assertion that due to the lack of dependence of the modulus of deformation on the stress level in the soil array, the value of deformation depends essentially on the thickness of the soil layer under the pit.

According to formula (3), an increased value of the modulus of deformation in the Coulomb-Mohr Model was specified for the entire massif and separately for the part of the excavated soil below the pit.



(a)

(b)

Fig. 3. Lifting the bottom of the pit after modeling the excavation process, mm:
(a) when using the Coulomb-Mohr Model
(b) when using the Hardening Soil Model

In both approaches, the results of the excavation of the bottom of the pit correspond to the obtained values when using Hardening Soil Model. Some differences are observed in the values of efforts in the retaining wall, the nature of the diagrams is consistent.

The use of the Hardening Soil Model with the adjusted parameters gave the expected results, which are consistent with the conclusions reached after the previous tasks have been solved.

Conclusions. The obtained results show that the possibility of using the Hardening Soil Model with the corrected parameters got using empirical formulas depends directly on the initial relations between the deformation characteristics of the soil. Therefore, formulas (2-3) should be refined depending on the type of rock, depth of occurrence, etc. after appropriate research. The same applies to the parameter m. It is necessary to carry out research for different breeds of different regions and to systematize the results obtained in tabular form, as they tried to do it in the publication [7].

At the same time, even such rough modeling with the Hardening Soil Model allows to use its advantages - nonlinear dependence between deformations and stresses, separation of the shear and bulk components of deformations, separate trajectory of deformations at unloading-reloading, dependence of deformation characteristics on the level of stresses in basis, etc.

However, not all software systems allow the use of Hardening Soil Model. Therefore, it is urgent to clarify the results when using the Coulomb-Mohr Model. The methods discussed in the article will help reduce the impact of this model's disadvantages on SSS and can be used depending on the task separately or in combination.

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ДОСЛІДЖЕННЯ НАПРУЖЕНО-ДЕФОРМОВАНОГО СТАНУ ПІДЗЕМНИХ СПОРУД НА ОСНОВІ ҐРУНТОВИХ МОДЕЛЕЙ З КОРЕГОВАНИМИ ВХІДНИМИ ПАРАМЕТРАМИ

В статті дана оцінка можливості застосування ґрунтових моделей з корегованими вхідними параметрами, шляхом дослідження НДС підземних споруд.

Сьогодні існує велика кількість різних математичних моделей ґрунту: Кулона-Мора, Hardening Soil Model та її похідні (Hardening Soil Small-strain), Soft Soil та її похідні, Cam-Clay тощо. Вони характеризуються різним ступенем складності та діапазоном використання.

В геотехнічній практиці для проведення розрахунків дуже часто використовується найпростіша ідеально пружно-пластична ґрунтова модель Кулона-Мора, яка має ряд недоліків. Hardening Soil Model – вдосконалена нелінійна модель ґрунту, яка є досить універсальною і підходить для моделювання широкого діапазону ґрунтів основ. До особливостей моделі можна віднести використання нелінійної залежності між деформаціями та напруженнями, розділення зсувної та об'ємної складових деформацій, окрема траєкторія деформацій при розвантаженні-повторному навантаженні, залежність деформаційних характеристик від рівня напружень в основі тощо. Однак, велика кількість вхідних параметрів, визначення яких не регламентовано нормативними документами, ускладнює можливість її використання.

Аналізується вплив на величина та характер розподілу напружено-деформованого стану підземних споруд при використанні моделі Hardening Soil з коригованими параметрами, отриманими за допомогою емпіричних формул.

Також актуальним є питання можливості використання моделі Кулона-Мора з залучення методик (різні варіанти збільшення модуля деформації з глибиною, використання модуля деформації E_{ur} при розвантаженні та повторному навантаженні), які дозволять зменшити вплив недоліків цієї моделі на напружено-деформований стан підземних споруд.

Ключові слова: підземна споруда, метод скінченних елементів (МСЕ), модель Кулона-Мора, Hardening Soil Model, напружено-деформований стан (НДС).

Solodei I.I., Petrenko E.Yu., Zatyliuk Gh.A.

THE STRESS-STRAIN STATE INVESTIGATION OF UNDERGROUND STRUCTURES ON THE BASIS OF SOIL MODELS WITH ADJUSTED INPUT PARAMETERS

The article evaluates the possibility of using Hardening Soil Model and Coulomb-Mohr soil models with corrected input parameters by investigating the stress-strain state (SSS) of underground structures.

Today there are many different mathematical models of soil: Coulomb-Mohr, Hardening Soil Model and its derivatives (Hardening Soil Small-strain), Soft Soil and its derivatives, Cam-Clay, etc. They are characterized by the varying degrees of complexity and the range of use.

In geotechnical practice, the simplest perfectly elastic-plastic soil model of Coulomb-Mohr is used very often for calculations, but having several disadvantages. Hardening Soil Model is an advanced nonlinear soil model which is versatile and suitable for modeling a wide range of soil bases. The features of the model include the use of a nonlinear relationship between strains and stresses, the separation of shear and bulk components of deformation, a separate trajectory of deformation during unloading-reloading, the dependence of deformation characteristics on the level of stresses at the base, etc. However, the large number of input parameters, which are not verified by some regulations, makes it difficult to use.

The influence on the magnitude and nature of the distribution of the stress-strain state of underground structures using the Hardening Soil model with the corrected parameters obtained using empirical formulas is analyzed.

Also the question is relevant regarding the usage of the Coulomb-Mohr method with the extension of the methods (different options for deformation of the module with depth, using E_{ur} deformation module during loading and reloading), it may be possible to reduce the number of inaccessible issues in order to inflict on the deformed condition of underground structures.

Keywords: underground structure, finite element method (FEM), Coulomb-Mohr model, Hardening Soil model, stress-strain station (SSS).

Солодей И.И., Петренко Э.Ю., Затылюк Г.А.

ИССЛЕДОВАНИЕ НАПРЯЖЕННО-ДЕФОРМИРОВАННОГО СОСТОЯНИЯ ПОДЗЕМНЫХ СООРУЖЕНИЙ НА ОСНОВЕ ГРУНТОВЫХ МОДЕЛЕЙ С КОРРЕКТИРОВАННЫМИ ВХОДНЫМИ ПАРАМЕТРАМИ

Сегодня существует большое количество различных математических моделей почвы: Кулона-Мора, Hardening Soil Model и ее производные (Hardening Soil Small-strain), Soft Soil и ее производные, Cam-Clay тому подобное. Они характеризуются разной степенью сложности и диапазоном использования.

В геотехнической практике для проведения расчетов очень часто используется простейшая идеально упруго-пластическая грунтовая модель Кулона-Мора, которая имеет ряд недостатков. Hardening Soil Model – усовершенствованная нелинейная модель почвы, которая является достаточно универсальной и подходит для моделирования широкого диапазона грунтов оснований. К особенностям модели можно отнести использование нелинейной зависимости между деформациями и напряжениями, разделение сдвиговой и объемной составляющих деформаций, отдельная траектория деформаций при разгрузке-повторном нагружении, зависимость деформационных характеристик от уровня напряжений в основании и т.д. Однако, большое количество входных параметров, определение которых не регламентировано нормативными документами, затрудняет возможность ее использования.

Анализируется влияние на величину и характер распределения напряженно-деформированного состояния подземных сооружений при использовании модели Hardening Soil с корректированными параметрами, полученными с помощью эмпирических формул.

Также актуальным является вопрос возможности использования модели Кулона-Мора с использованием методик (различные варианты увеличения модуля деформации с глубиной, использование модуля деформации E_{ur} при разгрузке и повторном нагрузке), которые позволят уменьшить влияние недостатков этой модели на напряженно-деформированное состояние подземных сооружений.

Ключевые слова: подземное сооружение, метод конечных элементов (МКЭ), модель Кулона-Мора, Hardening Soil Model, напряженно-деформированное состояние (НДС).

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Солодей І.І., Петренко Е.Ю., Затилюк Г.А. **Дослідження напружено-деформованого стану підземних споруд на основі ґрунтових моделей з корегованими вхідними параметрами** // Опір матеріалів і теорія споруд: наук.-тех. збірн. – К.: КНУБА, 2019. – Вип. 103. – С. 63-70.

В статті дана оцінка можливості застосування ґрунтових моделей Hardening Soil Model та Кулона-Мора з корегованими вхідними параметрами, шляхом дослідження напружено-деформованого стану (НДС) підземних споруд.

Іл. 3. Бібліогр. 7 назв.

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Solodei I.I., Petrenko E.Yu., Zatyliuk Gh.A. **The stress-strain state investigation of underground structures on the basis of soil models with adjusted input parameters** // Strength of Materials and Theory of Structures: Scientific-and-technical collected articles – Kyiv:KNUBA, 2019. – Issue 103.– P. 63-70.

The article evaluates the possibility of using Hardening Soil Model and Coulomb-Mohr soil models with corrected input parameters by investigating the stress-strain state (SSS) of underground structures.

Fig. 3. Ref. 7.

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Солодей И.И., Петренко Э.Ю., Затылюк Г.А. **Исследование напряженно-деформированного состояния подземных сооружений на основе грунтовых моделей с корректированными входными параметрами** // Сопротивление материалов и теория сооружений: науч.-тех. сборн. – К.: КНУСА, 2019. - Вып. 103. – С. 63-70.

В статье дана оценка возможности применения грунтовых моделей Hardening Soil Model и Кулона-Мора с корректированными входными параметрами, путем исследования напряженно-деформированного состояния (НДС) подземных сооружений.

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